High Penetration of PV in Tropical Island Systems

Experiences from Indonesia

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***Abstract*—Power generation on small islands, especially in tropical areas, is typically provided solely by diesel generators. The cost of electricity in such systems is high due to the fuel cost and the high maintenance efforts required especially for small high-speed diesel generators. As economics of scale have led to a stark reduction of PV panel and inverter prices over the last two decades, PV became an economically feasible alternative to diesel generation. Tropical islands usually have moderately high solar potential, and PV can usually generate at a lower cost than diesel generators, especially in more remote areas, where fuel is more expensive due to transportation cost. Indonesian state utility Indonesia comprises more than 17,000 islands, in which Indonesian state utility PLN runs more than 600 islands grids, many with a peak load and generation capacity below 1 MW. With the recent reduction in PV prices and the official goal of 23 % renewable electricity in Indonesia by 2025, PLN is greatly interested in expanding the generation portfolio in the smaller islands systems to include PV and possibly batteries, if necessary, for secure operation. This paper presents findings from a pilot study in an island with a 1 MW power system, in which the generation capacity expansion was optimized to meet the 2025 renewable generation target with a cost-effective and technically feasible solution. The study is part of the REEP 1000 Islands programme by the German Technical Cooperation GIZ.**

Keywords - PV; island; hybrid system, diesel battery PV hybrid; Indonesia; spinning reserves, dynamic stability.

I. Indonesian Island Systems: Facts and Challenges

Utility Perusahaan Listrik Negara (PLN, translating to State Electricity Company) is in charge of power generation, transmission and distribution in Indonesia, resulting in a vertically integrated power system. Privately owned generation (independent power producers, IPP) is allowed with the approval of PLN, and such generators run under power purchase agreements (PPA).

Besides the main grids on Java, Sumatra and Bali, which supply most of the population, PLN runs smaller systems on Kalimantan (Borneo), Sulawesi, Timor and Western New Guinea (Papua) as well as on a multitude of small and very small island systems. These small islands, which were the focus of the research leading up to this paper, are almost 100 % powered by diesel generation, with the exception of some few off-grid installations of PV-battery systems in very remote locations, and small coal power plants on some of the larger islands (> 10 MW peak load). With consumer tariffs for electricity in Indonesia independent of the customer's location, and the generation cost of diesel only systems considerably higher than the national average, PLN is basically cross-subsidizing these islands. The utility is thus greatly interested in reducing generation cost on the islands. The main objective of GIZ's REEP 1000 Islands programme is to support PLN in the integration of renewable energy on those ilands.

To make the systems more cost efficient, PLN is looking into different options. The simplest one is the upgrade from often ancient small (< 100 kW) and inefficient diesel generators to new engines that consume considerably less fuel and can be operated flexibly. But even deploying such new generators, the fact is that diesel, which needs to be transported to the islands by ship, remains an expensive fuel. The deployment of renewable energy can help drive the cost of electricity further down. For most islands, renewable resources are limited to PV potential (see Figure 1), due to low average wind speeds. In some of the larger islands, agricultural waste from coconut and palm oil production is available to be used for power generation.

PV integration in small island systems presents some unique challenges. If PV is to contribute significantly to energy supply to save diesel and reduce costs, installed capacities need to be high, leading to high instantaneous penetrations of load and generation during the mid-day peak. This may lead to the following issues:

- Grid forming inverter technology was still relatively new for systems of this size at the time of this research (2018)– thus it was assumed that some diesel generation has to remain online at all times;
- Diesel generators have an inherent minimum stable output power, below which they cannot operate, limiting PV penetration;
- PV fluctuations need to be balanced out by diesels; thus, the ramping speed of the diesels may limit PV penetration;

- With very high instantaneous penetration levels of PV (non-synchronous generation), inertia in the grid is very low, possibly leading to stability issues.

Moreover, the load in small tropical islands with little industry and a possibly low state of development tends to be lower during the day and have its peak during early night time hours due to cooking, lightning and air conditioning. This further aggravates the inherent issues with PV integration.

While those factors must be considered, they do not mean that large shares of PV are not feasible on such islands. Enabling technologies such as different energy storage options and demand side management exist and are used in other parts of the world. Moreover, new diesel generators are usually more flexible than older designs, facilitating PV integration.

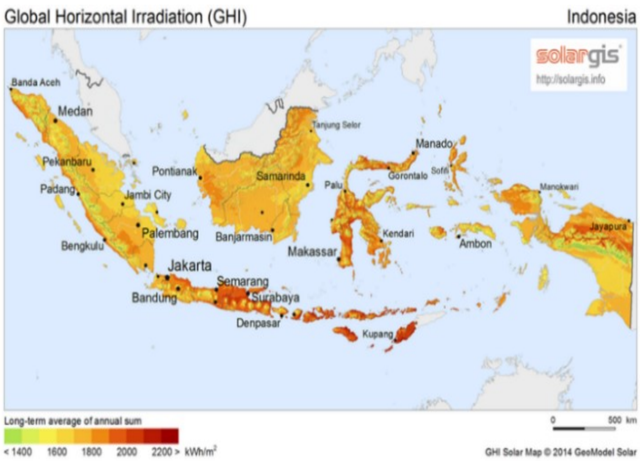

Figure 1: GHI map of Indonesia as published by SolarGIS, showing a potential for capacity factors between 15 and 20 % for PV in Indonesia.[1]

II. PILOT ISLAND: STATUS QUO

Energynautics was commissioned in 2017 by the German development agency GIZ, to assess the potential for PV integration in a number of small island grids. The findings for one of these islands, Kaledupa, are presented in this paper. As there are several hundred islands in this category in Indonesia, mostly displaying similar characteristics, information and results can be taken as indicative for further development in other parts of the country.

Kaledupa is located south east of Sulawesi, at a distance of 500 km from the equator. It is inhabited by approximately 20,000 people, with fishery and agriculture as the main sources of income. The general state of development is low, compared to the Indonesian main islands.

Power is supplied to approximately 90 % of the population by a radial 20 kV distribution grid, using overhead lines. No low voltage feeders exist, and houses are connected to the 20/0.4 kV distribution transformers by individual cables. Generation takes place in a single diesel power plant in the main town of the island. The power plant has recently been upgraded to two new 650 kW diesel generators with automatic frequency and voltage control. These replaced small, manually controlled gensets ranging from 70 to 250 kW of installed capacity, some of which date back to the 1980s. Average electrical efficiency of generation increased from 28 % to around 40 % with this upgrade.

The per capita electricity consumption of around 100 kWh p.a. is only 1/8 of the national average. Besides the lack of energy intensive commercial and industrial operations, the main reason for this low usage is the fact that PLN is supplying electricity to the population during the night time hours only. The system is switched on at 6 p.m. and switched off at 6 a.m. on normal weekdays, with additional hours being provided on Friday and Sunday. The main reason for this constraint is the high cost of electricity, which is insufficiently recovered through the tariff system. PLN has expanded supply to 24 hours on a trial basis in early 2018, but concluded that, without a significant share of cheaper generation (i.e. PV), this regime is financially unsustainable, thus delivering the motivation for the planned PV expansion.

Peak load in the evening hours (between 6 and 7 p.m.) is currently 900 kW, with the load curve then declining until a second smaller peak appears in the early morning hours (5 a.m.), before power is switched off. During the 24 h supply trials, the peak remained in the evening hours, but was reduced to ca. 600 kW, while daily load was in the range of 250 – 400 kW (see Figure 2).

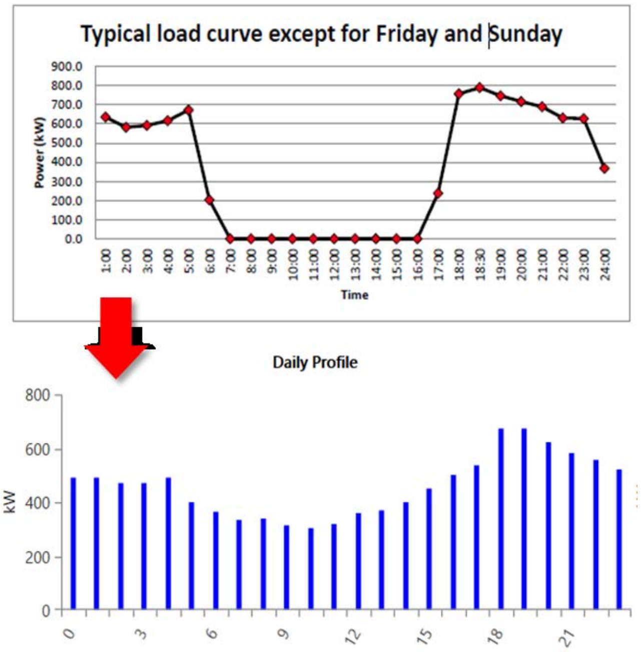

Figure 2: Load curve development with the switch from 12 h to 24 h supply. Source: measurement data from Kaledupa (PLN / Energynautics).

The two 650 kW gensets are powered by high-speed diesel engines driving 50 Hz generators at a synchronous speed of 1500 rpm. Typically, one of the gensets operates at a manually entered setpoint to provide baseload generation, while the other one is in isochronous mode, automatically regulating the frequency. Running both generators in isochronous load sharing mode is possible. Voltage control at the generator terminals is also provided automatically. As the genset type was designed for off-grid applications in mines and on construction sites, the gensets can provide a high amount of flexibility. Minimum stable output is 20 kW per genset, and maximum ramp rates exceed 150 kW/s across the

[1] Licensed under Creative Commons, © 2017 The World Bank, Solar resource data: Solargis.

entire power range (with 25 kW/s given as a recommended ramp rate). Startup time from cold stand-still is around one minute. This, however, comes at a price of a mean time between overhaul of less than 2500 operating hours and thus higher O&M costs than (larger) less flexible low or medium speed diesel generators.

Renewable energy potential on the island is limited to PV, because wind potential is too low to be exploited. No considerable biomass or hydro potential is present on the island. PV potential allows for capacity factors around 16 %, which is acceptable and considerably better than the 9 – 11 % reached for example in Germany, but lower than the >20 % possible in dry, sunny areas.

III. Software

Two different power system software environments were used during the study, HOMER Energy and DIgSILENT PowerFactory. HOMER Energy is an economic optimization tool tailored to small systems, either island grids or off-grid systems, based on a search space. It can optimize installed capacities and generator dispatch (including battery use and curtailment of renewable energy) for a number of consecutive years, taking into account cost development, inflation and discount rates, fuel prices etc. Detailed references on the development of Homer and the underlying algorithms can be found under [1]. DIgSILENT PowerFactory is a grid modelling and simulation software, which was used for power flow calculations according to Newton-Raphson as well as RMS dynamic stability analysis.

IV. Objective and Methodology

Under the REEP 1000 Islands project, the main objective is the implementation of hybrid power systems that can achieve the national target of 23 % renewable energy in the power sector by 2025 for each island. For this particular small island, the objective also includes the expansion of electricity supply from 12 to 24 hours. This incurs a chicken-egg-problem:

- Without significant contribution of PV, lowering the cost of electricity, supply will not be expanded to 24 hours;
- With no power system operation during the daylight hours, PV integration is either infeasible, or requires large amounts of storage.

The result is a requirement for the direct installation of high capacities of PV as soon as possible to enable expansion of services, as opposed to a “slow learning” approach with incremental installations.

Assuming that 24 h supply is resumed in 2019 with the installation of the first PV capacities, load is expected to grow quickly at around 20 % per annum. New customers are connected and existing customers install AC and other equipment that can be used to its full extent with a constant power supply. However, even with this projection, per capita consumption will remain below Indonesian average in 2025.

The main objective of the study is the development of an economically and technically feasible system with a minimum share of 23 % from PV by 2025. A general two-step approach was chosen:

- The system was modelled in the island optimization tool HOMER Energy to find the economically optimal system setup;
- The results were imported into the island grid model in PowerFactory (kindly provided by project partner STT-PLN) to determine the technical feasibility of the system and develop technical requirements for new generators.

With the cost of PV dropping further in the future, the demand on the island growing quickly over the next ten years, and the requirement for high PV shares right from the beginning, a stepwise approach with two year steps between 2019 and 2025 was used for the economic optimization (see Figure 3). For each step, the installed capacities from the previous step were taken as fixed, while the HOMER optimizer was given the freedom to install new PV, batteries and diesel generators as economically feasible at adjusted costs (CAPEX adjusted for inflation, base CAPEX for PV and batteries reduced each year). Simulations were then expanded to 2027 to provide the input for a 10-year development plan analogous to PLN’s RUPTL (ten year investment plan).

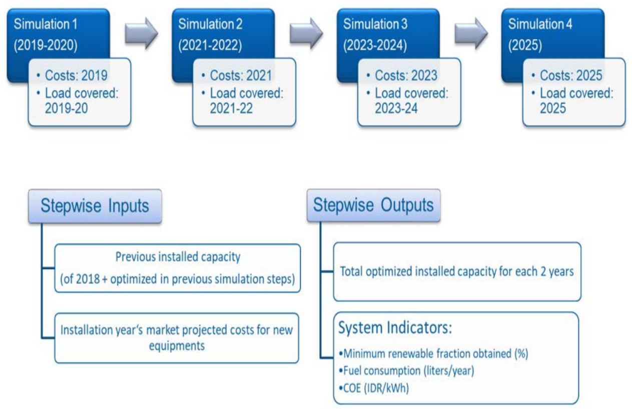

Figure 3: Stepwise approach to economic optimization.

This approach ensures that demand can be covered in every year, as cost efficiently as possible, with the generator technologies available on the market and the legacy installations already installed. Large PV capacities will be installed in the first year already, although they may become cheaper in later years, to enable 24 h supply. In subsequent years, PV capacities and new diesel generators are installed to keep up with the rising demand. For 2025, a constraint was set in the optimization to ensure that at least 23 % of energy was provided by PV and the renewable target is fulfilled.[2]

V. Modelling

A. *Inputs to economic optimization in HOMER*

Modelling in HOMER requires the basic setup of the system as well as a number of economic parameters and techno-economic constraints as inputs for the optimization. Main data and assumptions include:

[2] This constraint turned out to be redundant, as the 2025 economically optimal scenario had a renewable contribution above 23 %.

- The load, with full 24 h power supply all year, is based on measurements from the 24 h trial runs on Kaledupa and scaled up linearly for subsequent years;
- The system is set up with the two 656 kW diesel gensets already installed on the island. At least one diesel generator must operate at all times, assuming no grid forming inverters for PV and batteries are installed;[3]
- HOMER is allowed to install new diesel gensets of the same type as currently installed, as well as PV installations and lithium ion batteries;
- Batteries and battery inverter are scaled separately by the HOMER optimizer to allow optimization for the intended use of the battery. Battery lifetime is assumed to be 8 years for LFP type lithium ion batteries, which is in line with the warranty most manufacturers grant;
- Minimum allowed output power of the diesels is 65 kW per genset (10 % of P_n);
- The solar resource data used in HOMER is based on reanalysis data obtained from the NASA Surface meteorology and Solar Energy database. Available in hourly resolution at [2];
- A very security-oriented operating reserve requirement of 10% of load as well as 80% of solar output is used, determined by the level of fluctuations that can be expected in the system. Fluctuations can be smoothened making use of spatial distribution of the PV capacity across the island (see section VI B). Nevertheless, the overall cost impact of reserve is rather low, as at least one diesel genset has to stay online for inertia and voltage support at all times anyway.

Economic inputs include the following:

- Inflation (4%) and discount rate (12%) reflect the current state of the Indonesian economy. CAPEX of new installations, fuel and O&M cost escalate with the inflation rate;
- Initial equipment and installation cost for PV units (2018) is based on a report on the expected development of PV in Indonesia published by the Danish Energy Agency [3]. PV and battery cost are assumed for state-of-the-art equipment, which includes functionality for reactive power, low voltage ride through (LVRT) and frequency control as required by grid codes in various countries; [4]
- The expected cost reduction of PV and Li-Ion equipment is taken from publications by the International Renewable Energy Agency IRENA; [5] [6]
- Cost for the diesel engines is based on the actual installation cost of the currently installed units as provided by PLN. Operation and maintenance cost is taken from the existing maintenance contracts;
- Fuel cost is based on the current fuel cost on Kaledupa (including transportation costs), kept constant until 2027 and adjusted for inflation. The efficiency curve of the gensets was provided by the manufacturer;
- Transportation cost for all equipment is based on the transportation cost of the actual diesel engines (quotation from the installer as provided by PLN).

B. *Grid and generator modelling in PowerFactory*

HOMER respects technical constraints such as reserve requirements, minimum generator output and equipment efficiency, however, it does not provide an in-depth technical analysis on the stability of scenarios with high non-synchronous generation penetration. Therefore, simulations of the island grid were conducted using the tool DIgSILENT PowerFactory to verify the frequency stability of critical scenarios. Simulations were performed for the existing grid (2018) for model verification, and for the target year 2025 using the generation capacity expansion results from HOMER. Simulations included steady state load flow and dynamic simulation of events such as load or generation steps, losses of elements and short circuits.

The grid model consists of a model of the 20 kV grid on the island, containing all 20/0.4 kV distribution transformers and a detailed model of the diesel power plant. The grid is operated radially and consists of ACSR overhead lines with cross sections of 35 and 70 mm^2. Customers on the low voltage side of the distribution transformers are aggregated and not modelled in detail. No selective protection scheme exists, the only protection is that of the generators, hence, the system will switch off in case of a fault. Grid reinforcements based on the expected peak load are included in the 2025 model.

VI. RESULTS

A. *Economic optimization in HOMER*

Using the inputs listed in Section IV as well as the methodology described in Section V, for each step, the optimal system was chosen based on the lowest cost of electricity and used as an input for the next year. With an annual load increase of 20%, the results indicate that the existing 2 diesel units (656 kW) are sufficient to cover the load until 2020, after which a new 656 kW diesel unit is to be installed every two years. The diesel, battery and PV panel capacities (the latter shown without 75% derating from inverter) per 2-year intervals can be found in Figure 4. The battery is relatively small (208 kWh) and dimensioned to provide full output (150 kW) for one hour without falling below 20% state of charge.

With this capacity expansion, the annual renewable energy contribution achieved can be seen in Figure 5. PV plant generation will be curtailed only if the diesel generation, when already in the must-run condition, has reached its minimum output limit and thus can reduce no further. The target of 23 % by 2025 is reached without an additional constraint, indicating that the 23 % PV contribution is the economic-technical optimal share for the 2025 system.

Furthermore, as shown in Figure 6, PV integration reduces the Cost of Electricity (COE) in the island. The 23% renewable fraction achieved with PV yields a 12% COE reduction by 2025 if compared to a system with only diesel

[3] Further information on grid forming inverter technology is presented in section VII.

generation, and by almost 30 % compared to the cost of 2017. Fuel consumption is reduced by 22 % as given in Figure 7.

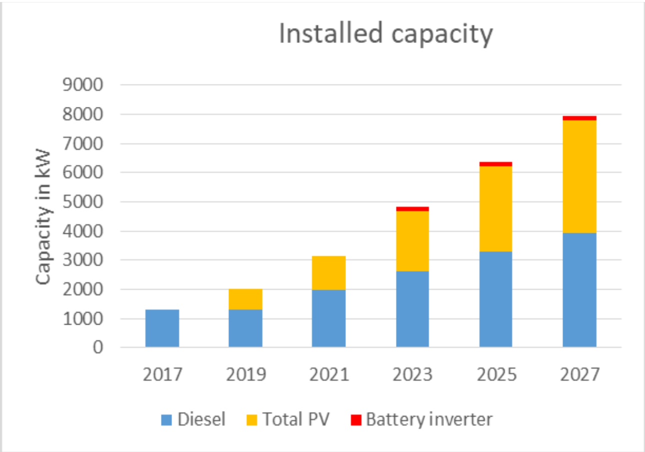

Figure 4: HOMER optimized installed capacities results (20 % demand growth).

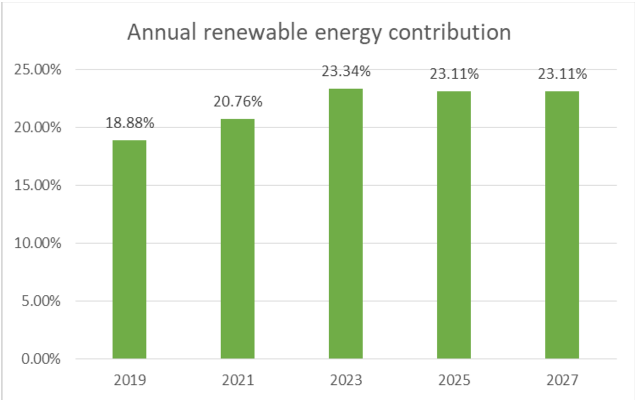

Figure 5: Minimum renewable fraction achieved per simulation step.

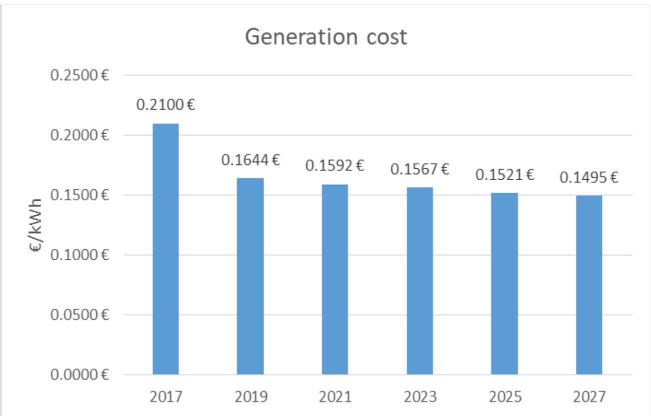

Figure 6: COE of the entire system with and without PV in 2018 Euro (20 % demand growth).

The COE includes the curtailment of some PV. With the cost assumptions used, HOMER results indicate that it is generally cheaper to install slightly more PV (to increase yield on cloudy days) and curtail an amount on sunny days, than to install less in the first place. The resulting curtailment, ranging from 8 % to 17 %, is very high compared to PV systems connected to large continental grids (where 3 % is often considered the highest acceptable value), but lower than in many island systems where curtailment of 20 – 30 % of PV production is not uncommon due to the limits imposed by older diesel generators. A shift of electricity usage towards the day could reduce curtailment and improve PV utilization.

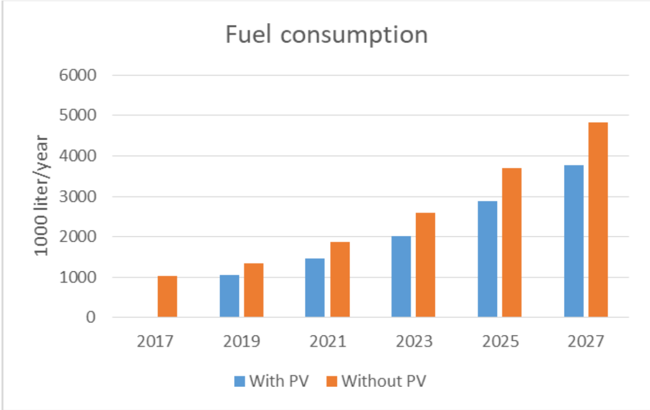

Figure 7: Fuel consumption with and without PV (20 % demand growth).

B. PV Distribution

As Indonesia in general (and Kaledupa, specifically) is located in the tropical climate zone close to the equator, average insolation is relatively high, but cloud movements are frequent and days with completely clear sky are rare. Hence, PV units will introduce a significant amount of active power fluctuation into the system, which must be covered by other generators. While no high resolution solar measurement data from Kaledupa itself was available, data from comparable sites revealed that, especially in the rainy season, a single PV site could easily expect fluctuations of 50 – 80 % of its output, within only a few seconds, on a regular basis (see Figure 8).

While it would be possible to provide the required PV share on Kaledupa – almost 4 MW by 2027 – from a single site, such an installation would obviously introduce fluctuations that the diesel generators are unlikely to be able to handle on a regular basis. For the economic optimization, a constraint was set that the diesels have to be able to handle an 80 % decrease in PV production within 5 minutes, however, covering the same decrease in a matter of seconds will, if at all possible, impose extreme strain on the generators.

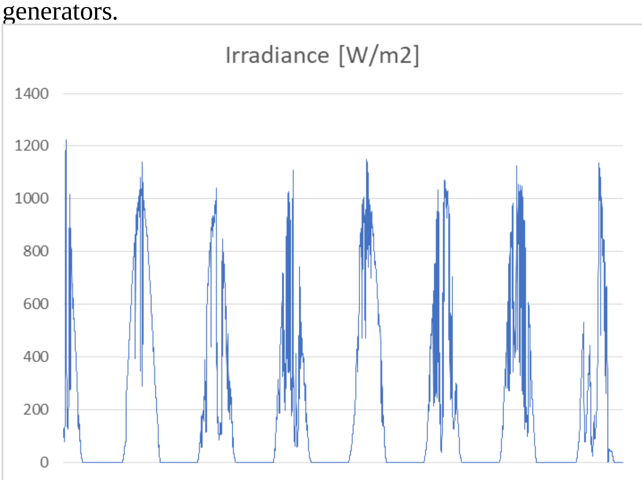

Figure 8: Solar irradiance data from a comparable site in Indonesia, for one week during the rainy season, in 1 second resolution.

Measures have thus to be undertaken to largely prevent such events. There are two basic strategies to reduce PV fluctuations:

- Installing a battery to smoothen the PV fluctuations at the PV site;
- Distributing smaller PV sites across the island to utilize spatial distribution effects.

The battery installation is the more commonly used strategy on small islands. However, the specific conditions in Indonesia would require a high output battery to smoothen the severe fluctuations from a single site. As battery lifetime is directly impacted by the charge and discharge C rate (ratio of output power in kW to battery capacity in kWh), the required power can only be provided by a relatively large battery (even high power, low energy Li-Ion batteries rarely reach C rates above C = 2). It is significantly cheaper to distribute multiple smaller PV sites across the island. Each one of these will still experience fluctuations of up to 80 % of output power, but even on the relatively small island of Kaledupa, the coincidence between these fluctuations on different PV sites within a time frame of less than a minute will be very low. The overall fluctuations can be covered by the diesel generators and a smaller battery, the latter being used primarily to prevent extremely fast ramps on the diesels which may negatively impact generator lifetime.

Figure 9: Planned PV distribution on Kaledupa 2027.

Based on the availability of land space, the distribution of load on the island, and the available 20 kV connections, the PV distribution shown in Figure 9, with 8 sites of 370 kWp each, was determined to be feasible for 2027. Sites can be installed one after the other, with the level in short term variation of PV output remaining largely unchanged with the scale-up.

C. Dispatch and Operations

With the results obtained through the economic optimization in HOMER, the system on Kaledupa reaches an annual PV contribution of more than 20 % and an instantaneous non-synchronous penetration of load in excess of 80 % relatively quickly (see Figure 10 for an example). While the system was found to remain dynamically stable even at this high level of non-synchronous penetration (see section D), this behavior largely owed to the flexibility of the new diesel engines, it is obvious that this diesel-PV-battery hybrid system requires a change in operational principles from today's purely diesel based operation.

The key upgrades to the system required for hybridization according to the economic results are the following:

- The system must be automatically operated, using a computer-based monitoring and control system or energy management system (EMS);
- The EMS must be able to collect operational data in real time and continuously optimize generator and battery dispatch;
- The EMS must be able to curtail PV if necessary, requiring a two-way communication link to all PV sites;
- A fallback mode in which the EMS is switched off and the system can be operated manually – albeit with more severely curtailed PV – must be included.

Systems providing this functionality are available on the market and can be integrated with the existing digital genset controllers. EMS are available as standalone system controlling the power system assets from the control center, or as battery integrated systems.

From 2023 onwards, a 208 kWh Li-ion battery with maximum power output (charge and discharge) of 150 kW is to be installed in the system. The battery will be mainly used to balance out PV fluctuations on days with cloud movement, while the shifting of PV power from the day to the evening peak has only a secondary role. The battery on Kaledupa can cover around 50-60% of the output of a single PV site very quickly, to give the diesel generators time to react to very fast output changes. The rest of the capacity is used to reduce daily curtailment and shift some load to the evening hours, discharging mostly during the PV reduction and load rise in the early evening. This reduces the necessary ramping speed of the generators. A dispatch example week using the data output from HOMER is shown in Figure 10, during which irradiance is high and PV production exceeds daily load on six out of seven days. The battery is charged as soon as PV generation exceeds load and discharged during the evening decline of PV production to prevent excessive ramp rates in the diesel generators. The state of charge never falls below 20 %, making the battery available for reserve provision at all times.

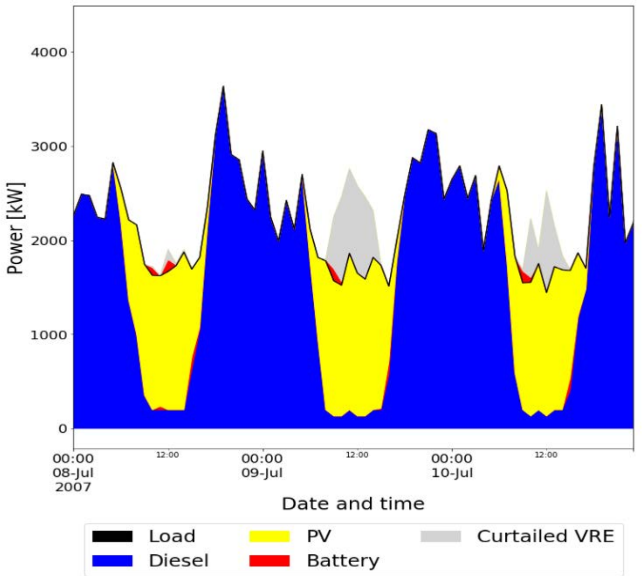

Figure 10: Example of dispatch on the island in the year 2027, during three days in July with high irradiance.

With high shares of PV available during sunny days, the diesel generators (or in this stage, the single diesel genset remaining online) must reduce their output power as far as necessary to obtain the maximum share of PV. The diesel gensets on Kaledupa were shown to be capable of running at a stable minimum output of 20 kW each. This is considerably lower than the larger medium speed diesel generators deployed in larger island systems, which can usually ramp down to 10 % of their rated output and are mostly dispatched not lower than 30 % of their rated output during normal operation. The reason for this is that these smaller gensets were originally developed for mining and construction applications with strong load fluctuations, imposing higher requirements for flexibility Even with low stable minimum load, diesel generators running at their minimum for extended periods of time may experience some technical issues, with wet stacking and increased consumption of lubricant being the most prevalent ones.

Wet stacking is the accumulation of unburned diesel fuel in the exhaust system, which then mixes with soot from the exhaust gases and accumulates in the exhaust system as an oily layer. If a diesel engine operates at very low load or even idle for extended periods of time, this mixture can harden, eventually damaging the engine. If the engine only operates at low load for a few hours, the fresh soot/fuel mixture is burned off as soon as the engine is ramped up again. For Kaledupa, the diesel genset will only operate at its lowest power output for 2-4 hours during the PV peak and will then ramp up again to near rated power during the evening peak. In this regard, wet stacking does not present an imminent danger to the diesel gensets. The higher specific fuel consumption during low load operation is outweighed by the benefit of lower cost generation from PV and the overall fuel savings.

D. System Stability

With instantaneous PV penetration of load reaching 90 % during the day on sunny days, system stability is a concern for Kaledupa from 2019 going forward. Similar instantaneous non-synchronous penetration levels have been observed on other islands with no stability issues, such as the Dutch Caribbean island of St. Eustatius, which would run on up to 89 % of PV during the day, the rest covered by diesels at low load, before the island was switched to grid forming inverters and diesel-off operation in late 2017.[4] While it has been proven that small island systems can be operated under such conditions, the matter must be investigated taking into account local conditions nonetheless. Results can also be used to develop technical requirements for PV and battery, which can contribute to system services and stability.

<u>Spinning Reserve</u>

The economic optimization in HOMER includes a constraint on spinning reserve, but does not consider the actual ramp rates of the generators. Results thus require ex-post analysis to assess whether sufficient reserves are always available. With the generators on Kaledupa capable of providing a ramp rate upwards of 25 kW/s (confirmed by measurements on site, see Figure 11), this is generally no problem. Generators are always able to ramp up to their full output power within 30 seconds, and the battery can react much faster. Hence, the available generators can always cover a relatively large PV fluctuation, given adequate control strategies.

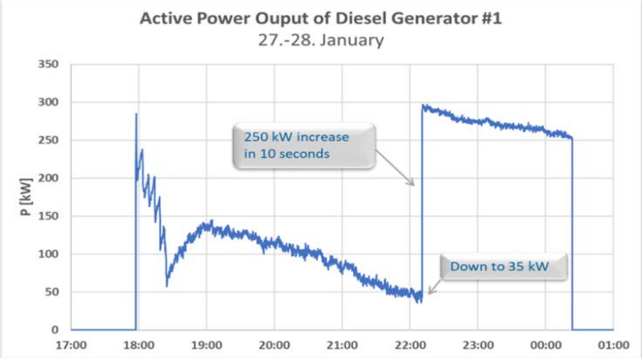

Figure 11: Output measurements, 10 s resolution, for an operational window of one of the diesels on Kaledupa.

The battery supports the diesel generators in providing reserves. It is usually charging quite early in the morning to be able to provide reserves during the PV peak. During the charging process it is capable of providing 300 kW of fast response reserve. When the charging process is completed, it can provide 150 kW.

<u>Load Flow Analysis</u>:

Steady state load flow simulations were conducted for the following cases:

- Peak load of 2025: 3000 kW load at 19:00, no PV contribution (night time);
- Maximum PV penetration in 2025: 1800 kW load at 12:00, 1670 kW PV, 2x 65 kW diesel (minimum output);

The peak load calculations showed that the 20-kV grid on Kaledupa is over-dimensioned, as is typical for a small system, because standard line types are used that were designed for more highly loaded grids. The ampacity of the overhead lines is between 5 and 10 MVA (depending on the age of the line). Due to the high ampacity of the overhead lines, there are also no inherent grid issues for the high PV penetration cases. Line load decreases compared to a similar day load case without PV as more electricity is generated closer to the load centers.

While the grid itself presents no problem at all, the characteristic of the demand leads to some reactive power issues if PV units do not contribute with reactive power provision. This functionality is commercially available, and typically, a range between $\cos \phi = 0.9$ inductive and $\cos \phi = 0.9$ capacitive is required. Reactive power can then be activated via remote control, with a fixed setpoint, or a Q(V) characteristic. All three options are suitable for Kaledupa, and the simplest one would be a fixed setpoint of $\cos \phi = 0.93$ capacitive. With the implementation of this reactive power participation, it was observed that no further steady state grid issues exist.

<u>Dynamic Stability Analysis</u>

Frequency stability is the critical parameter in an island system, while dynamic voltage stability is a secondary issue in a small grid, and rotor angle stability is uncritical in a

[4] https://www.sma.de/produkte/referenzen/st-eustatius-karibik.html

system with only one conventional generation site. Dynamic stability analysis was conducted for a number of scenarios and contingencies in DIgSILENT PowerFactory, to the following conclusions:

- The system generally remains stable at a PV penetration of up to 90 % during the loss of generation, load and feeder, as well as during PV fluctuations and short circuits (assuming the protection upgrades mentioned below);
- Inertia and RoCoF remain at values similar to the current state of the system, as one (up to year 2024) or two (year 2025 onwards) diesel generators are always online and provide the required inertia;
- PV and battery need to participate in primary frequency response, with full frequency control required from the battery and overfrequency sensitivity required from the PV units;
- PV must be controllable and dispatched by the EMS;
- The system currently lacks selective protection. In case of a short circuit, the entire system shuts down. A selective feeder protection scheme is recommended for the future;
- With a selective protection scheme, LVRT capability of PV is required to prevent the loss of up to 90 % of generation capacity in a short circuit case.

VII. Conclusion and Outlook

The results of the study indicate that a diesel-battery-PV hybrid system with a PV participation of 23 % is technically and economically feasible on the island. Economically, a system with a high PV participation is considerably cheaper than a system relying only on diesel and allows an expansion to 24 h supply at much reduced cost, as shown in Figure 6.

From a technical point of view, the realization of such a scenario with instantaneous PV penetration exceeding 90 % of load during the day is challenging. However, due to the strong grid and the new and flexible diesel generators on the island, such a system can be operated stably if a number of minimum requirements for the new generators are set. These include functionalities like reactive power provision, over frequency sensitivity and low voltage ride-through, which are commercially available at reasonable prices, as they are already prerequisites for grid connection in many countries. The introduction of a small battery storage system on Kaledupa can greatly reduce strain on the diesel generators (thus saving maintenance cost) and increase PV utilization.

After the completion of the study, PLN are currently planning to implement a PV-diesel-battery hybrid system on Kaledupa as a pilot project according to the study results. With the recent progress in grid forming inverter technology, the installation of grid forming inverters, allowing diesel-off operation during the day, has recently been brought back into discussion. Such systems – mostly on a smaller scale, but with some notable exceptions like SMA's 2 MW system on St. Eustatius – have been realized utilizing large batteries and inverters that can take over the entire load in case of a PV outage. This approach is economically not yet feasible for Kaledupa, as PLN's prime objective is cutting generation cost. However, the possibility of diesel-off operation during sunny days with just a small battery and grid forming inverters (with the PV inverters as grid following inverters slaved to the battery inverter) is currently under investigation. PLN have, on a much smaller scale with low voltage only systems (380 V), already implemented such systems.

If implemented, the Kaledupa hybrid system can be a model case for more than 600 small island grids owned and operated by PLN, all of which suffer from high generation cost. The REEP 1000 Islands project will continue until at least the end of 2020 and aim to deploy the experiences in other Indonesian island systems to enable PLN to implement a cleaner and cheaper power supply.[5] [7]

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References

[1] HOMER Energy, "Algorithms used in HOMER," [Online]. Available: https://www.homerenergy.com/products/pro/docs/3.10/references.html. [Accessed 2019].

[2] NASA, "NASA POWER - Prediction of worldwide Energy Resources," [Online]. Available: https://power.larc.nasa.gov/. [Accessed 2018].

[3] Danish Energy Agency, "Technology Data for the Indonesian Power Sector, Catalogue for Generation and Storage of Electricity," Jakarta, Indonesia / Copenhagen, Denmark, December 2017.

[4] T. Ackermann et al., "Scaling Up Variable Renewable Energy: The Role of Grid Codes," Abu Dhabi, United Arab Emirates, 2017.

[5] P. Ralon, M. Taylor, A. Ilas, H. Diaz-Bone and K.-P. Kairies, "Electricity Storage and Renewables: Costs and Markets to 2030," Abu Dhabi, United Arab Emirates, 2017.

[6] IRENA, "IRENA Cost and Competitivenes Indicators - Rooftop Solar PV," Abu Dhabi, United Arab Emirates, 2017.

[7] Gesellschaft für Internationale Zusammenarbeit, GIZ GmbH, *2017 Annual Report: 1,000 Islands -Renewable Energy for Electrification Programme (REEP)*, Jakarta, Indonesia: Gesellschaft für Internationale Zusammenarbeit, GIZ GmbH, 2018.

[5] http://reep-indonesia.info/