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5 Photovoltaic Modules and BoS Components
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Session Type

P = Plenary Session
O = Oral Session
V = Visual Session

Day Codes

A = Monday, 24 September 2018
B = Tuesday, 25 September 2018
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PERFORMANCE OF A REMOTE HYBRID PV SYSTEM BASED ON REAL AND MODELLED DATA IN INDONESIA

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ABSTRACT: This paper is aimed at assessing the performance of a remote hybrid PV/diesel system located on the Island of Kri in Papua, Indonesia. For this purpose, monitoring data of electrical variables at 5 minutes recording intervals were used. Using the INSEL simulation environment, in-plane irradiance (G_i) was modeled from global horizontal irradiance (G_h) data from five weather stations at various distances from the hybrid PV system. Also, PV module temperature (T_m) was predicted from ambient temperature (T_a) and wind speed (v) according to the Sandia model for module temperature. The performance of the PV element of the hybrid system was compared with data from another PV system in Jayapura (also in Papua) which is grid-connected. We found that the performance ratio (*PR*) of the PV systems in Kri and Jayapura during the observation period were 41% and 90%, respectively. We also found that data from remote weather stations with a distance of up to 100 km from the reference PV system could be used to get the same *PR* values. However, with greater distance, the *PR* deviates non-linearly in the range of 20% to 50%, which is in line with previous findings indicating no correlation occurs. Our advice is, therefore, to apply local irradiance monitoring at PV sites instead of extrapolating irradiance over significant distances.
Keywords: Grid-Connected, Modelling, Monitoring, Performance, PV System, Rural Electrification.

1 INTRODUCTION

For many years, diesel generators (gensets) have been used for producing electricity in remote areas of Indonesia. However, they have high operation and maintenance costs, create noise, cause pollution, and emit carbon dioxide (CO_2) [1]. Given the increasing costs of diesel fuel and decreasing costs of PV modules, hybrid PV/diesel have become favorable alternatives for diesel gensets. They are economically viable for 15-20 years of project lifetimes [2], especially in rural areas and remote islands [3].

Highly performing hybrid PV systems are required and therefore, understanding their performance is important for further improvements. However, the essential variables that are needed for analyzing their performance are not always measured on-site. This especially applies to small hybrid PV systems [4] for which monitoring systems are considered to be too expensive. Alternatively, their performance can be assessed using data from other locations, such as meteorological stations or other PV systems that are monitored [5].

Based on that background, this study evaluates the use of remote data to estimate the performance of a selected hybrid PV system in Indonesia. This study proposes a modeling and statistical approach for performance analysis of a PV system with incomplete on-site datasets. The procedure involves two PV systems and seven automatic weather stations (AWS) of the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) which are available online (Figure 1).

This study is relevant for Indonesia because Indonesia lacks best practices in implementing PV systems while these could be a proper alternative power source for thousands of communities in rural areas or small islands.

Figure 1: Locations of PV systems and the automatic weather stations.

2 MONITORING AND METHODS

2.1 Hybrid PV/diesel system on Kri Island

The hybrid system on the island of Kri (0º 557 'S, 130º685 'E) in the Raja Ampat Regency, the Province of West Papua, Indonesia, consists of three PV arrays with a total capacity of 28.8 kWp and two 42 kVA and a 60 kVA Yanmar gensets connected in an AC-coupled configuration (see Figure 2). The PV arrays are ground-mounted close to the equator with 15º tilted angle to the North (two arrays) and to the South (one array). Each array consists of 6 panels which contain 8 monocrystalline PV modules of 200 Wp from Sky Energy. Every two panels are connected to one inverter from Murata.

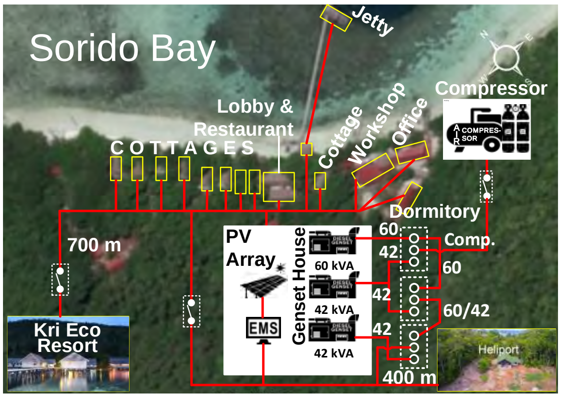

Figure 2: Schematic diagram of the hybrid PV/diesel systems on Kri Island, reproduced with permission of Murata. Photo credits: Kri Eco Resort (Herbert Innah).

Being a diving resort, two main electrical loads on Kri include the resort load and the compressor load. The resort load comes from guest accommodations, restaurant, offices, and workshop located at two locations namely Kri Eco Resort and Sorido Bay Resort. The two resorts are about 700 m apart. The compressor load comes from three compressors for filling the compressed air tanks for divers. The energy management system (EMS) of Murata measures power and energy from the PV panels, gensets, and loads with 5 minutes recording intervals. However, global in-plane irradiance (G_i) and PV module temperature (T_m) were not measured on-site.

2.2 Grid-connected PV system in Jayapura

As a reference, a 34 kWp grid-connected PV system has been operating since 2012 in the City of Jayapura (2º562 'S, 140º692 'E) for research purpose and has been extensively monitored and analyzed [6-8]. The PV modules are tilted 10º to the North. It consists of four arrays of different sizes and types of PV modules. Due to the availability of data, in this study, we use only the 7 kWp array of micro-amorphous silicon modules (Ample Sun) which are connected to an SMA Sunny Mini Central (SMC) inverter.

All variables for performance analysis were measured on-site at a recording interval of 5 minutes for electrical variables and 1 minute for meteorological variables. They include the following variables: total energy production, currents, power, voltage, global horizontal irradiance (G_h), global in-plane irradiance (G_i), ambient temperature (T_a), and PV module temperature (T_m).

2.3. Automatic weather stations (AWS)

Data from seven AWSs were used as modeling inputs. Three variables monitored by the AWSs used in this study include G_h, T_a, and wind speed (v). The data sampling varies from one sensor to others, but the recording intervals were the same, namely 10 minutes.

Because the timeframe of the available data from the PV systems at Kri and Jayapura do not match one and each other, we selected only AWSs that provide data in similar time frames. Therefore, the AWS stations used for the performance analysis of PV system in Jayapura are different to the AWS stations used for the analysis of PV system in Kri. As shown in Figure 1, stations with green background refer to Kri and orange refer to Jayapura. To model the G_i and T_m for the performance analysis of power system at Jayapura, data from AWSs at Lereh, Timika, and Labuha with the distance of 100 km, 475 km, and 1,500 km, respectively, from PV system at Jayapura, will be used. Also, the AWSs at Sorong, Labuha, Manokwari, Timika and Jayapura with the distances of 70 km, 355 km, 375 km, 820 km, and 1,147 km respectively, from Kri island, will be used to model the G_i and T_m for the performance analysis of power system at Kri, see Figure 1.

The big distances among the PV systems and the AWSs are proportionate to the size of Indonesia which lies over more than 5,000 km length from its easternmost to its westernmost.

2.4. Modeling G_i from G_h

Some models offer validated approaches of estimating G_i from the G_h. Each model differs from others depending on how the diffuse fraction of the solar irradiance is handled. The Liu and Jordan model [9], for example, assumes an isotropic distribution over the complete skydome, while Hay [10] assumes a brightening of the horizon band and the circumsolar region [11].

In general, modeling the G_i from G_h involves two steps. First, the decomposition of G_h to its direct and diffuse components. Second, the transposition of these components to G_i. The conversion has a typical uncertainty of 2% to 5% [12].

In this study, we evaluated 60 combinations of decomposition and transposition models available in INSEL® software. INSEL is a simulation tool that uses block diagram for engineering programming, including applications of the renewable energy sector, which is mainly intended for use in research and education [13].

2.5. Modelling T_m from T_a and v

Because the PV module temperature (T_m) is often not measured on-site in many PV systems, including in Kri, we use the Sandia Module Temperature Model (SMTM). SMTM uses T_a and v as inputs to predict the Tm.

The T_m according to the SMTM is given by:

$$T_m = G.(e^{a+b.v}) + T_a \quad (1)$$

where a and b are parameters that depend on the module construction and materials as well as on the mounting configuration of the module. A more detailed explanation about the SMTM including the values of a and b can be found at the Sandia Laboratories website [14].

2.6. Performance assessment

Performance assessment of the hybrid PV system and the reference system was be conducted according to monitoring standard IEC 61724 [5]. Figure 3 shows the complete procedure applied in this study which involves the modeling of the G_i and Tm, and the calculations of the performance of the PV systems. The performance assessment will involve two main operations. First, using the G_h as input, the G_i will be calculated using INSEL. Then, using the T_a and v, T_m will be modeled according to the Sandia Temperature Model [14]. This step will be first applied to the reference PV system in Jayapura.

Second, based on the results from the first step, the performance of the PV system in Jayapura and Kri be calculated. This process will use the modeled G_i and T_m and measurement data from each PV system.

The procedure used to calculate the performance analysis according to IEC 61724 was developed in Python environment.

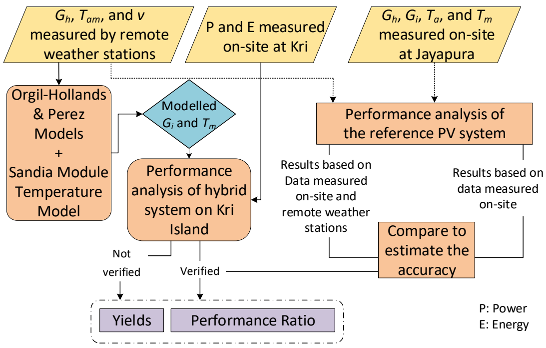

Figure 3: Flowchart of the method.

2.7. Treatment to the datasets

All irradiance values, either measured or modeled, which lie beyond 10 W/m^2 and 1500 W/m^2 have been removed from the datasets. The reason for this is because the former is prone to error due to extraneous night-time data values and the latter is because it is too high. Further, all the daytime data, between 06:00 and 18:00 local time, were kept for the analysis. All missing data were excluded from the analysis.

For the ambient temperature, only values between -40 and 60 ºC were used. For the module temperature, values between ambient and ambient plus 40 ºC were used because the studied PV systems are open rack-mounted systems. As such, any T_m values lower than T_a that might occur in the early morning due to irradiation to the sky were not included in the analysis.

For the electrical data of the PV system, the values used for the array voltage only those between 0 and 1.3 x V_{oc} of the array under STC. Also, the array current values between 0 and 1.5 x I_{sc} under STC were used in the analysis. Various Python codes were written for managing the data.

3. RESULTS AND DISCUSSION

As shown in Table I, weather data from seven remote weather stations and electrical data from two PV systems were used in this study. Weather data four stations were used for performance analysis of PV system at Jayapura (τ:15 January to 15 March 2015), while data from five stations were used for PV system at Kri (τ:20 September 2017 to 20 February 2018). Data from Labuha and Timika were commonly used for performance analysis of both PV systems.

All data have been checked for consistency and gaps to identify obvious anomalies. All nighttime data (between 18:05 and 15:55) have been excluded from the analysis, including outliers and discovered missing data.

Table I: Data locations and measured variables

Location	Measured Variables	Record Interval (min)	Time Period
1. Jyp *(AWS)*	G_h, T_a, v	10	20/9/17-20/2/18
2. Jyp *(PV)*	E_{Tot}, I_{ac}, I_{PV}, P_{ac}, V_{ac}, V_{PV}	5	15/1/15-15/3/15
3. Jyp *(AWS_{PV})*	G_h, G_i, T_a, T_m	1	15/1/15-15/3/15
4. Kri *(PV)*	L_R, L_C, P_{DG}, P_{PV}, E_R, E_C, E_{DG}, E_{PV}	5	20/9/17-20/2/18
5. Labuha	G_h, T_a, v	10	15/1/15-15/3/15 20/9/17-20/2/18
6. Lereh	G_h, T_a, v	10	15/1/15-15/3/15
7. Manokwari	G_h, T_a, v	10	20/9/17-20/2/18
8. Sorong	G_h, T_a, v	10	20/9/17-20/2/18
9. Timika	G_h, T_a, v	10	15/1/15-15/3/15 20/9/17-20/2/18

Jyp: Jayapura; L: Load (kW); P: Power output (kW); R: Resort; C: Compressor; DG: Diesel genset; PV: PV array; E: Energy (kWh); AWS: automatic weather station of BMKG, AWS_{PV}: automatic weather station included in a PV system.

3.2. Dealing with missing parameters

3.2.1. Tilted irradiance

An INSEL model was developed to convert G_h to G_i using 60 combinations of decomposition and transposition models. First, the horizontal extraterrestrial irradiance (I_o) was extracted using G_h measured by the AWS during the τ as input. Second, using the G_h and I_o, the diffuse component (I_d) of the irradiance was generated.

Third, the G_i was produced with inputs of G_h, I_d, tilted angle, azimuth degree, and ground reflectance. The last step can also generate other elements of irradiation, namely tilted beam radiation, tilted I_d, and tilted ground reflected radiation, but they were not used in this study.

Only 46 of 60 model combinations have produced acceptable results, while all models containing the Gueymard transposition model [15] were excluded because they gave very small or very large values in this particular study.

In the analysis, we found that the combination of Reindl Beckman and Dufie (RB) [16] and Willmott (WM) [17] models performs best in this study. However, their capability cannot be generally justified over the other model combinations because we tested them only at one location. Therefore, for further analysis in this study, we use the commonly accepted Orgill & Hollands (OH) [18] decomposition model and Perez (PZ) [19] transposition model instead [20]. Some other model combinations give small variation in their results.

The comparison of all modeled G_i with ground measurements was assessed using scatter plots, and on the basis of the coefficient of determination of linear regression (R^2) and root mean square error (RMSE), where the measured G_i was used as the reference data. Figure 4 shows small differences of R^2 ranging between 0.70 and 0.99 with the mean value equal to 0.97. A wide range of RMSE from 16.98 to 201.24 takes place with the

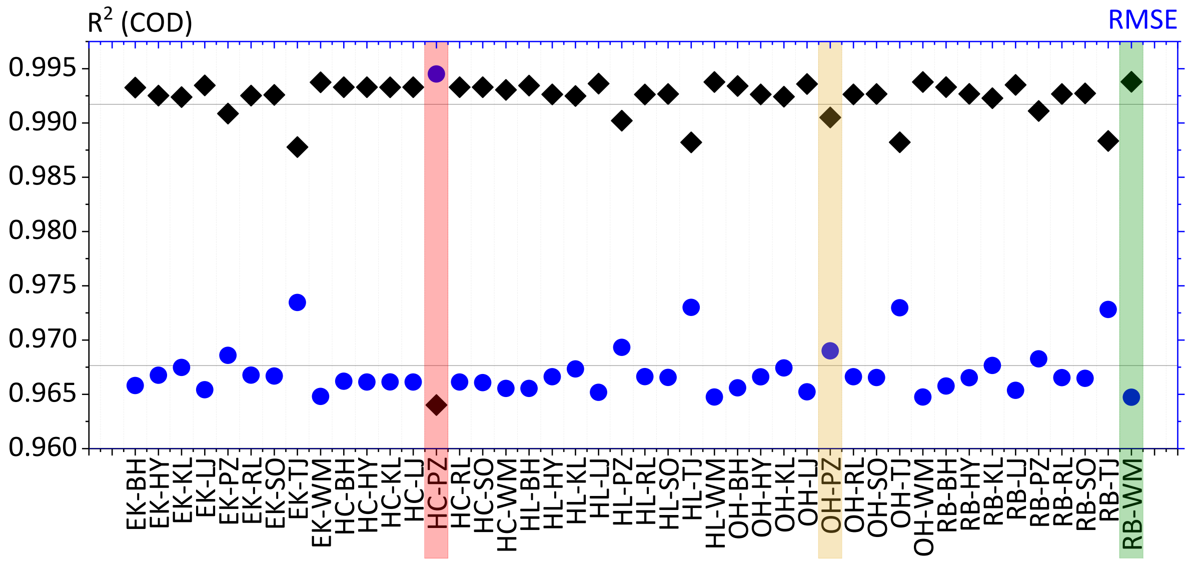

Figure 4: Modelled G_i versus measured G_i on the basis of R^2 and RMSE from Jayapura.

contribution from the Gueymard transposition model. However, the mean RMSE was 31.36.

Figure 5 shows a simple linear fitting between the measured G_h and measured G_i from Jayapura. It shows a small difference between the two data sets with the R^2 of 0.98284. This occurs because the study location is near the equator. This also indicates that modeling G_i from G_h in the equatorial region would be interesting only if a detailed evaluation is of importance. However, for further analysis in this study, we use the modeled G_i to give a better result.

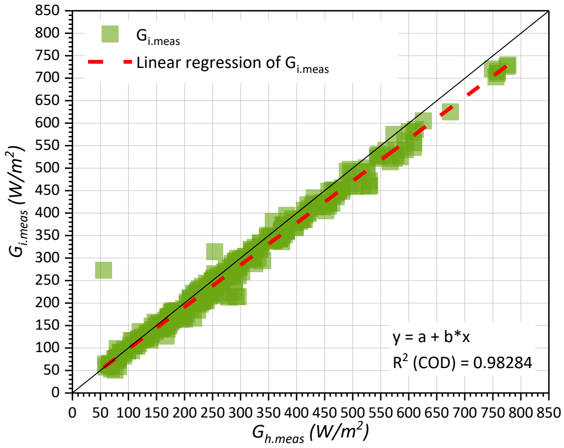

Figure 5: Scatterplot of the measured global horizontal irradiance (G_h) versus the global tilted irradiance (G_i) based on data from the PV system in Jayapura (15 January – 15 March 2015).

Next, the comparison statistics of the measured G_i in Jayapura to the modeled G_i from remote AWSs were separately calculated to assess whether these statistics were dependent on location. The statistical significance of the differences in the comparison statistics derived for the weather stations was tested using the two-sided paired linear fitting tests. Figure 6 shows significant reductions in the R^2 values. Referring to G_i in Jayapura, R^2 value for Lereh was 0.48411, 0.32156 for Timika, and 0.30392 for Labuha (a). The distances, however, do not correlate with the fitness of the G_i datasets (b and c).

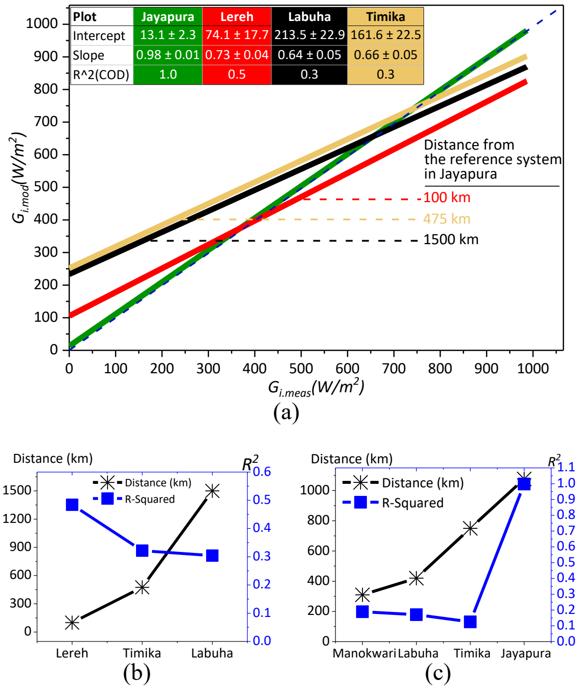

Figure 6: The measured versus the modeled tilted irradiances respectively based on data from PV system in Jayapura and remote AWSs; (a) R^2 of measured G_i and modeled G_i, (b and c) relation of R^2 and the distance.

3.2.2. PV module temperature

The SMTM has been applied to predict the T_m using the T_a and v as inputs. Further, the similar statistical approach used for analyzing the G_i (see Sec. 3.2.1) was also applied to analyze the T_m.

Although the previous datasets showed for the G_i were not linearly fit, the hourly means of G_i (daytime) were close to one and each other. This also applies to T_m as shown in Tabel II and Figure 7.

3.3. Performance of the PV systems

The performance of the PV system in Jayapura has been extensively monitored and analyzed as appear in the publications [6-8]. In general, the present analysis produces the same performance ratios (PR) as those publications.

Table II: The hourly averaged values of G_h, G_i, and *Tm*

Location	G_h	G_i	T_m
Jayapura *(PV)*	368	353	39
Jayapura *(AWS)*	385	348	39
Labuha	452	441	39
Lereh	338	332	36
Manokwari	405	384	41
Sorong	394	348	38
Timika	419	394	40

R^2 values from Jayapura (AWS), Labuha, Manokwari, and Timika are referred to Sorong. R^2 values from Labuha, Lereh, and Timika are referred to Jayapura.

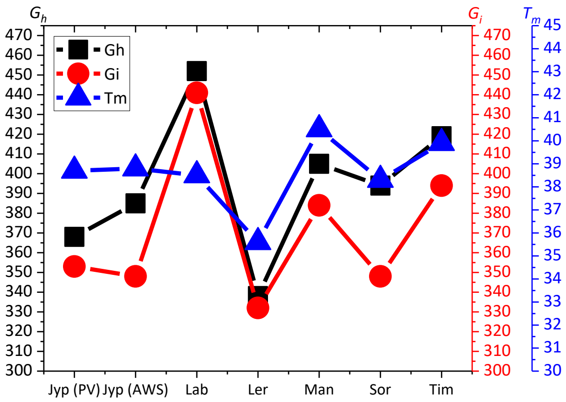

Figure 7: The hourly averaged values of G_h, G_i, and T_m

Figure 8 shows the weekly *PR* calculated using five meteorological stations. They were calculated based on eight weeks of measurements from 22 January 2015. For the calculation, the PV system in Jayapura was used as the reference. According to the IEC 61724 [5], data during system unavailability were excluded from the analysis. Therefore some missing points can be observed on the graph.

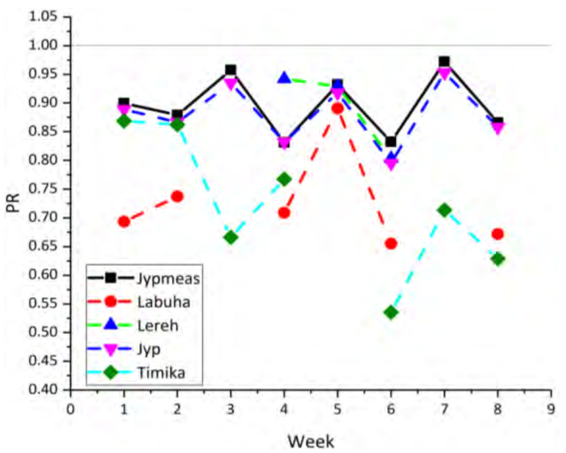

Figure 8: The weekly PR calculated based on data from the reference system in Jayapura and five remote meteorological stations (22 January - 15 March 2015).

As shown in Figure 8, the measured data show PR of 90% which was very close to PR 91% as reported in previous studies [6-8]. We found that, as expected, the PRs calculated using data from AWSs in Jayapura and Lereh were very close to 90% because they are relatively closely located, namely 3 km and 100 km from the reference PV system, respectively. However, with the distance above 100 km, the same PR of 70% was observed, although the great difference of distance from Timika and Labuha to the reference system exists (475 km and 1500 km for Timika and Labuha, respectively). Therefore, it can be concluded that with the distance greater distance 100 km, the correlation between the G_h and G_i cannot be observed.

Figure 9 shows the weekly *PR* calculated using 22 weeks data from five meteorological stations measured from 20 September 2017 to 20 February 2018. Because the PV system at Kri does not measure meteorological parameters on-site, the G_i and *Tm* were taken from AWS measurement in Sorong which is 70 km separated by sea from Kri. The data regarding power production from the PV system at Kri, however, was measured on-site.

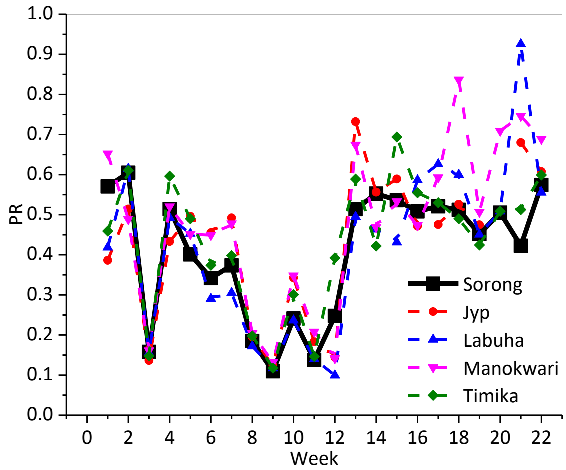

Figure 9: The weekly PR calculated based on data from the reference system in Sorong and four remote meteorological stations (20 September 2017 - 20 February 2018).

As shown in Figure 9, the mean *PR* of PV system in Kri using the reference meteorological data in Sorong is 41% (solid line). The *PR* calculated based on modeled data from other remote AWSs (dash lines) were 48%, 42%, 43%, and 50% for Manokwari, Labuha, Timika, and Jayapura, respectively. The distance from Sorong to Manokwari, Labuha, Timika, and Jayapura are 310 km, 420 km, 750 km, and 1077 km, respectively. Again, distances from the source of data and the reference system do not show any correlation in the calculation of PR.

There are three possible reasons for the low PR of the PV system at Kri. First, the value of the PR depends on the local energy consumption on the island. It means that the loads do not always utilize the produced energy from the PV array. Second, the efficiency of the system component, particularly the inverter. The inverter used at Kri is a new model with no information about its efficiency. Third, the measurement accuracy issues both from the PV system and from the AWSs.

However, if compared to the PR of other stand-alone PV systems, the PR of the PV system at Kri lies in the correct range. The majority of stand-alone PV systems have PR ranging from 0.3 and 0.4 [21].

4. CONCLUSION

In the absence of in-plane irradiance and PV module temperature, the performance of the PV system can still be estimated using the global horizontal irradiance and ambient air temperature and wind speed, respectively. This approach has been applied in this study under the tropical climate of Indonesia. A 34 kWp grid-connected PV system in Jayapura, Papua, was used as a reference system. The analysis results from the reference PV system was applied for predicting the performance of a 28.8 kWp PV array, which is part of a hybrid power system on a remote island of Kri in Raja Ampat, West Papua.

It has been found that the PR of PV system in Jayapura was 90%. We also found that using data from remote AWS with the distance up to 100 km from the reference PV system produce the same result. However, with distance more than that, the PR deviate in the range from 20% to 50%, which is in line with previous findings indicating no correlation occurs. Our advice is, therefore, if possible, to always apply local irradiance monitoring at PV sites instead of extrapolating irradiance over significant distances.

The PR of the hybrid PV system at Kri was 41% which is characteristics for stand-alone PV systems including in Indonesia [21].

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7. REFERENCES

1. Kusakana, K. and H.J. Vermaak, *Hybrid renewable power systems for mobile telephony base stations in developing countries.* Renewable Energy, 2013. **51**: p. 419-425.
2. Vetter, M. and G. Bopp, *Stand-Alone and Hybrid PV Systems*, in *Photovoltaic Solar Energy: From Fundamentals to Applications*, Angèle Reinders, et al., Editors. 2017, John Wiley & Sons, Ltd: West Sussex, United Kingdom. p. 539-552.
3. Sen, R. and S.C. Bhattacharyya, *Off-grid electricity generation with renewable energy technologies in India: An application of HOMER.* Renewable Energy, 2014. **62**: p. 388-398.
4. The Australian Photovoltaic Institute, *Australian Technical Guidelines for Monitoring and Analysing Photovoltaic Systems* in *Version 1*. 2013, The Australian Photovoltaic Institute.
5. IEC, *IEC 61724-1 IEC standard for photovoltaic system performance*, in *Part 1: Monitoring*. 2017, The International Electrotechnical Commission: Geneva, Switzerland.
6. Veldhuis, A.J. and A.H.M.E. Reinders, *Performance of a 34 kWp Grid-Connected PV System in Indonesia-A Comparison of Tropical and European PV Systems*, in *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*. 2014, IEEE: Denver, CO, USA.
7. Veldhuis, A.J., et al., *An Empirical Model for Rack-Mounted PV Module Temperatures for Southeast Asian Locations Evaluated for Minute Time Scales.* IEEE Journal of Photovoltaics, 2015. **5**(3): p. 774-782.
8. A.H.M.E. Reinders, et al., *PV Electricity in Indonesia – A Sustainable Transition with Great Potential*, in *29th European Photovoltaic Solar Energy Conference and Exhibition*. 2014, WIP Wirtschaft und Infrastruktur GmbH & Co Planungs KG: Amsterdam, The Netherlands. p. 4109 - 4112.
9. Benjamin Y. H. Liu and R.C. Jordan, *The interrelationship and characteristic distribution of direct, diffuse and total solar radiation.* Solar Energy, 1960. **4**(3): p. 1-19.
10. Hay, J.E., *Calculating solar radiation for inclined surfaces- Practical approaches.* Renewable Energy, 1993. **3**(4-5): p. 373-380.
11. Schumacher, J., *INSEL 8 Tutorial: Simulation of Renewable Energy Systems*. 2014, Doppelintegral GmbH: Stuttgart.
12. Richter, M., et al., *Technical Assumptions Used in PV Financial Models: Review of Current Practices and Recommendations*. 2017, International Energy Agency: Paris, France.
13. Doppelintegral. *INSEL 8: Software for simulation, monitoring, and visualization of energy systems*. n.d. [cited 2018 16 June]; Available from: http://www.insel.eu/en/what-is-insel.html.
14. Sandia National Laboratories. *Sandia Module Temperature Model*. n.d. [cited 2018 23 February]; Available from: https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/module-temperature/sandia-module-temperature-model/.
15. Gueymard, C.A., *Direct and indirect uncertainties in the prediction of tilted irradiance for solar engineering applications.* Solar Energy, 2009. **83**(3): p. 432-444.
16. D. T. Reindl, W. A. Beckman, and J.A. Duffie, *Diffuse fraction correlations.* Solar Energy, 1990. **45**(1): p. 1-7.
17. Willmott, C.J., *On the climatic optimization of the tilt and azimuth of flat-plate solar collectors.* Solar Energy, 1982. **28**(3): p. 205-216.
18. J. F. Orgill and K.G.T. Hollands, *Correlation equation for hourly diffuse radiation on a horizontal surface.* Solar Energy, 1977. **19**(4): p. 357-359.
19. Perez, R., et al., *Modeling daylight availability and irradiance components from direct and global irradiance.* Solar Energy, 1990. **44**(5): p. 271-289.
20. Lave, M., et al., *Evaluation of Global Horizontal Irradiance to Plane-of-Array Irradiance Models at Locations Across the United States.* IEEE Journal of Photovoltaics, 2015. **5**(2): p. 597-606.
21. Mayer, D. and M. Heidenreich. *Performance analysis of stand alone PV systems from a rational use of energy point of view*. in *The 3rd World Conference on Photovoltaic Energy Conversion*. 2003. Osaka, Japan: IEEE.