Analysis of Distributed Geographical Locations Impact on Intermittency Reduction of Solar Power Plants in Java, Madura, and Bali, Indonesia

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Abstract- To meet its energy demands, Indonesia is taking on an ambitious initiative to broaden its solar power plant portfolio. Despite this, apprehensions persist about how the sporadic nature of solar power supply could impact the system. By exploring the role of distributed geographic location in reducing aggregated intermittency, this study assesses the potential impact and capacity of solar power plant installation that can be integrated into the grid. To perform the research, 54 measurement equipment are dispersed among the islands of Java, Madura, and Bali. By applying the Power Spectral Density (PSD) technique, this study evaluates the potential of these irradiation data to minimize intermittency. Then, to illustrate the resulting improvement, this study calculates solar power plant capacity that could be connected to the Jamali grid. According to our findings, inter-connecting 54 locations decreases the intermittency by 37 to 78% percent, depending on the frequency, and yields an aggregated intermittency of 3%. This would allow up to 6.67 GW of solar power plants spread across 54 locations.

Keywords solar irradiance; measurement; intermittency; power spectral density; hosting capacity.

1. Introduction

Nearly two-thirds of Indonesia's electricity is generated by coal power plants, particularly on Java Island [1]. The power plants serve as a dependable source of electricity for the Java, Madura, and Bali (Jamali) network. However, due to the shortage supply of coal and the need for greener energy, stakeholders are compelled to look for alternative energy sources. Solar energy is presently seen as a potential alternative energy source because of the ease of installation employing photovoltaic (PV) modules.

Although some high-capacity solar power plants have been connected to the electricity grid in Indonesia, they have not yet played a significant role in electricity production. The State-Owned Utility Company, PT. PLN Persero, plans to achieve Net Zero Emission by 2030 with the help of solar generation supporting 4,680 MW peak, as per the 2021-2030 National Electricity Supply Business Plan (RUPTL) [2]. Although Indonesia has set an ambitious goal for renewable energy generation, concerns remain about the intermittency of solar power output, which is highly variable in the short-term due to seasonal changes and cloud cover. Moreover, the storage technology available for addressing this issue is still inadequate.

The deployment of renewable energy sources, particularly solar photovoltaic (PV) systems, is being pushed forward globally. Intermittent resources create challenges for maintaining uninterrupted power supply, as voltage and power fluctuations, manifesting as frequency deviations, risk causing system failures and blackouts when exceeded [3]. Due to their typically intermittent nature, distributed generations such as solar power plants present new opportunities and difficulties as their penetration into the power system increases. To ensure a smooth and manageable functioning, additional support is needed when these distributed generation units are deployed in the medium voltage distribution systems as parts of the smart grid. [4]

The intermittency of solar generation caused by seasonal cycles results in need for alternative resources; thereby, system operation costs increase. When PV is built across a large area, intermittency can be significantly decreased, balancing the electricity market cost [5].

A study compared distributed and centralized PV systems. A distributed system is better for reducing the ramp rates in short periods of 5 minutes. The range for a 100MW PV system is up to 50 MW/5 min [6]. Distributed PV can offer demand response, voltage management, and other grid functions when combined with other new distributed energy resources (DERs), such as battery storage and electric vehicles (EVs). When a considerable number of DERs are aggregated and called upon to supply these services simultaneously, they may deliver the same or more value as significant, centralized power providers [7].

According to a study conducted by Aldeman et al. [8], every 80 kilometers of separation results in a roughly 0.1 drop in the correlation. An output that closely matches its predicted output, with a normalized power output variation of 0.2 kW/kW or less, is 31% more likely to be produced by the four aggregated systems that are spread out far apart. Additionally, the probability that the overall output of the four aggregated systems, described as having a normalized power output variation of 0.4 kW/kW or greater, will be considerably different from the predicted output is 54% lower for the distantly situated systems.

When the results of a novel approach used to measure solar radiation at 1 Hz at 8 locations that traverse the island are added together, compared to individual basis, a smaller number of most intense changes are observed in the cumulated radiation dataset, comprising only 1.7% of the analyzed time, compared to 5.5% to 15.5% for the separately collected data from various sites. With this class accounting for only 0.13% of the time, optimization of the territorial compensation technique results in an almost complete absence of intense fluctuations [9].

To assess the equal distribution of PV power among various sites, Hookoom et al. [10] created a prototype program in MATLAB using the Generalized Reduced Gradient (GRG) Solver Solution optimization. That study found that areas with higher levels of insolation experienced a significant reduction in the intermittency of PV power, resulting in a more even distribution of power output. The total PV power output was increased by up to 8.7% without affecting the levelized cost of energy (LCOE). This suggests that higher levels of insolation can help to smooth out fluctuations in PV power output and improve overall energy production.

Several studies have shown the correlation between solar power variability with distance and time intervals. Perez et. al [11] shows that the relationship between the solar power variability, distance and time scale is predictable. Their research reveals that the correlation between site pairs for cloud transient variability diminishes as the distance increases. Mills and Wiser [12] determine that the costs associated with handling the short-term fluctuations in solar power are significantly lowered through the presence of geographic diversity.

There are different ways to characterize variability of solar power. Perez et. al [11] used the standard deviation and 99.7th percentile of step changes which are commonly used in wind integration studies. Lave and Kleissl [13] used Power Spectral Density (PSD) analysis which provides insight into how much of the variability in solar power can be explained by events at different frequencies such as daily and seasonal cycles. Klima and Apt [14] also used PSD to assess solar power smoothing by combining output of geographically separated plants. The PSD, which shows how energy has been dispersed in the frequency domain, will represent power as a function of frequency. Lower intermittency on corresponding timesteps indicates a lower power spectrum on said frequencies. Hafsah et al. [15] examined the overall irradiation of 18 places for its intermittency also using PSD. This study shows that linking all stations lowers intermittency by 70 to 93 percent. The analysis also shows that the decrease becomes minor beyond 10 sites.

This research determines to what extent dispersed solar power plants can reduce the variability of solar intermittency. Furthermore, it also evaluates the potential number of PV power units that could replace coal-based power units in the Jamali network as they are phased out. This endeavor has difficulties since solar power plants cannot function as dependably as coal power plants, which continuously produce electricity because they cannot supply energy. The sporadic nature of the power supply can negatively affect the stability of the electricity system. To mitigate this issue during integration, a study should be conducted.

The structure of this paper is: the methodology utilized in this study is explained in Section 2 along with the data and analysis techniques. Results and discussion are presented in Section 3. A summary of the results is presented in Section 4 to conclude.

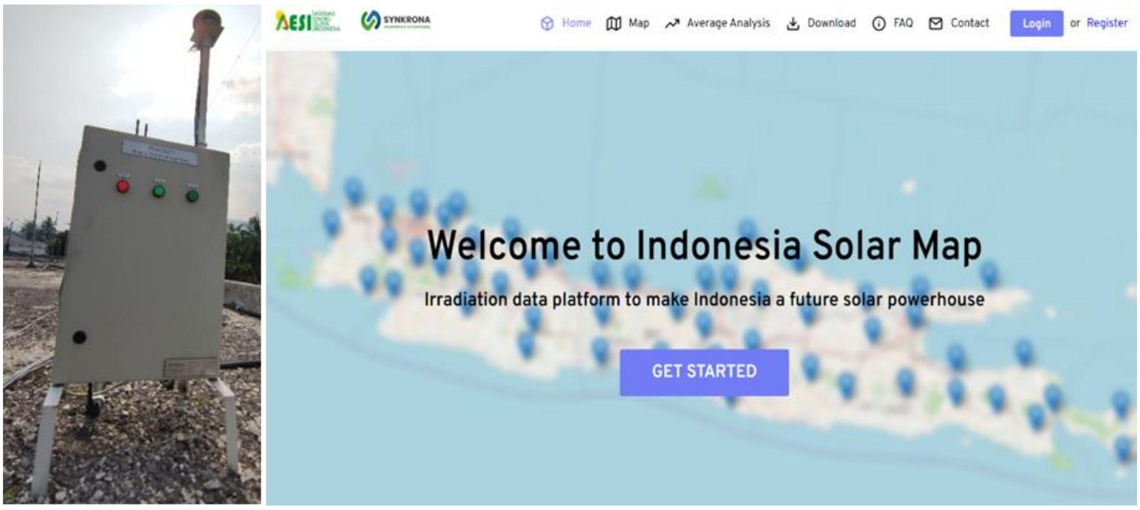
2. Methods

The research requires three major steps to get the variability reduction analysis and the estimated possible solar power plants installed to the grid; measurement, intermittency analysis, and hosting capacity.

2.1. Irradiation Measurement

As seen in Figure 1, irradiation measurement equipment is mounted in each location. The installation is primarily done in universities, PT. PLN Persero substations, and government offices. The instrument's irradiation sensor is a pyranometer and a minicomputer that records the information. The data is transmitted to a central server using a router that has an internet package. The information is subsequently displayed on the public website indonesiasolarmap.com. This study makes use of three months' worth of data at 30 second intervals.

Figure 2 illustrates that the 54 locations were selected to achieve a geographically uniform distribution of measurement devices. Consequently, the devices collectively represent the irradiation of the entire Jamali Grid System.



Welcome to Indonesia Solar Map

Irradiation data platform to make Indonesia a future solar powerhouse

Fig. 1. Real-time irradiation measurement system [16]

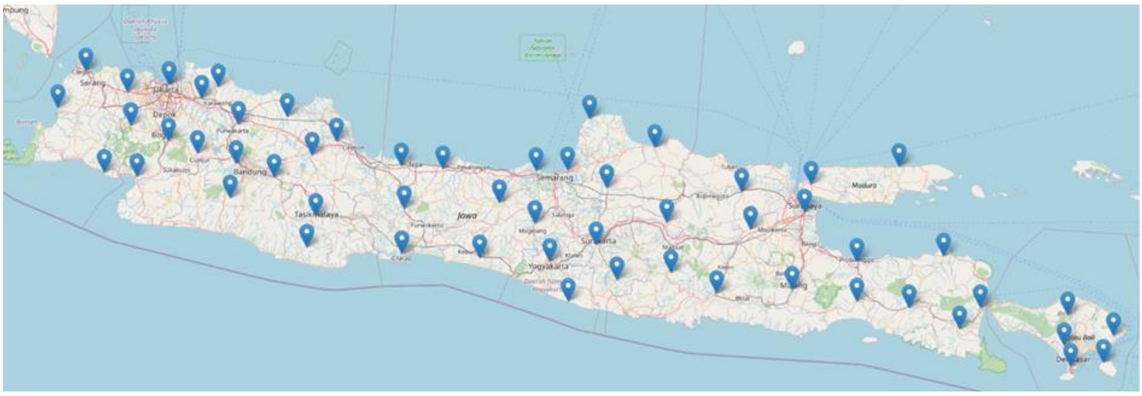


Fig. 2. The distribution of the device's location around Java, Bali, and Madura island [17]

2.2. Intermittency Analysis

Each location's irradiation data are mixed with one another to create combinations of 2, 3, and as many as 54 locations. The sequence moves from a predetermined site to the closest position, measured in kilometers (km). According to this study, the power generated by solar power plants is assumed to have the same intermittent characteristics as irradiation, as the effects of factors such as humidity, temperature, and inverter efficiency on power output are not considered. Therefore, the solar power plant output is intermittently variable like irradiation.

The Power Spectral Density (PSD) for each combination is then determined. The relative variability at the corresponding timestep increase if the PSD value is significantly high for a specific frequency. The variability here refers to the intermittent nature of solar irradiation, which directly affects solar power generation. To calculate the PSD, the Welch method is used. The Welch Method represents an enhancement over the periodogram technique for estimating spectra, particularly when the signal-to-noise (SNR) ratio is high. It addresses noise in the calculated power spectra by sacrificing some frequency resolution. reduction [18]. This results in lower variances than the periodogram-based approach. Meanwhile, the disadvantage of this method is losing the sharp peaks and corners that the actual PSD has. This method involves four steps [19]:

1. The N-point data sequence is broken into M segments, with L being the segment length and T being the i-th sequence's starting point. T allows for overlapping segments, with a 50% overlap between segments if T = L/2 (Eq. 1)

$$x_i\,(n) = x\,(n + iT) \qquad \begin{array}{l} n = 0.1, \ldots, L\text{-}1 \\ i = 0.1, \ldots, M\text{-}1 \end{array} \tag{1}$$

x_i : i-th segment data
T : i-th segment starting point
i : segment increment
L : length of segment
n : data increment
M : number of segments

2. Window w(n) is used to window each data segment (Eq. 2)

$$x_{iw}(n) = x_i(n)w(n) \tag{2}$$

x_{iw} : windowed data in i-th segment
n : increment of data
w : window function

3. The power spectrum $P_{xx}^{(i)}$ is calculated for each windowed section as (Eq. 3)

$$P_{xx}^{(i)}(f) = \frac{1}{L}\left|\sum_{n=0}^{L-1} x_{iw}(n)e^{-j2\pi fn}\right|^2 \qquad i = 0.1,\ldots M-1 \quad (3)$$

4. For the M segments, the whole power spectrum is averaged (Eq. 4)

$$P_{xx}(f) = \frac{1}{M}\sum_{i=0}^{M-1} P_{xx}^{(i)}(f) \qquad (4)$$

In this assessment, we assume that the frequency range f = 1.15 × 10^{-5}Hz to f = 1.67 x 10^{-2}Hz (corresponding to times of 24 hours to 30 seconds) is approximately linear, as shown in [20]. The Welch Method should therefore be used in this situation.

2.3. Hosting Capacity

The occurrence of intermittency will be regarded as a fluctuating negative load by the Jamali Grid, and this abrupt change will damage the operational frequency. The degree of influence is determined by the grid stiffness, intermittency rate, and installed solar power plant capacity.

Grid stiffness represents the frequency deviation brought on by a change in load measured in MW/Hz. The composite frequency response (β) is another name for it. The system's overall regulating feature is equal to 1/β [21]. The stiffness is formulated as (Eq. 5)

$$\beta = dP/df \qquad (5)$$

which is affected by the power change to changes in frequency.

Further investigation measures the intermittency from a one-time point to the initial time point throughout all time. The intermittency rate is calculated using (Eq. 6).

$$\text{Int} = \frac{\text{Irr}_n - \text{Irr}_{n-1}}{\text{Irr}_{\text{STC}}} \times 100\% \qquad (6)$$

where $(Irr_n - Irr_{n-1})$ is the difference in irradiation between the two points in time, and Irr_{STC} is the maximum irradiation value of about 1,000 W/m. For instance, the intermittency rate said -40% if the irradiation changes from 900 W/m^2 to 500 W/m^2 in thirty seconds.

The maximum of a solar power plant's capacity that can be linked to the current grid can be evaluated to keep the frequency stable during unfavorable intermittency by considering the Jamali grid's stiffness, as well as the intermittency. In the end, the hosting capacity (HC) of solar power plants can be determined by dividing the grid stiffness with the highest intermittency rate (Int_{high}) [21], as shown in the formula (Eq. 7).

$$HC = \frac{\beta}{Int_{high}} \qquad (7)$$

Voltage levels rise when the infeed power by solar photovoltaic increases, and energy consumption is low [22]. Understanding hosting capacity is essential to efficiently integrate distributed generation, such as solar, into power grids, as having many generators can cause problems like voltage spikes, overheating, and device malfunctions [23]. Other problems such as increasing short circuit current and power quality issues can also limit the hosting capacity of the renewable energy sources in distribution networks. Hosting capacity in distribution networks can be limited by voltage violations, overload of lines and transformers, increasing of short circuit power and power quality issues [22].

3. Results

3.1. Intermittency Reduction Analysis

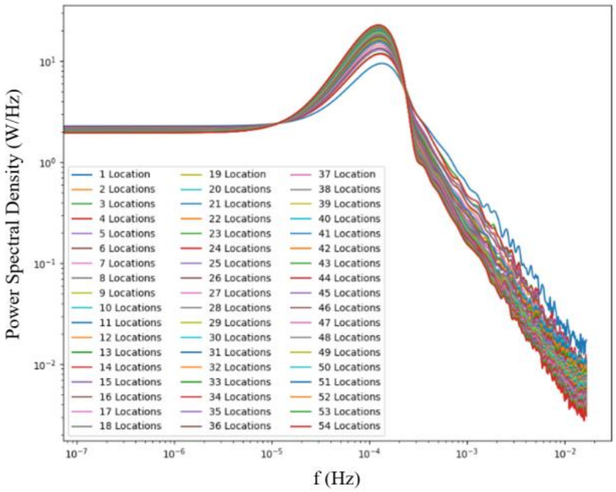
Irradiation data from the first of April 2022 to the last day of June 2022, or a period of three months, are utilized. This is based on the availability and integrity of the data. Using the following settings, Python is used to calculate the power spectrum: the overlap is set to 50% (T = L/2), the segment length L is set to 256, and the total number of data points N is set to 127,243. Hann Window is selected as the window function (Eq. 8). The Nyquist frequency (shown as the maximum frequency of the power spectrum) is 1/60s or 1.67 x 10^{-2} Hz because the data is sampled every 30 seconds.

$$w(n) = 0.5\cos\left(\frac{2\pi n}{L-1}\right) \qquad 0 \le n \le L-1 \qquad (8)$$

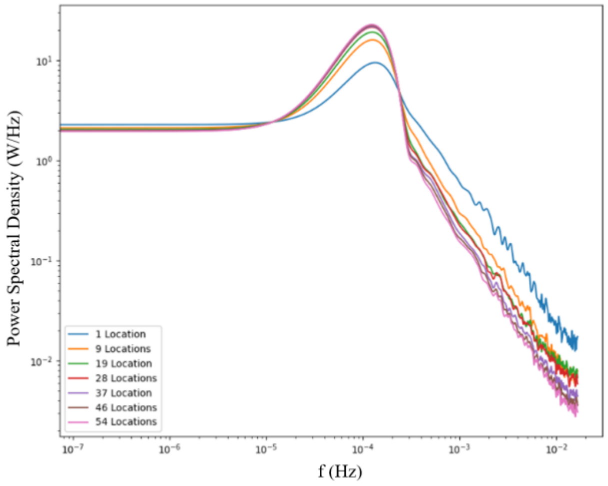
$w(n)$: Hann window (window function)

L : length of segment

n : data increment



(a)



(b)

Fig. 3. Power Spectral Density (PSD) Calculations for (a) 1-54 locations and (b) 1, 9, 19, 28, 37, 46, 54 locations (others are not shown for clarity)

Figure 3 shows the PSD calculation using the Welch approach for the combined irradiation data from 1 to 54 locations. As there would not be an intermittency reduction in this timestep, the power spectra were normalized so that they overlapped on f = 1/24h = 1.15 x 10^{-5} Hz [24]. Figure 3 already demonstrates lower power spectrums on higher frequencies with more aggregated sites. This means that the need for another power sources to compensate power fluctuations at high frequencies (fast response) is reduced.

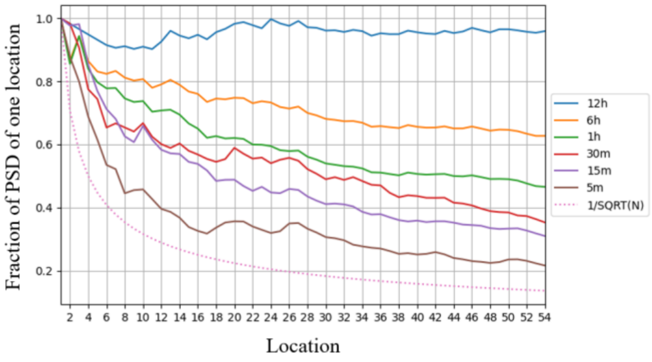


Fig. 4. The intermittency reduction per timestep

To investigate the reduction on certain response times, we evaluate the intermittency for each timestep as a proportion of the power spectrum of one location. Figure 4 illustrates that at a 12-hour timestep, hardly any intermittency decrease occurs (blue). As the timestep shorten from 6-hour to 5-minutes, the intermittency reduction grows more effective with the additional number of locations. At 5-minutes timestep, the reduction in intermittency nearly matches $N^{-0.5}$, the greatest possible reduction in intermittency with additional N locations proposed by Hoff and Perez [25].

The sharp reduction was demonstrated by linking the first 5-8 locations, as in the majority published papers. Interconnecting with 54 dispersed locations reduced intermittency by 37% at the 6-hour timestep, 53% at the 1-hour timestep, 65% at the 30-minute timestep, 69% at the 15-minute timestep, and 78% at the 5-minute timestep. It was also clear that at the 6-hour and 1-hour timesteps, there was no decreasing effect in any additional location addition.

3.2. Estimated Solar Power Plants Hosting Capacity

The estimation of solar power plant capacity that can be connected into the Jamali grid had been assessed in the previous work [26]. The research also used the irradiation data measurement across Java and Bali islands. The resulting housing capacity can then be used to estimate the amount of coal-based power plants that can be replaced several years ahead.

The approach for calculating the Jamali system stiffness is based on historical information about a generator fault in a Java power plant in the second half of 2012 [27]. It showed a linear relation between generation change (dP) and frequency shift (df), resulting in Jamali stiffness around 916.91 MW/Hz.

However, P2B PLN, the Load Control and Dispatch Center of PT PLN, stated that the stiffness value for the Jamali system is typically 1,000 MW/Hz in 2022. The final deal can be approximated by the latest report from the grid operator, PT PLN. Additionally, the system's stiffness will change by incorporating variable renewable energy (VRE) power plants [28]. Grid stiffness decreases as VRE power plant penetration increases. Despite that, as the hosting capacity will only be based on the irradiation fluctuation in this research, that will not be considered.

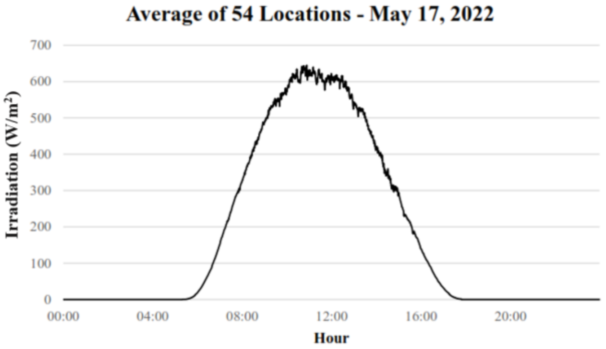


Fig. 5. Combined irradiation graph for 54 individual locations

The aggregation of 54 measurement points is shown in Figure 5. The graph is a smooth chart, like the ideal bell curve of the irradiation pattern. Table 1 summarizes the calculations for all locations and times. The highest intermittency observed was only 11%, and no values exceeded 50% compared to individual sites. It proves the hypothesis and verifies [29] that dispersing solar power plants can reduce intermittency.

Table 1. The percentage of intermittency occurred in all locations and times

No.	Percentage (%)	Sum
1	0	89,812
2	0 - 0.1	32,162
3	0.1 - 1	47,974
4	1 - 2	5,218
5	2 - 3	474

6	3 - 4	27
7	4 - 5	5
8	5 - 10	7
9	10 - 50	1
10	50 - 90	0
11	90 - 100	0
12	> 100	0

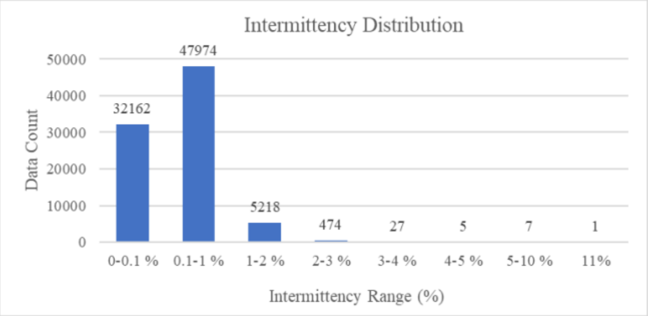


Fig. 6. The intermittency range of all the sites

Looking deeper into the statistics, Figure 6 reveals that the worst intermittency (11%) occurs just once during the period, while the intermittency occurs only 0.1% to 1% of the time. The grid code [30] limits the frequency increase to 0.2 Hz, allowing for a sudden increase or decrease in power of up to 200 MW. This change is equivalent to a maximum of 11% intermittency rate. Thus, using the formula (Eq. 7), it can be depicted that the estimated solar power plants connected to the grid are:

$$HC = \frac{\beta}{Int_{high}} = \frac{200}{11\%} = 1.82\ GW_{AC} \qquad (9)$$

However, according to Figure 7, the worst-case scenario is 11%, which only occurs once every two months. As a result, the hosting capacity estimate in equation (Eq. 9) yields the most pessimistic result. The intermittency statistics and their associated hosting capacity value are shown in Table 2 for a more optimistic figure. Since there are only 36 intermittencies that are greater than 3%, it is safe to pick 3% as the preferred aggregate intermittency based on the abovementioned data. The hosting capacity increases significantly to 6.67 GW_{AC} when the intermittency is set at 3%.

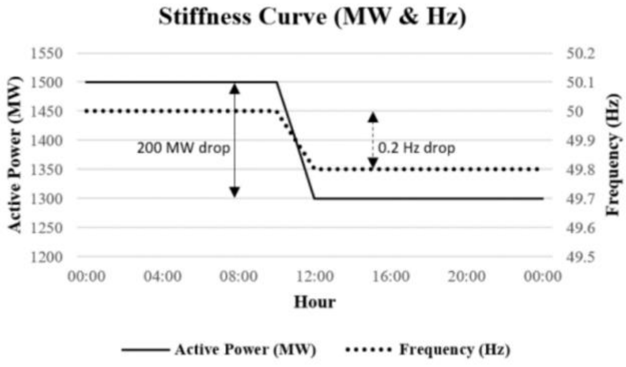


Fig. 7. The deviation of frequency based on the power changes

Table 2. The nominal of hosting capacity on the intermittency value differences

Intermittency	Stiffness (MW/0.2 Hz)	Hosting Capacity (GW)	Count	Percentage (%)
0.1	200	200	53,706	62.5448
1	200	20	5,732	6.6754
3	200	6.67	13	0.0151
5	200	4.00	7	0.0082
11	200	1.82	-	0.0000

The total amount of solar power plants that may be deployed over 54 locations is 6.67 GW_{AC}. Every 54 locations will have a 123 MW_{AC} solar power plant if the capacity is distributed evenly among them. In the worst situation, even if one site has 100% intermittency or the power decreases significantly, the frequency will remain within the grid code by only falling by 0.12 Hz.

4. Conclusions

Our findings show that aggregating irradiation data from scattered sites across Java, Madura, and Bali can reduce intermittency by 37-78% depending on timestep matching frequencies. By interconnecting 54 solar power generators of similar capacity, the Jamali grid system's need for an additional power source with a response time of 1 hour or less can be reduced by about 50%. In this study it was found that using a 1-hour timestep caused the most effective intermittent reduction, shown by interconnecting 5-8 locations, with a final reduction of 25%.

Our study also finds that when 54 locations are used, the worst-case intermittency is only 11% and the occurrence is extremely low. This concludes the most pessimistic of the Jamali's hosting capacity is 1.82 GW_{AC}. However, by examining the occurrences of intermittency, we determine that only 3% of the total intermittency needs to be considered. This means that the Jamali system can take in up to 6.67 GW_{AC} of solar power plants across 54 locations, or 123 MW_{AC} per location.

We should note that the effects of grid-tied solar photovoltaic inverters on power grid, which could cause additional problems like low power factor or voltage unbalance [31], were not examined. This could act as additional constraints to refine the analysis of the Jamali's hosting capacity. In addition, the data length was still capped at three months. To fully comprehend the characteristics of the irradiation data in the Java, Madura, and Bali regions, more data will need to be evaluated in the future.

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