Technical Report

Measuring System Performance of Isolated Photovoltaic Mini-grid in Rural Indonesia

July, 2017

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1. Abstract

The Government of Indonesia through Ministry of Energy and Mineral Resources (MEMR) has been consistently developing more than 600 PV mini-grids since 2012. To complement MEMR work in building the energy access infrastructures, GIZ through EnDev project has been conducting technical support which covers technical inspection, monitoring and evaluation, capacity development and knowledge management in the field.

Nonetheless, based on EnDev cumulative experiences, there is an inadequacy of understanding about how the PV mini-grids have performed in generating electricity for the remote rural area beneficiaries. This insufficient knowledge limits the ability of MEMR to improve for the next deployment of PV mini-grids in the other rural areas. This situation also become a threat in sustaining the rural mini-grids.

The study aims to formulate key parameters to measure PV mini-grid performance. The parameters should be concise yet effective to capture the PV mini-grid performance in a certain period of time. This study bases its research on two research questions, which are: 1) what parameters to be used to indicate the system performance of rural isolated PV mini-grids in Indonesia? ; and 2) how well are the PV mini-grids performed?

To obtain data, the study collected data from the inverter during PV technical inspection activities in 2015. Despite of limited data sets which only 75 operational data of 83 inspected mini-grids, this study takes two samples of PV mini-grids for thorough examination, which are the mini-grid in Maluku (MALS11) and the Java Island (JATENGS06). Each of them represent different characteristic, namely AC-DC configuration, and type of villages. Rural PV mini-grids in Indonesia are not connected to national utility grid and are designed to be able providing electricity within two to three days without sunray.

The research has formulated four key performance parameters for PV mini-grid, that comprise of: PV module performance, overall system performance, battery performance, and load behaviour. Based on these parameters, it is found that both PV mini-grids were operating in between 0.2 to 0.3 ratio of performance, with similar capacity factor at 5%. It means that the energy generated is not yet used in the optimal condition. Despite its small electricity load, there is an indication that **the load was increasing.** Rapid load increase was found in JATENGS06 with 20% monthly increase rate, while load in MALS11 was relatively steady with less than 10%.

Energy curtailment and losses in the electricity generation process are haunting these PV mini-grids. Less than 40% of potential energy was able to be converted into electricity. Additionally, battery losses were dominating in MALS11, while battery caused most losses in JaTengS06. One of the reason are that components ran in low power, which resulted in system inefficiency. More load coming from productive appliances are expected to aim energy balance in the PV mini-grid system.

1.1 Introduction

Government of Indonesia through Ministry of Energy and Mineral Resources (MEMR) has been consistently building more than 600 PV mini-grids since 2012. The objective is to reach 100% electrification by 2019 while also increase the use of renewable energy in the national energy mix up to 23% in 2025. It aims to provide energy access to the utmost corner of the archipelago. Thus, the mini-grids in this scheme are not connected to national utility grid.

The energy access initiative is strongly supported by Energising Development (EnDev) Indonesia, as a form of cooperation between GIZ and MEMR. Complementary to MEMR work in building the energy access infrastructures, EnDev conducts technical support which covers technical inspection, monitoring and evaluation, capacity development and knowledge management in the field. The locations for PV mini-grids are proposed by the provincial government who will be the owner of the PV mini-grid in their area.

Among all the 600 PV mini-grids, there is an inadequacy of understanding about how the PV mini-grids perform in generating electricity in the remote rural area. This situation limits the ability of MEMR to improve for the next deployment of PV mini-grids in the other rural areas while also become a threat in sustaining the rural mini-grids. Ensuring the quality of PV mini-grids shall be supported by a thorough understanding on how the systems have performed while also devising strategy to overcome any shortcomings in the operation.

1.2 Objective

The study aims to formulate key parameters to measure the performance of PV mini-grid that is not connected to national utility grid. The parameters should be concise and effective when measuring its performance within a defined period of time. The parameters are proposed to be used by MEMR for various purposes, such as, evaluating their rural PV mini-grids while also improving the PV specification, system sizing, and business process involved for next implementation process. Currently, more literatures are available discussing about grid-connected system (GCS) but less in the isolated PV mini-grid system. This study aspires to add more discussion on the performance of isolated PV mini-grid topic.

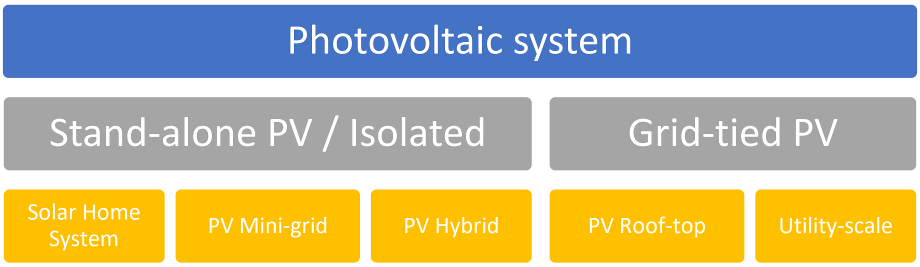
1.3 Research question

This study bases its research on two research questions, which are:

1) What parameters to be used to indicate the system performance of rural isolated PV mini-grids in Indonesia?
2) How well are the PV mini-grids performed?

2. System Description of Rural PV Mini-grids in Indonesia

Rural PV mini-grids in Indonesia are not connected to national utility grid, or called isolated PV mini-grid, and designed to be able providing electricity without sunray within two to three days. The main difference between grid-connected and isolated PV mini-grid is on the use of storage which adds more constraint in the stand-alone or isolated PV.



Despite of its large number of installation, there is only few data can be obtained from the systems. Therefore, this study uses two samples from different geographical setup which are Maluku and Jawa Tengah, see Table 1 for more details.

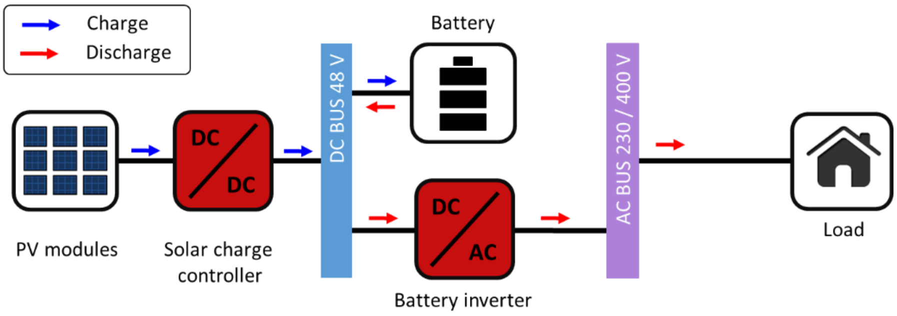
Table 1 Research objects

Location	**: Jawa Tengah (JATENGS06)**	**: Maluku (MALS11)**
Capacity	: 15 kWp	**: 50 kWp**
GPS	: 7°11'55.1"S 109°05'58.0"E	: 8°00'55.0"S 125°45'47.6"E
Configuration	: **DC Coupled – 48 V**	**: AC Coupled – 48 V**
PV Modules	: 75 x ***200 Wp***	: 252 x **200 Wp**
Charge controller	: 6 x ***3.5 kW MPPT 60 150***	**: 2 x 15 kW; 1 x 20 kW**
Battery Inverter	: 3 x ***6 kW XW 7048***	: 9 x **6 kW Sunny Island**
Battery	: 144 kWh ***Lead acid***	: 432 kWh **Lead acid**
Costumers	: 75 hh @ **260 Wh (max)**	: 157 hh @ **260 Wh (max)**
Streetlights	: 19 units @ 11 W in 5 h	**:** 26 units
Captured period	: ~ **6 Months** (Feb – Aug)	**: ~ 10 Months** (Jan – Oct 2015)

The mini-grid in Maluku, MALS11, is located in an isolated small island that has limited and unreliable access to outside. In parallel, the mini-grid in the Java Island (JATENGS06) is more accessible by any means of transportation. Both systems were built in 2014 and inspected in 2015. Thereby, they had been operating for up to ten months before inspection, thus it became the analysis period for this study. Configuration of the systems consist of DC-coupling and AC-coupling, which later being explained in the following paragraphs.

2.1 Direct Current (DC)-Coupling System

All components in DC-coupling system configuration are connected together in the DC bus. The generated power from PV module is used to charge the connected batteries through solar charge controller (SCC). The SCC is typically a DC-DC converter that is equipped with maximum power point tracker (MPPT). DC-DC converter means that it converts direct current (DC) from PV module to direct current (DC) to charge the batteries, while MPPT optimises the captured energy and brings down the voltage to battery voltage level.



System layout of a DC-coupling system

During daylight with sufficient solar irradiance, the battery is being charged to reach the maximum state of charge (SoC). As the electricity demand rises beyond the PV input power, the battery inverter will deliver the energy from the battery to the loads and will stop operating when the SoC of the battery reaches the minimum limit. It is recommended to keep 20% of energy in the batteries.

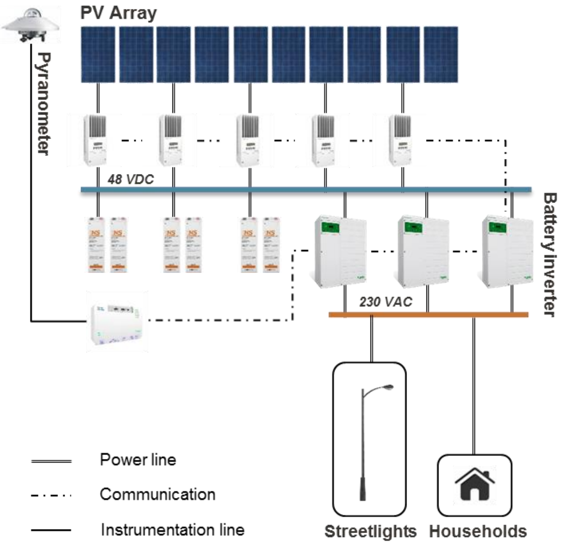
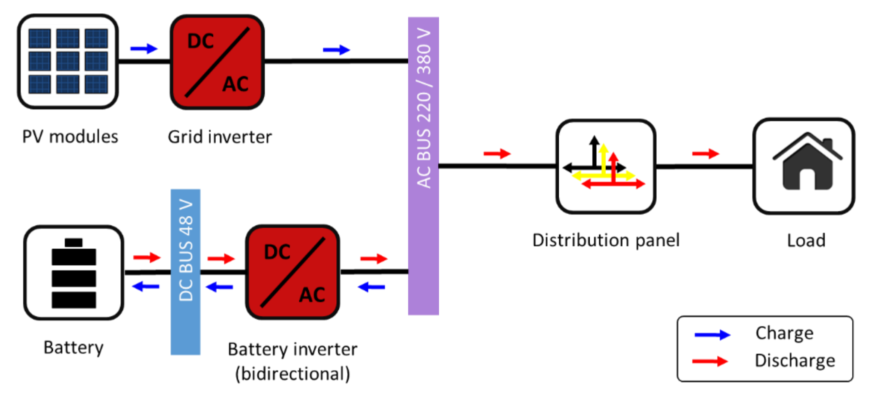


Figure 1 DC Coupling system

2.2 Alternating Current (AC)-Coupling System

Key component that differs between AC and DC coupling system is grid inverter. In AC-coupling configuration, PV modules and batteries are coupled in the AC bus through its inverters. The PV modules are connected to a grid inverter where the power is converted from DC to AC thus can be use directly for loads. In the meantime, if the power from PV is not used by load, it is stored in batteries after being converted into DC form by battery inverter. Similar to charge controller, grid inverter is also equipped with MPPT to optimize the captured energy. Based on this mechanism, power from PV array can be directly used by the load during the day and to charge battery via battery inverter simultaneously.

Unlike in DC-coupling, the battery inverter in AC-coupling works bidirectionally. It is functioning as a charger (AC to DC converter) when there is sufficient irradiance while batteries are at low SoC. As soon as the load goes higher than the PV input power, typically during the night or cloudy day, the inverter will then switch to DC-AC inverter and the energy from battery will be used to meet the load demand.



System layout of an AC-coupling system

Losses from the conversion of current are higher in AC-coupling as a consequence of bidirectional work. However, the AC-coupling is more favourable especially when electricity peak load in the service area is happening during daylight thus inversion losses only occur once in the grid inverter. Moreover, AC-coupling is more flexible to system expansion with additional PV arrays or to hybridize with another electricity generator.

Similar to DC-Coupling system, battery inverter should work in parallel to achieve a high-power output. Battery inverter is the main controller of grid distribution in mini-grid, hence there should be at least one battery inverter acting as a master providing reference voltage and frequency while the remaining inverters act as slaves joining the grid.

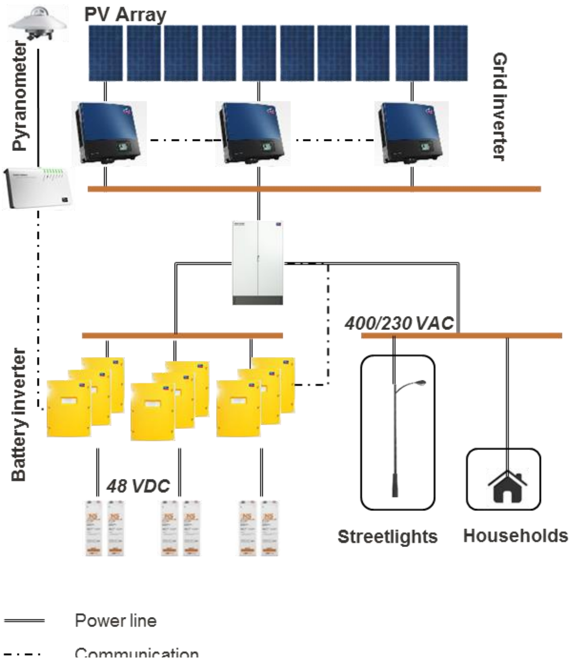


Figure 2 AC Coupling system

Some types of battery inverter configuration may require a clustering network with maximum number of three inverters connected. It means one inverter should act as a master with the other two as its slaves. If more than three battery inverters are used, the additional inverters should form another cluster. In this case, a distribution panel is required to organize, control, and communicate among clusters. Some manufacturers use multi-cluster box terminology to describe distribution panel in PV system that control more than three inverters.

3. Evaluation Method

3.1 Process Flow

The research was conducted using the process flow in Figure 3. Remote monitoring system (RMS) in the mini-grids were not functioning due to limited communication network coverage at the mini-grid sites. To obtain data, the study manually collected data from the inverters during PV technical inspection activities in 2015 thus it only had limited datasets to be analysed. There were only 75 operational data from 83 inspected mini-grids with different type of data. The study selected data that are feasible to be analysed in evaluating the mini-grid performance.

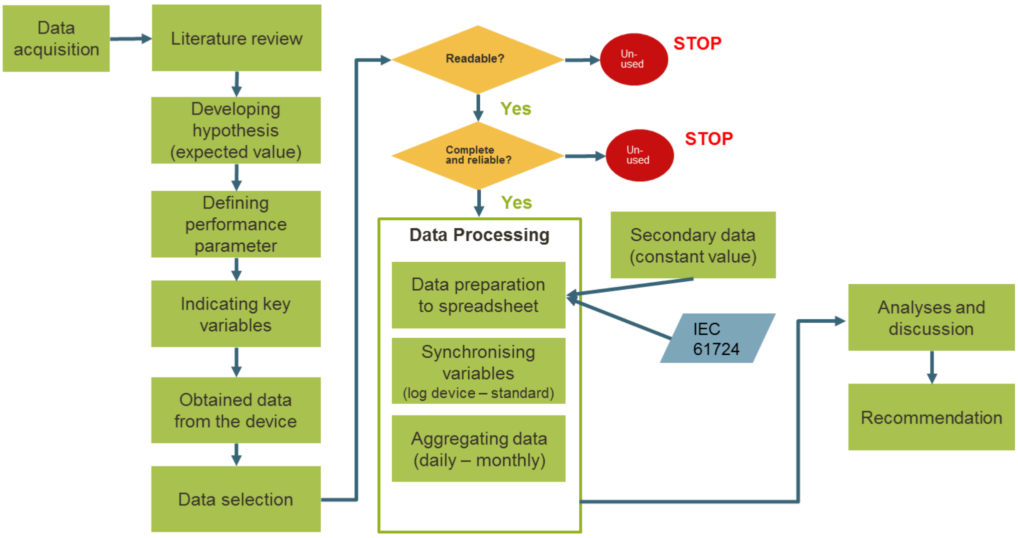


Figure 3 Research method

3.2 Data

The data used in this study is more reliable compare to the other available data, represented by “sufficient data” in the Figure 4. In the meantime, “incomplete data” consist of data with missing variables or values. Difficulties in harvesting reliable data are the results of an inadequacy of skill to install the PV mini-grids system, especially during setup of the system.

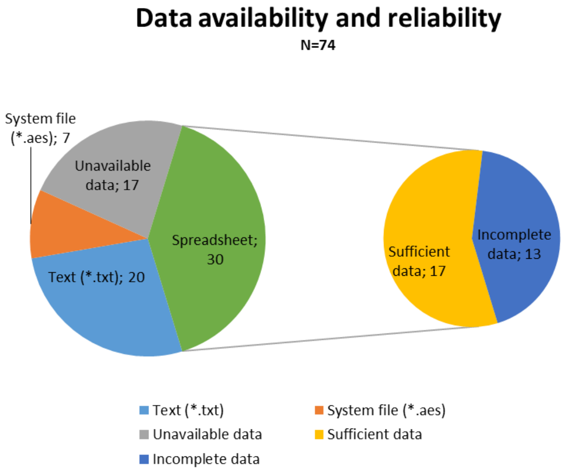


Figure 4 Data availability

3.2.1 Parameters of Performance

The study examines two PV mini-grids with different system configuration. The mini-grid in MALS11 is an AC-coupled system, while JATENGS06 site with DC-coupled system. There are four parameters to measure the performance of PV mini-grid as shown in the Figure 5. The key parameters comprise of: (a) PV module performance; (b) overall system performance; (c) battery performance; and (d) load behaviour. These parameters follow the guideline of IEC Standard 61724.

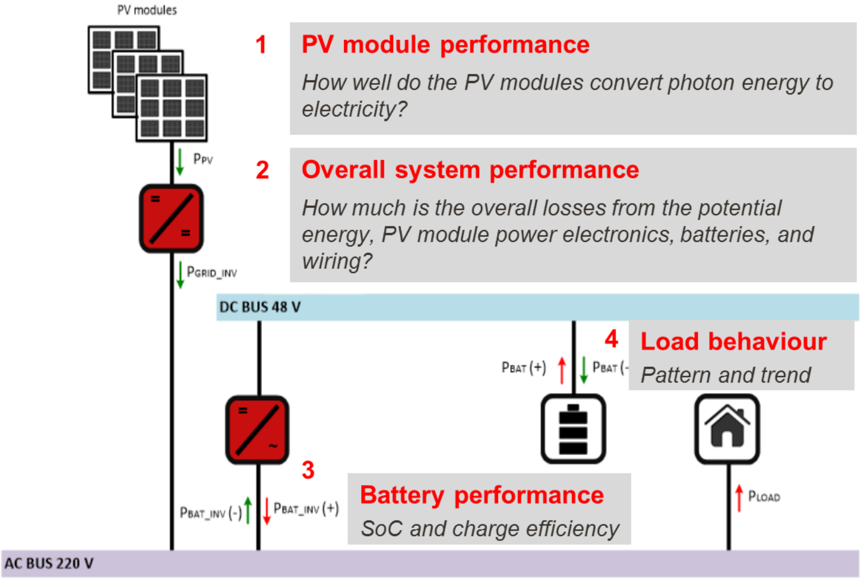


Figure 5 Performance parameters

3.2.1.1 PV module performance

PV module performance parameter measures effectiveness of PV module in converting photon energy to electricity. It is then represented by production factor and array efficiency. The potential power represents theoretically possible power output from the PV plant ($Epot$)

(1) $$\textbf{Potential power} = \textbf{Irradiance}_{\textbf{Measured}}\left[\frac{W}{m2}\right] \textbf{x}\; \boldsymbol{P}_{\boldsymbol{PV},\,\textbf{nom}};$$

$P_{PV,nom}$: Nominal power of the PV mini grid system

Energy curtailment is an involuntary reduction in the generator output from its theoretically possible energy output

(2) $$\textbf{Energy}_{\textbf{curtailment}} = (\,\textbf{Irradiation}_{\textbf{Measured}}\left[\frac{Wh}{m2}\right] \textbf{x}\; \textbf{Power}_{\boldsymbol{PV},\;\textbf{nom}}\,[\boldsymbol{Wp}]) - \textbf{Energy}_{\boldsymbol{PV}}\,[\boldsymbol{Wh}]$$

Production factor measures the effectiveness of PV array in producing electricity

(3) $$\textbf{Production Factor}\;(\boldsymbol{PF}) = \frac{\textbf{Energy}_{\boldsymbol{PV}}\,[\boldsymbol{Wh}]}{(\,\textbf{Irradiation}_{\textbf{Measured}}\left[\frac{Wh}{m2}\right] \textbf{x}\; \textbf{Power}_{\boldsymbol{PV},\;\textbf{nom}}\,[\boldsymbol{Wp}])};$$

$Energy_{PV}\;[Wh]$: energy output from PV array

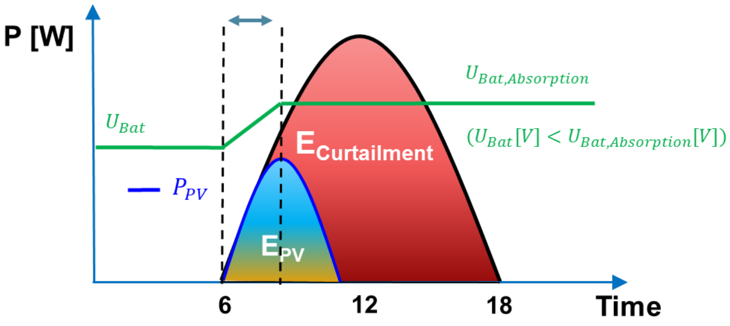


Figure 6 Energy absorption

PV array efficiency represents losses due to temperature rising, shading, soiling, MPPT and array mismatches, and wiring.

(4) $$\boldsymbol{Efficiency_{PV\_array}} = \frac{\boldsymbol{Energy_{PV}}\,[\boldsymbol{Wh}]\,(\boldsymbol{U_{Bat}}[\boldsymbol{V}]<\boldsymbol{U_{Bat,\,Absorption}}[\boldsymbol{V}])}{\boldsymbol{Irradiation_{Measured}}\left[\frac{\boldsymbol{Wh}}{\boldsymbol{m2}}\right](\boldsymbol{U_{Bat}}[\boldsymbol{V}]<\boldsymbol{U_{Bat,\,Absorption}}[\boldsymbol{V}])\,\boldsymbol{x}\;\boldsymbol{Power_{PV,\;Nom}}\,[\boldsymbol{Wp}]}$$

3.2.1.2 Overall system performance

The overall system performance measures the overall losses of the potential energy, PV module, power electronics, batteries, and wiring. It is represented by performance ratio, capacity factor and efficiency from each power electronic component. Performance ratio indicates the overall effect of losses on the system output (IEC 61724).

(5) $$\boldsymbol{Performance\ Ratio}\ (\boldsymbol{PR}) = \frac{\boldsymbol{Energy_{Load}}\,(\boldsymbol{Wh})}{(\,\boldsymbol{Irradiation_{Measured}}\left[\frac{\boldsymbol{Wh}}{\boldsymbol{m2}}\right]\boldsymbol{x}\;\boldsymbol{Power_{PV,\;nom}}\,[\boldsymbol{Wp}])}$$

Capacity factor measures the capability of PV mini-grid to generate electricity in comparison with its hypothetical maximum generation capacity. Although capacity factor is not able to accommodate intermittency of wind and PV power plant, it is still used as a comparable indicator with other types of power plant.

(6) $$\boldsymbol{Capacity\ factor}\ (\boldsymbol{CF}), \boldsymbol{annual} = \frac{\boldsymbol{E_{Load}}\,[\boldsymbol{Wh}]}{\boldsymbol{P_{PV,\;Nom}}\,[\boldsymbol{Wp}]\;\boldsymbol{x}\;\boldsymbol{8760h}};$$

$E_{Load}\ [Wh]$: amount of energy used by the user]**:**

Efficiency of each power electronic component will provide insight on how the sub-systems work and affect the overall PV mini-grid performance. The power electronic components comprise of solar charge controller (SCC) for DC-coupling system, grid inverter for AC-coupling system, and battery inverter.

(7) $\eta_{SCC} = \frac{E_{SCC}}{E_{PV}}$ (DC-coupling);

E_{SCC}: *Energy out from solar charge controller*;
E_{PV}: *Energy generated from PV module array*

(8) $\eta_{GridInv} = \frac{E_{GridInv}}{E_{PV}}$ (AC-coupling);

$E_{GridInv}$: Energy out from grid inverter;
E_{PV}: Energy generated from PV module array

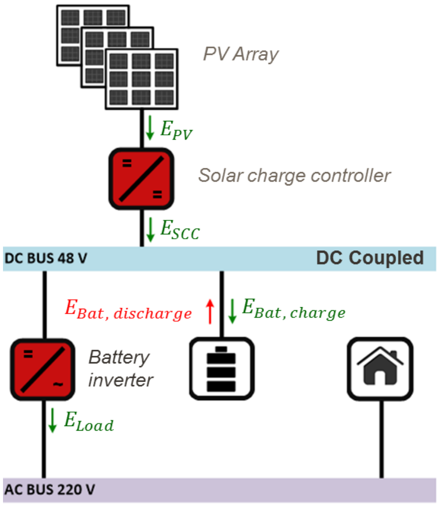


Figure 7 DC-coupled energy flow

(9) $\eta_{BatInv} = \frac{E_{Load}}{E_{Bat,\ discharge} + E_{SCC}}$; E_{BatInv}: Energy out from battery inverter; E_{Load}: Energy from load

3.2.1.3 Battery performance

Isolated PV mini-grid relies on energy storage to back up its energy. In isolated PV mini-grid, the storage is critical as load reaches its peak at night and to maintain electricity during rainy or cloudy days. Back-up system for isolated PV mini-grid comes with various forms, such as battery, generator, and other sources of renewable energy power.

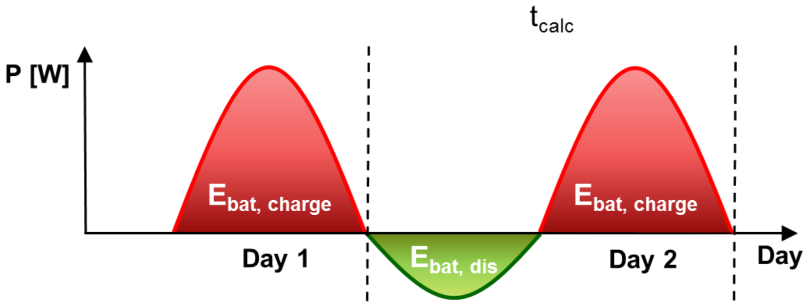


Figure 8 Battery charging state

Nevertheless, the objects in this study use battery as their energy storage thus its reliability is measured by its battery performance. Performance parameters of battery is measured by: (a) indicating the operating area of the battery and (b) how well the battery charge acceptance is able to restore the original capacity. There are two measurements for this:

(10) Estimation of the battery state of charge (SoC)

$$SoC = SoC(0) + \int \frac{P_{Bat}(t)}{C_{Bat}}\, dt;\ SoC\text{: state of charge; } P_{Bat}\text{: Battery power; } C_{Bat}\text{: Battery capacity}$$

(11) Battery efficiency

$$\eta_{Bat} = \frac{U_{Bat,\ dchg}}{U_{Bat,\ chg}} \cdot \frac{Ah_{Bat,\ dchg}}{Ah_{Bat,\ chg}} = \frac{E_{Bat,\ dchg}}{E_{Bat,\ chg}};$$

U_{Bat}: battery voltage (V); Ah_{Bat} : battery charge/capacity (Ah); E_{Bat} : Energy battery (kWh)

3.2.1.4 Load behaviour

The electricity produced by isolated PV mini-grid is being used by the surrounding village community. Its performance considers how much electricity is being used as load. Load behaviour indicates how the pattern in electricity consumption has affected the PV mini-grid performance. It also gives insight about the demand pattern of electricity in rural context. The load behaviour is represented by two measurements, namely:

(12) Load profile; which represents load behaviour of the consumers, amount of energy per household, and the trend in electricity consumption

$$\overline{\boldsymbol{Power_{Load,\ daily}(t)}}$$

(13) Demand factor; which measures the ratio of maximum demand of electricity in comparison with the ability of system to generate electricity

$$\boldsymbol{Demand\ factor} = \frac{\boldsymbol{Power_{Load,\ peak}}}{\boldsymbol{Power_{Inverter,\ nom}}}$$

4. Analyses

Each parameter provides different insights that are beneficial to understand the PV mini-grid in rural setup. Result from each parameter is discussed into four sections in which consist of analysis from the two PV mini-grid sites. The study

4.1 Performance of PV Module

Losses in PV array are caused by temperature, soiling, shading, wiring, and mismatch in MPPT[1] . In average, JATENGS06 mini-grid had 10% losses, while tMALS11 mini-grid had reached 35% losses, as seen on Figure 9.

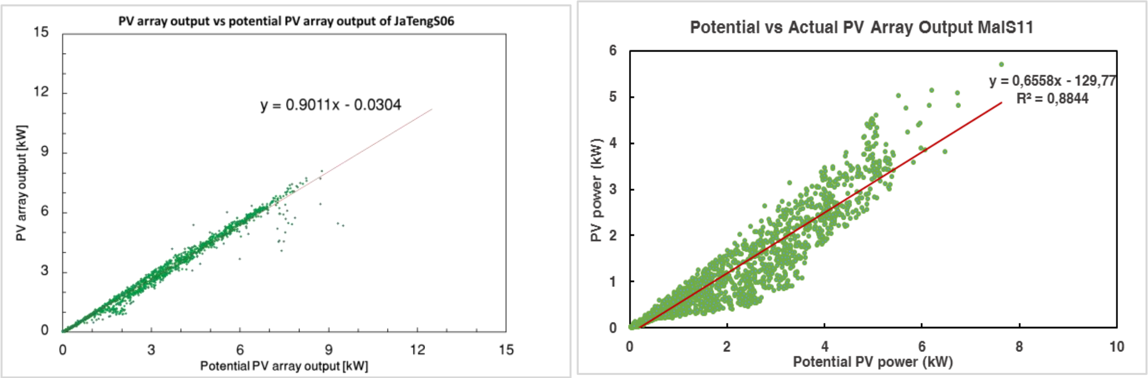


Figure 9 PV array output of Jawa Tengah – JATENGS06PV (left) and Maluku – MALS11 (right) sites

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[1] *Maximum Power Point Tracking*

The low number of production factor is a result of high irradiation days but fewer people are using the electricity. In the meantime, high number in production factor indicates high electricity demand occurred during cloudy days or with short sun-hours. Optimal production factor is achieved when there is a balance between load and the amount of energy generated from PV.

Production factor of JATENGS06 was ranging from 0.1 to 0.9, while its PV arrays generated 34% of the potential PV energy production. In Maluku, average production factor of MALS11 PV arrays was 27% of the potential energy. Lower production factor in MALS11 might be caused by higher irradiation level in MALS11 with lower load. Based on the pyranometer data, average irradiation in Maluku reached 5.6 kWh/m^2

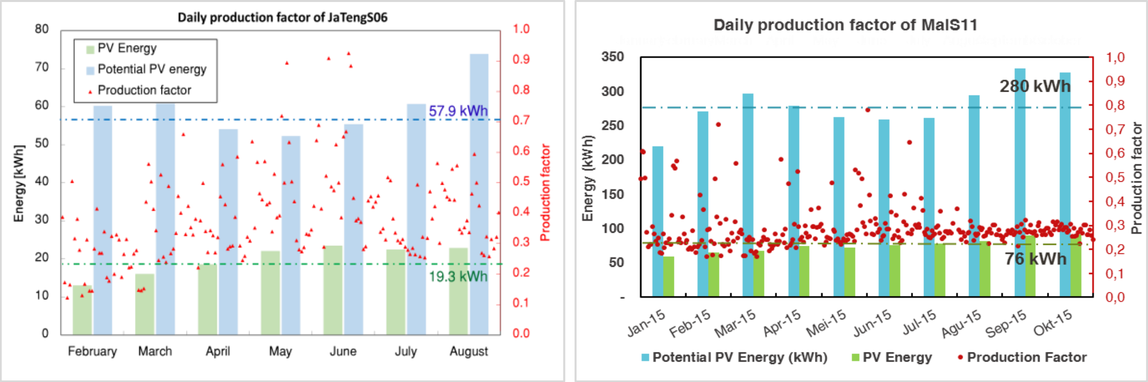

Figure 10 Daily production factor of Jawa Tengah- JATENGS06 (left) and Maluku-MALS11 (right) sites

Temperature data could only be obtained from the data in MALS11 site. Nonetheless, it known from the module specification that each module has nominal power of 200Wp with -0.44% temperature coefficient which means that as the module undergo 1 degree-Celcius increase in temperature, its power is reduced by 0.44%. Increasing temperature in the PV module had contributed as much as 8% of total losses in the PV arrays. The highest percentage of losses due to temperature was 12% of the overall losses when the module temperature had reached 53 degree-Celcius.

Resume and recommendation for PV module performance

From the analyses above, it is indicated that both systems have the potential to connect more productive use appliances during daytime. To achieve higher system performance, load in both sites can be utilised more for productive activities during daytime. It will not interfere with electricity peak load between 6 to 11 pm in the evening.

JATENGS06 has better PV module efficiency than MALS11. It might be caused by:

a. Lower ambient temperature in Jawa Tengah, which was 25 degree-Celcius, than ambient temperature in Maluku of 27 degree Celcius, in accordance to NASA historical data
b. Soiling on PV arrays was more apparent in Maluku because of less rainfall that is usually beneficial for self-cleaning mode on arrays, moreover, losses in wiring might add to PV losses

To reduce temperature losses, the design can be improved by adding self-cooling mechanism in the PV arrays by considering proper distance between PV arrays. Regular cleaning on PV modules can also tackle the soiling problems.

4.2 Overall Photovoltaic Performance

Operation of PV mini-grids is examined to understand the effectiveness of the system to generate energy. Indicators for the performance assessment considers losses that has occurred in the installed power electronics, batteries, and wiring as its indicators. By using the procedures described in the Evaluation Method, the study found that performance ratio of JATENGS06 was higher than MALS11.

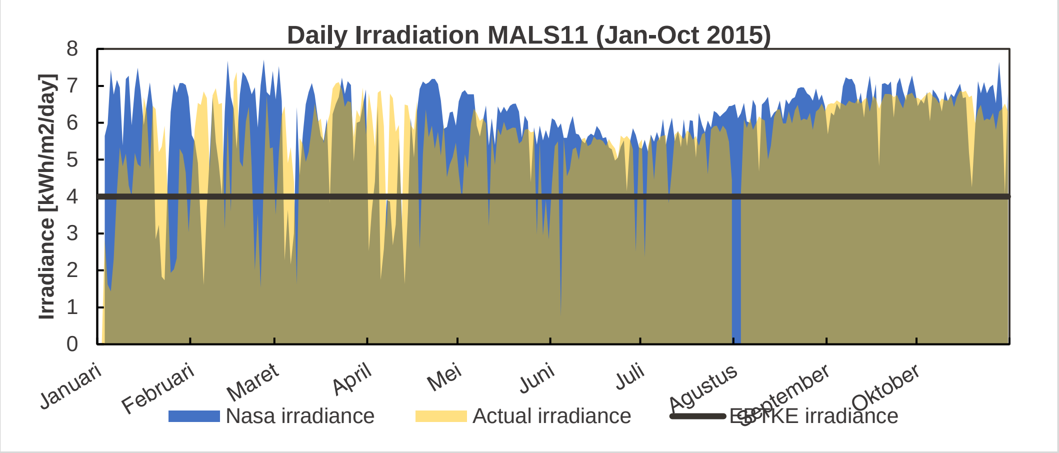

Figure 11 Daily solar irradiation of MALS11

One of the main input for the analyses of PV performance is solar irradiation. Therefore, the study compares three sources of solar irradiation data in Indonesia, namely actual measurement by on-site pyranometer, NASA historical data, and DJEBTKE[2] estimation of 4 kWh/m2.day. Actual irradiation data from JATENGS06 could not be obtained hence the data only represents daily solar irradiation in Maluku as seen in the Figure 11. The graph exhibits that solar irradiation from NASA historical data and actual on-site measurement have similar pattern with higher amount of solar irradiation from NASA record. Intense solar irradiance occurred from May until October 2015. Nonetheless, adjustment on DJEBTKE assumption of 4 kWh/m2.day solar irradiation is important to more optimum system design. Current estimation deviates far from the other data sources.

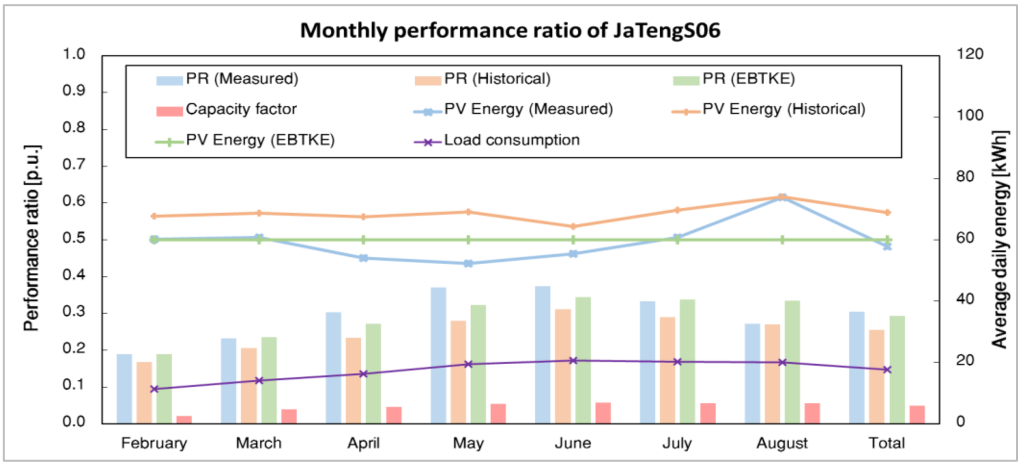

Figure 12 Monthly performance ratio of JATENGS06

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[2] *DJEBTKE/EBTKE: Directorate General for New Renewable Energy and Conservation Energy, Ministry of Energy and Mineral Resources of Indonesia*

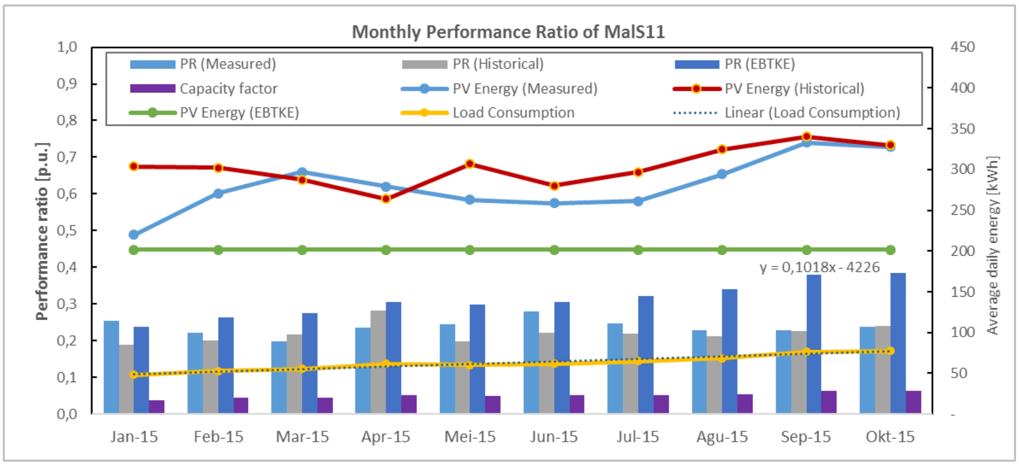


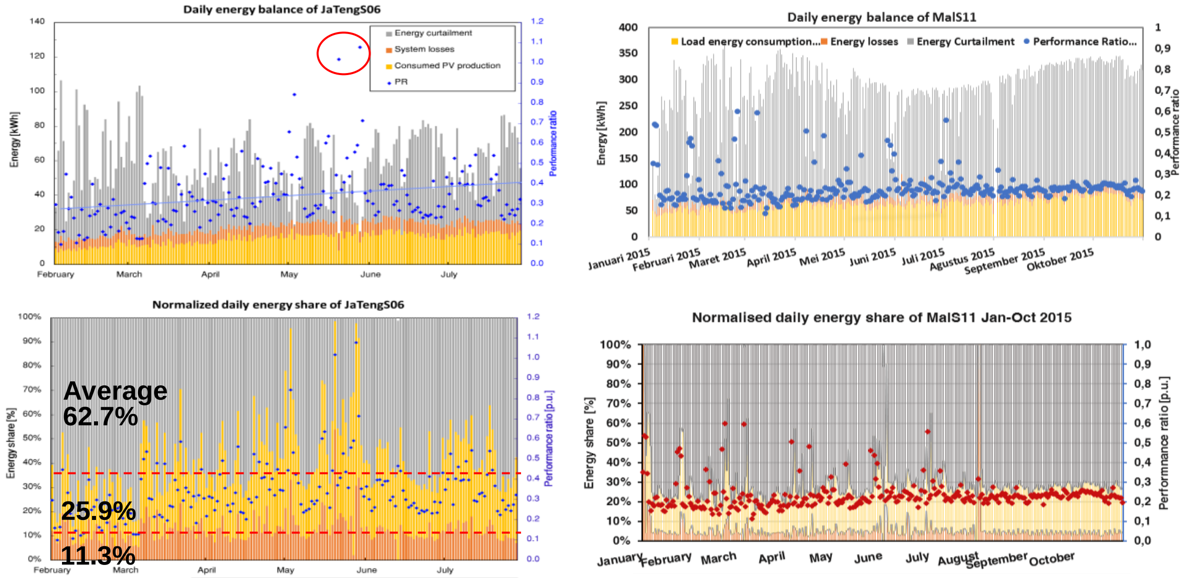
Figure 13 Monthly performance ratio of MALS11

Performance ratio (PR) of each site was examined and compared among the three different sources of solar irradiation data. PR is represented by the bar diagram while the line diagram represents the average daily energy, as shown in Figure 12 and Figure 13.

> Average PR value of JATENGS06 (PR=0.3) is higher than MALS11 (PR=0.24), whilst both had similar capacity factor (CF) of 5%. These findings indicated that both systems were underperformed. Nevertheless, for PV technology, CF could not represent the PV system's ability to produce energy accurately, hence, it is only relevant to compare the PV system with power plants from diverse energy sources. Possible cause of lower PR values in MALS11 was imbalance of energy flow that the use of electricity in the area was very low despite high solar irradiation of 5.6 kWh/m2.day in the area. There was an increase of PR in JATENGS06 in parallel with the load growth. Despite the high irradiation in MALS11, its performance was stagnant as a result of modest load increase at 9%. More details will be discussed in

Load Behaviour section.

Daily potential energy is shown in the graph by the line diagram. The results differ between various solar irradiation values. For JATENGS06, the difference of daily energy value is not apparent since the value range of solar irradiation among the three data is narrow. It deviates with average daily energy of MALS11 where the discrepancy in relation to disparate solar irradiation data is much more obvious. PV



aily energy share

performance is also reflected in the daily energy balance. The daily energy balance graph exhibits the amount of consumed energy in comparison with the potential solar energy captured by the PV. Meanwhile, the normalised daily energy share shows the portion of energy consumption from the total potential energy.

Based on the daily share of energy chart, there were high proportion of energy lost at both mini-grid sites. Data in the logger shows that the PV had stopped capturing daily potential energy since 10 am, it means the system had lost most of its daily sun hours. While there were 62.7% of energy lost in JATENGS06, higher energy curtailment occurred in MALS11 with 65% energy lost from the potential energy. The imbalance of daily energy share might be caused by limited energy allocation for each connected house to anticipate abrupt increase on load demand. Because the load is concentrated during night time, big battery capacity was installed to store more energy. Despite the choice to limit energy load to conserve more energy in the battery, with low depth of discharge (DOD), the remaining energy in battery had blocked the PV to generate more energy. Outliers in JATENGS06's performance ratio value greater than 1 indicates that JATENGS06 had some days with low irradiation and more people used electricity. *More details about load is discussed in Load Profile section*.

Indication of how efficient the operation of PV mini-grid is represented in the total system efficiency. It summarises efficiency of all components in the system. The results are that JATENGS06 was able to operate in 63% of efficiency while MALS11 was running in 40% of system efficiency.

Resume and recommendation of overall PV performance

Performance ratio (PR) from both PV mini-grid sites were increasing during the analysis period which aligns with their load growth. The overall performance of JATENGS06 is higher compare to MALS11, both in performance ratio and total system efficiency. Nonetheless, it is observed that both systems have potential for more productive uses of energy since the systems have more disposable energy to be used during daytime, especially in MALS11 with less load than JATENGS06 moreover it uses AC-coupled configuration.

To anticipate imbalance energy that curb system's performance, it is advised to conduct better system sizing and design during planning. The system sizing comprises of:

- Demand assessment, which requires demand forecasting of the potential electricity users
- Resource assessment, by measuring potential energy using historical data from reliable sources such as NASA, IRENA Solar Map
- System design, which includes designing PV mini-grid system and simulating with reliable efficiency data for each component

4.3 Battery Performance

It was observed in the overall PV performance section that daily energy balance had significant effect to the PR value of a PV system. To balance its daily energy share, isolated PV mini-grid is dependant to energy storage or backup system. Thus, the state of charge and its battery efficiency is considered as an important indicators of PV performance.

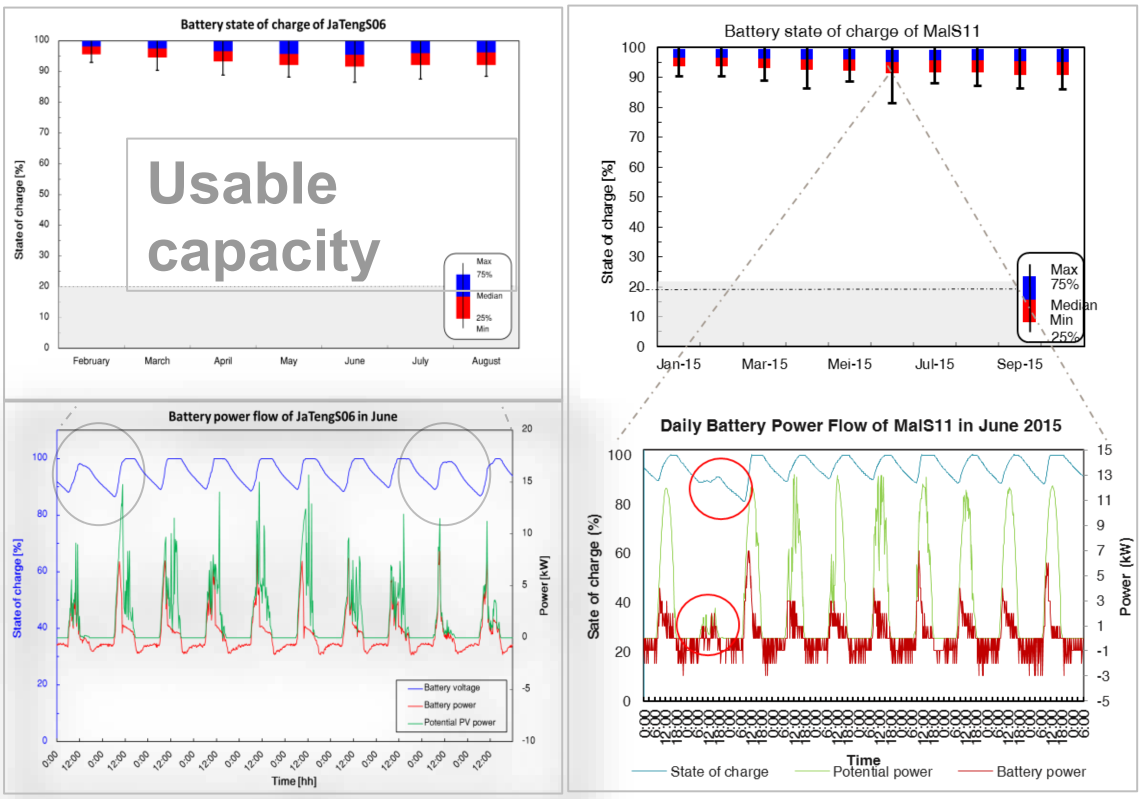


Figure 15 Battery state of charge and power flow

State of charge (SoC) in Figure 15 exhibits that both PV mini-grids were operating in between 80 to 100%. It indicates that only 20% out of 80% usable battery capacity was used and it had never reached beyond 20% depth of discharge (DoD). In the meantime, at 0.1 C, higher efficiency is achieved when battery operates in between 10 to 70% SoC as shown in Figure 16. This is happened because as battery internal resistance increases, higher state of charge is achieved.

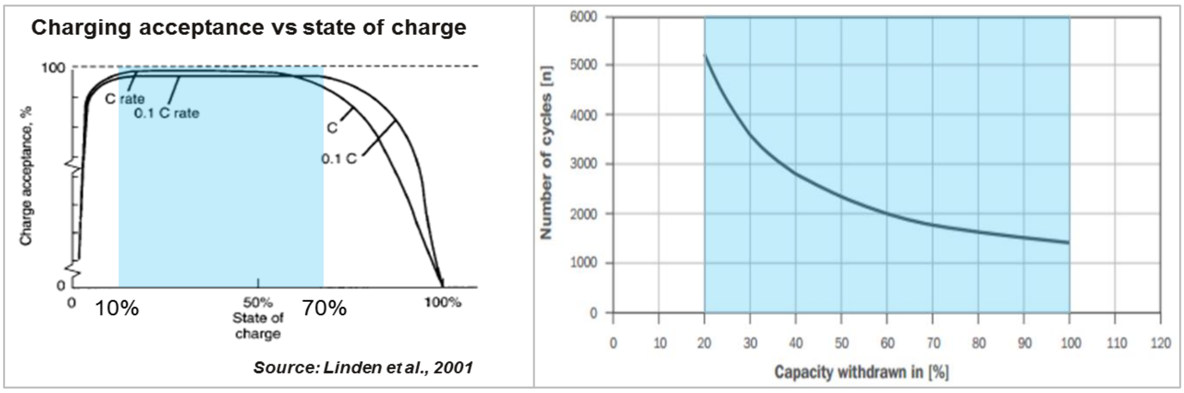


Figure 16 Charging acceptance curve (left) and battery cycle (right)

Theoretically, operating the battery at low DoD may increase the number of cycles up to 5000 cycles or equivalent to 13 years lifetime, neglecting the effect from temperature. Despite expecting longer lifetime on battery, by only utilising 10-20% of usable energy, it reflects inefficient use of storage.

Resume and recommendation of battery performance

In light of the battery performance examination, there are some recommendation to be considered by the authorities as follow:

a. The amount of energy allocation per household can be recalculated, higher allocation is possible depending on measurement of usable capacity in each isolated PV mini-grid system
b. The required autonomous days of storage should be reconsidered to achieve more efficient system and longer battery life
c. Optimising the setup of energy allocation and autonomous days of storage that aims to secure energy supply; higher system efficiency; and longer battery life cycle.
d. Despite the big potential to increase electricity demand, load management should be applied in advance and alongside the process of resetting user's energy limiter

4.4 Load Behaviour

How consumer uses the electricity highly affects the PV mini-grid performance. Load behaviour indicates strong relation between load and PV mini-grid performance.

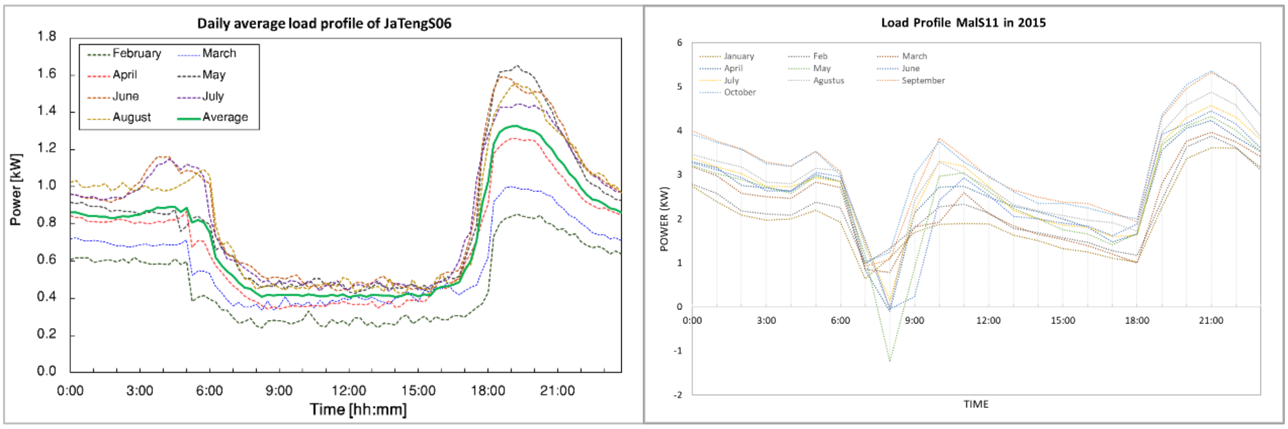


Figure 17 Daily load profile

Figure 17 exhibits daily average load profile from each mini-grid site. The average daily energy consumption in JATENGS06 increased rapidly with monthly average rate of 33 Watt-hour or 20% of the overall load. With this rate, the electricity users in JATENGS06 had reached the daily energy quota of 260 Watt-hour within three months of operation. During peak hours, the highest load had only reached 9% of the inverter capacity, that indicates low utilisation of energy. However, its peak load rose up from 840 Watt to 1650 Watt.

Discrepancy between load behaviour of AC-coupled and DC-coupled in the isolated PV mini-grid is expressed on the Figure 17. Unlike JATENGS06 which had consistent low load during the day, load in MALS11 was drained in the morning between 7:00 and 8:00 am, but rose up again starting from 9:00 am until noon. Highest load in both systems happened during the evening with peak time at 21:00.

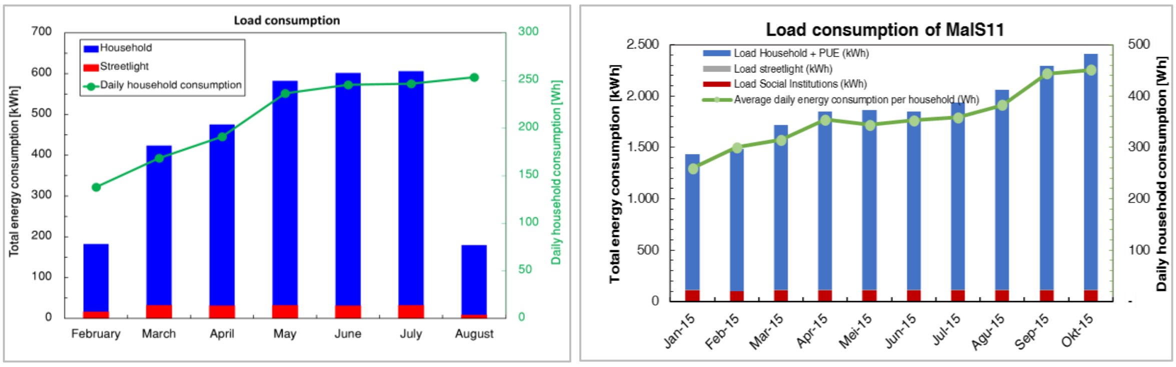


Figure 18 Load consumption

Negative value in load profile of MALS11 was caused by differences between estimation and actual value of the energy from array. The analysis uses estimation data from the available data from one out of three installed grid inverters. Negative value happens when the energy from array was actually higher than it was estimated. However, it highlights the importance of quality installation to be able to provide reliable and accurate data for further analysis.

Most of the electricity consumption were coming from household connections, as seen in Figure 18. Each household in MALS11 received 300 Watt-hour electricity per day, higher than those in JATENGS06 at 260 Watt-hour per day. In average, daily energy consumption in MALS11 increased 21 Watt-hour per month, much less than JATENGS06 with 33 Watt-hour increase per month (from February to May). Lower energy consumption in MALS11 is also indicated by lower peak-load that took up 8% of the usable inverter capacity at maximum.

The low electricity load was a consequence of lacking access and connectivity to market that occurred in the community that was served by MALS11 system. Unlike JATENGS06 which had better access to market both to sell and purchase goods, MALS11 is located in an isolated island with limited transportation. It is challenging to drive economic activities from there, let alone electricity load growth.

Resume and recommendation of load behaviour

The load profile graphs summarise several key information that represents the load behaviour from the two mini-grid sites. The key takeaways are:

a. Load in both sites was dominated by household consumption, in JaTengS06 streetlights consumed more energy than those in MalS11. In the meantime, electricity consumption for public institutions in MALS11 was higher than in those in JATENGS06 which might related to culture and policies in managing the PV mini-grid.
b. Load per household had significant increase in both sites. Monthly electricity consumption per household in JATENGS06 has increased by 30 Watt-hour while in MALS11 has monthly increased by 21 Watt-hour in average. There might be correlation between economic situation and the increase rate of electricity utilisation, considering MALS11 had lower load increase compared to JATENGS06
c. Demand factor in both sites was less than 10%, which resulted in lower inverter efficiency. Higher load power is favourable or preferably proportional to the installed system size.

Considering existing load behaviour in both mini-grid sites, it is recommended to incorporate electricity as a valuable asset to drive economic activities in the area. It can be done by identifying existing business in the village, then using electric appliances to leverage their production or service quality, such as agricultural processing, packaging, etc. If rural business does not exist yet, it is suggested to form collaboration with other relevant partners in business coaching.

Ideally, load behaviour is already considered in the design of isolated PV mini-grid system as an important variable in the design input. Hence, more energy balance can be achieved that contributes in higher efficiency of the system.

4.5 Overall System Efficiency

Assessment of system efficiency was conducted to: PV array; solar charge controller (for DC-coupled); grid inverter (for AC-coupled); battery; and inverter.

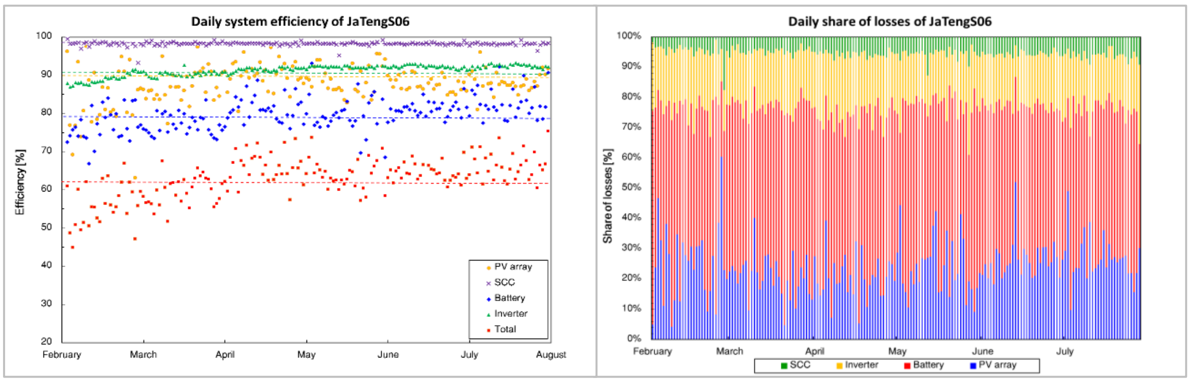


Figure 19 Daily system efficiency and losses JATENGS06

For JATENGS06, the total system efficiency reached 63% which is considered low. The SCC operated well at 98% efficiency, although it was rarely operating at high solar irradiance. Meanwhile, the average inverter efficiency was only 91%, which might be caused by operating with low power. Highest energy losses contribution came from battery (53%), and was followed by PV array losses (24.7%). However, the trend shows that as the load consumption increases, the overall efficiency also increases

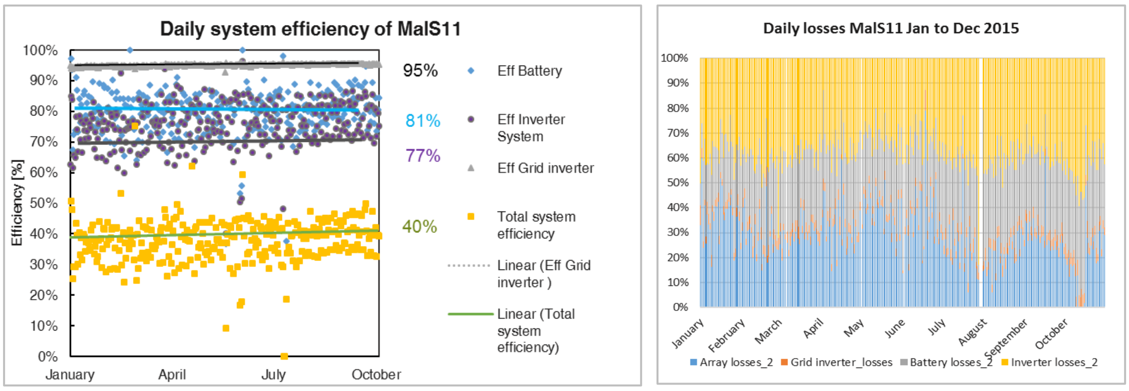


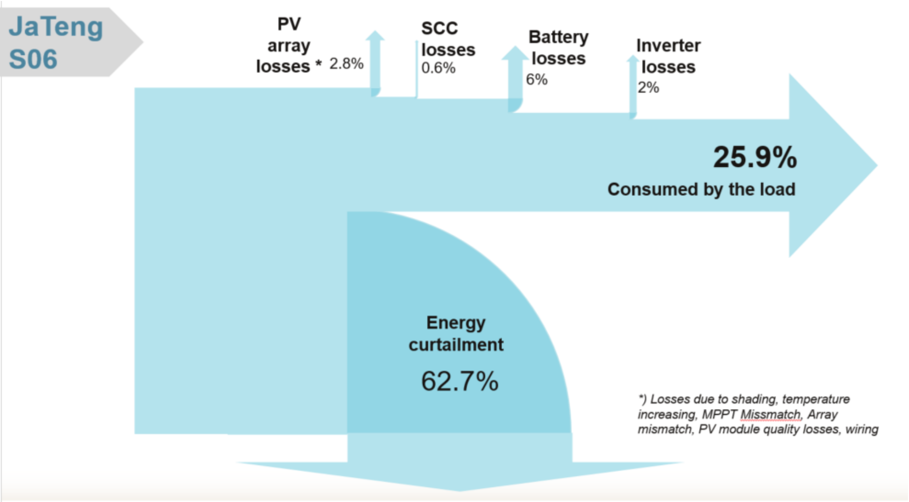
Figure 20 Daily system efficiency and losses MALS11

In the meantime, MalS11 operated at 40% total system efficiency and relatively constant during 10 months of evaluation. The grid inverter run at 95% efficiency with high solar irradiance in the area. Battery inverter contributed most losses at approximately 38% from total system losses with system efficiency of 77% while the battery had operated at 81% efficiency.

There are three outliers, in March, May, and June 2015 when the use of energy from battery were exceptionally higher than the energy generated. In those 3 days, solar irradiation was ranging from 0.70–1.20 kWh/m^2.day. It was very low considering that the average irradiation of MalS11 is at 5.60 kWh/m^2.day. As a consequence, the system discharged more energy from battery hence created outliers of battery efficiency, as seen in Figure 20.

System losses

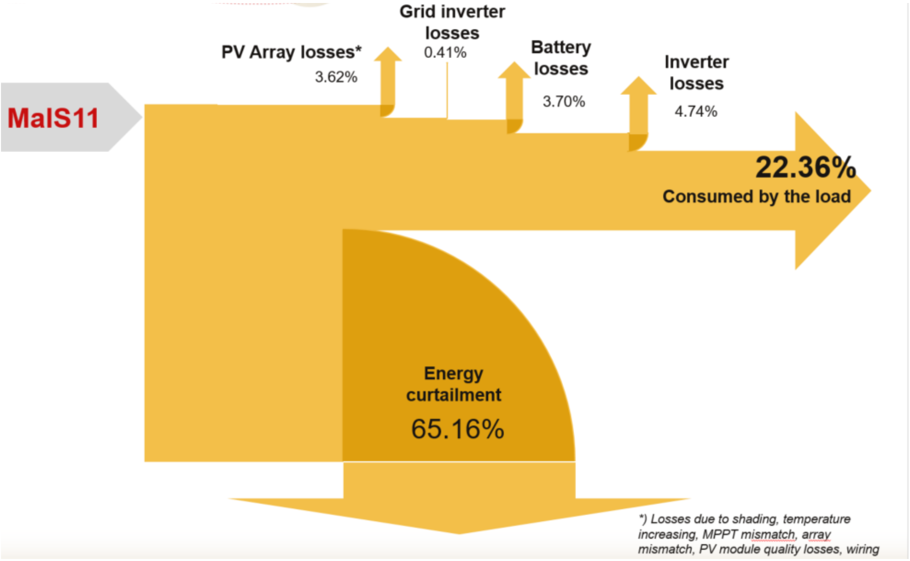
Analyses of system efficiency includes measurement of losses occurred in the energy generation process, as illustrated in the following Sankey diagram in Figure 21 and Figure 22. There was only 37% of energy potential could be captured by PV module in JATENGS06, while only 25.9% that was consumed by the users. MALS11 had more unused potential energy and lower electricity load compare to JATENGS06.



*) Losses due to shading, temperature increasing, MPPT Missmatch, Array mismatch, PV module quality losses, wiring

Figure 21 Sankey diagram of JATENGS06

Most energy losses occurred in the battery for JATENGS06, while in MALS11 it happened in the inverter. Energy in MALS11 lost as much as 12.47%, during electricity generation process, as well as 11.4% energy cutback in JATENGS06 system.



*) Losses due to shading, temperature increasing, MPPT mismatch, array mismatch, PV module quality losses, wiring

Figure 22 Sankey diagram of MALS11

Resume and recommendation for system efficiency

Both sites have good workmanship quality based on technical inspection by GIZ in 2015. It is represented by the readability of data in the system, which was exceptionally good compare to the other similar isolated PV mini-grid sites. Despite its good quality on system installation, both systems had more unused potential energy, as indicated by the high proportion for energy curtailment.

Most energy losses in JATENGS06 was in its battery that took 6% of the total system losses, while in MALS11 most losses occurred in its battery inverter by 4.74% of the total system losses. Overall, JATENGS06 system run more efficiently with 63% than in MALS11 that run in 40% efficiency. It is indicated that on system losses took 12.47% from daily energy share in MALS11.

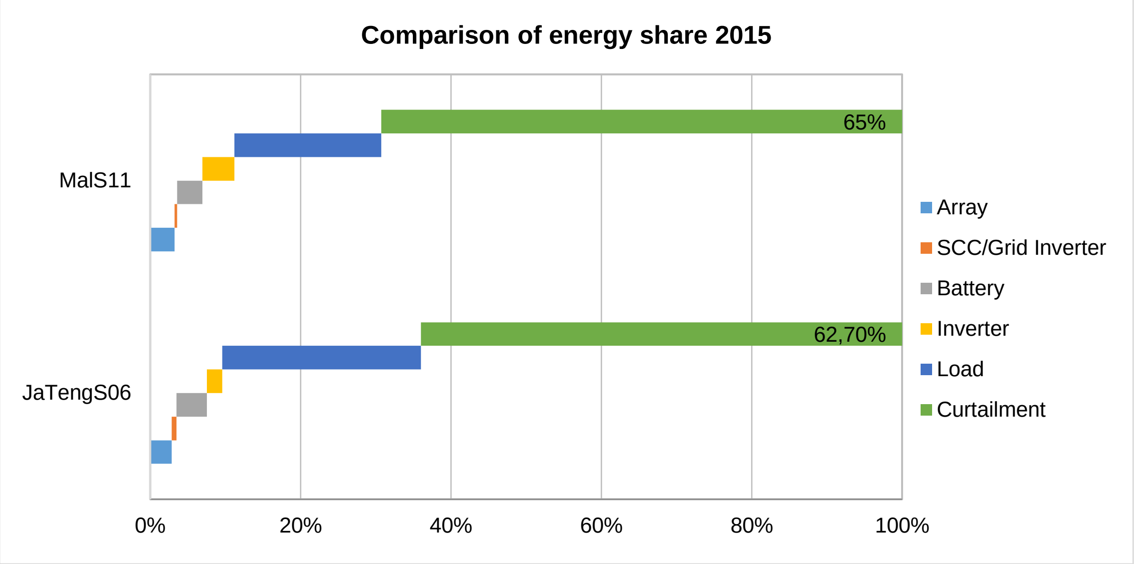


Figure 23 Comparison of energy share

5. Conclusion

The study addresses questions on what parameters to examine performance of the isolated PV mini-grids and how they are performed during operation. Hence, this study concludes that:

a. There is a huge challenge in collecting operational data from the rural PV mini-grid systems. Very **few technical data can be obtained** which may cause huge knowledge loss from the world's biggest rural electrification initiative using PV mini-grid.

b. Availability and reliability of data such as irradiance, module temperature, battery temperature, etc. are highly important for a comprehensive monitoring and performance evaluation of the system.

c. The **key performance criteria** comprise of:
    i. **PV module performance,**
    ii. **overall system performance,**
    iii. **battery performance, and**
    iv. **load behaviour**

d. Both systems had more untapped energy by PV modules. M**ost of the potential energy was not absorbed** by both system, thus less than 40% potential energy was able to be generated to electricity.

e. **Range of performance ratio is in between 0.2 to 0.3**, with similar capacity factor at 5%.

f. PV mini-grid in JATENGS06 operated more efficiently than MALS11 with 63% efficiency, while MALS11 operated in 40% efficiency.

g. There is a trend that **the electricity load in both systems were increasing**. Rapid load increase was found in JATENGS06 with 20% monthly increase rate, while load in MALS11 was relatively steady with less than 10% load growth.

h. During peak hours, the load in JATENGS06 could take up 9% of available capacity, while MALS11 had reached 8% of the total usable energy. As a consequence, MALS11 had lower inverter efficiency than JATENGS06. Inverter is preferably operated in high-load to have better efficiency value.

i. The **battery operated between 80% to 100%**, which means that the battery was never been used beyond 20% depth of discharge (DOD). **Low DOD causes inefficiency in battery**, hence, it is recommended to have DOD ranging between 20 to 80%.

j. Most losses were caused by battery inverter in MALS11, while in JATENGS06 losses occurred more in its battery. One of the reason was that the components ran in low power, which resulted in system inefficiency.

6. Recommendation

Despite all the challenges in the rural PV mini-grid implementation, there is always an opportunity to improve. Based on the study, we have summarised recommendations for improvement, which are:

1. **Incorporate detailed system sizing since planning phase to achieve better PV utilisation and system efficiency.** System sizing includes:
    a) Demand assessment, which covers forecasting load or electricity demand in the targeted area
    b) Resource assessment, as a minimum, use historical data from reliable and actual sources, as well as thorough site visit to the targeted area
    c) Define number of autonomous days, which allows the mini-grid to operate even without the presence of sunray or potential energy
    d) System design, that includes selecting suitable components and incorporating reliable efficiency data from each component
2. **Improving the method of feasibility study hence reliable data is used to achieve** better designs of array configuration (good air circulation, free of shade, and good inclination)
3. **System efficiency can be improved by increasing PV system utilisation. Thus, it encourages more productive uses to drive more economic activities in the area**. Moreover, it creates a balanced supply and demand of electricity.
4. Creating a more comprehensive PV monitoring and performance evaluation protocol to provide better benchmarking of the installed PV mini-grid
5. **Ensuring continuous monitoring and evaluation of the system for faster response and improve the system performance**. It can be initiated by:
    a) Incorporating system performance parameter into the commissioning process
    b) Comprehensive commissioning methodology which requires the contractor to submit log data from the installed remote monitoring system (RMS) as a pre-requisite for work acceptance. It is important to prove the quality of installation, performance of monitoring system with reliable data and the interconnection between components.
    c) Data quality and analyses should be continuously maintained by EBTKE or any appointed institution
6. Despite the opportunity to increase electricity consumption, load management should be applied prior and alongside to its implementation. One of the alternatives is to cluster the productive use (PUE) activities and separate the connection between households and the PUE cluster. The arrangement will help the operators when they maintain electricity quality and load balancing.

7. Acknowledgement

- Indonesia has the world-largest initiative on rural PV mini-grids and has so many lessons that can be shared with the other countries.
- Nevertheless, this brave initiative is only known by few whilst DJEBTKE deserves good recognition about their extensive work
- This study aims to enrich the lessons from the project thus EBTKE and more relevant stakeholders can learn from it, and most importantly, to improve the implementation
- The study is open for further comments and considerations

8. Appendix a List of Variables

Obtaining data from inverter needs the system practical guide from the manufacturers. Inverter systems that are used by DJEBTKE consist of Leonics, SMA, and Schneider. In this study, we took samples from SMA and Schneider system.

8.1 SMA Variable

Variables in SMA system consist of more than 100 parameters, thus they have prepared the guide to read the datasheet. Thus, in this table, we only mentioned few parameters that were used in the data processing.

Parameter SMA		**Description**	**Unit**	**Component**
	Array Power Nominal (P0)		**kWp**	
IntSolIrr	Radiation (G)	Solar Irradiance	W/m2	Pyranometer
E-Total	Energy array daily (EA)	Energy counter Out direction SMADEF	kWh	Grid Inverter
BatVtg	(n) Voltage	Battery voltage device	V	(n) Inverter Sunny Island
	Mean VS			
A.Ms.Watt	PDC (System power Output – DC)	Power from grid inverter in DC form	Watt	Grid Inverter
Pac	PAC (System power Output – AC)	Power from grid inverter in AC form	Watt	Grid Inverter
BatEgyCntIn	(n) Storage Energy Input (ETS)	Energy meter for battery charge	kWh	Inverter
BatEgyCntOut	(n) Storage Energy output (EFS)	Energy meter for battery discharge	kWh	Inverter
AhCntIn	(n) Storage Current IN(ITS)	Meter for battery charge	Ah	Inverter
AhCntOut	(n) Storage Current OUT (IFS)	Meter for battery discharge	Ah	Inverter
EgyCntIn	(n) Inverter Energy Total IN (EITS)	Absorbed energy of the off-grid inverter	kWh	Grid inverter
EgyCntOut	Inverter Energy OUT	Output energy of the off-grid inverter	kWh	Grid inverter
EgyCntOut + E-Total	Total Load (EL)			**Grid inverter**
	SOC		**%**	
	Potential power		**kW**	
BatEgyCntOut	Ebat	Energy meter for battery discharge	kWh	Inverter
Pac	Pac grid	Total inverter active power (cluster) SMADEF	kW	Grid Inverter
TmpAmb	Ambient temperature	Surrounding temperature	Celcius-degree	Pyranometer
TmpMdul	Module temperature	Temperature on the module	Celcius-degree	Pyranometer

8.2 Schneider Variables

In Schneider system, each parameter is set during the system setup. There is a possibility that the list of parameters in Schneider system are different for each PV mini-grids. The table below represents the list of parameters that were set up for JATENGS06.

	Source: Schneider Electric. Connect ComBox - Custom Data Logging. Application note, 2015			
No	**Parameter Name**	**Unit**	**Description**	**Location**
System level				
1	SYSTEM Weather station Irradiance	W/m2	Solar Irradiance	Pyranometer connected to ComBox via Modbus
2	SYSTEM Weather station Temperature	°C	Ambient temperature	Pyranometer connected to ComBox via Modbus
3	SYSTEM PV Total Power	W	Total input PV power of all solar charge controllers	Solar Charge Controller
4	SYSTEM PV Harvest Power	W	Total output power of all solar charge controllers	Solar Charge Controller
5	SYSTEM PV Voltage	V	Input PV voltage measured at a solar charge controller	Solar Charge Controller
6	SYSTEM Total PV Current	A	Total input PV current of all solar charge controllers	Solar Charge Controller
7	SYSTEM Battery Voltage	V	Battery voltage of all battery banks	Solar charge controller, battery inverter
8	SYSTEM Battery Current Net	A	Net battery current to and from all battery banks (discharging (-), charging (+))	Solar charge controller, battery inverter
9	SYSTEM Battery Power Net	W	Net battery power to and from all battery banks (discharging (-), charging (+))	Solar charge controller, battery inverter
10	SYSTEM Battery Temperature	°C	Battery temperature of all battery banks	Solar charge controller, battery inverter
11	SYSTEM Battery Bank (n) Voltage	V	Battery voltage of a battery bank	Solar charge controller, battery inverter (specific bank)
12	SYSTEM Battery Bank (n) Current	A	Net battery current to and from a battery bank (discharging (-), charging (+))	Solar charge controller, battery inverter (specific bank)
13	SYSTEM Battery Bank (n) Power	W	Net battery power to and from a battery bank (discharging (-), charging (+))	Solar charge controller, battery inverter (specific bank)
14	SYSTEM Battery Bank (n) Temperature	°C	Battery temperature of a battery bank	Solar charge controller, battery inverter (specific bank)
Component level				
15	(n) MPPT Input DC Voltage	V	PV input voltage of individual solar charge controller	Solar charge controller
16	(n) MPPT Input DC Current	A	PV input current of individual solar charge controller	Solar charge controller
17	(n) MPPT Input DC Power	W	PV input power of individual solar charge controller	Solar charge controller
18	(n) MPPT Output DC Voltage	V	PV output voltage of individual solar charge controller	Solar charge controller
19	(n) MPPT Output DC Current	A	PV output current of individual solar charge controller	Solar charge controller
20	(n) MPPT Input DC Power	W	PV output power of individual solar charge controller	Solar charge controller
21	(n) MPPT Battery temperature	°C	Battery temperature of individual solar charge controller	Sola charge controller
22	(n) XW Load AC Voltage	V	Output voltage of individual battery inverter	Battery inverter

	Source: Schneider Electric. Connect ComBox - Custom Data Logging. Application note, 2015			
No	**Parameter Name**	**Unit**	**Description**	**Location**
23	(n) XW Load AC Current	A	Output current of individual battery inverter	Battery inverter
24	(n) XW Load AC Power	W	Output power of individual battery inverter	Battery inverter
25	(n) XW Load AC Frequency	Hz	Output frequency of individual battery inverter	Battery inverter
26	(n) XW Battery Voltage	V	Battery voltage measured at terminal of individual inverter	Battery inverter
27	(n) XW Battery Current	A	Battery discharging current (input current) of individual inverter	Battery inverter
28	(n) XW Battery Power	P	Battery discharging power (input power) of individual inverter	Battery inverter

Energising Development

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