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PV Integration on Existing Diesel Mini-grids in Australia: Comparison of operational modeling and actual system performance

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Abstract

This paper presents operational analysis from a Photovoltaics-Diesel (PV-Diesel) mini-grid system at Ti Tree – one of the TKLN PV-Diesel mini-grids operating in Northern Territory, Australia. The work expands on a previous, more-qualitative study of the projects by introducing and utilizing ASIM, an open source and freely available time step simulation software that can be used for modeling hybrid mini-grid control systems and therefore operation. Analysis is undertaken to firstly examine recorded operational data for the site and then simulate the operational behavior. This simulated model is then used as a basis to develop alternative reference scenarios and estimate the original system operation without PV. This allows for accurate quantification of the impact of PV integration on important operational and economic metrics, such as relative fuel savings, generator run hours and number of starts. This paper also demonstrates a further use of ASIM, to simulate the addition of a smaller generator in order to better match the operating conditions introduced with PV, and assesses the impacts this would have over a full year.

1. Introduction

There is a significant market opportunity for PV in remote electrical mini-grids that rely solely on diesel generators as a source of power. The integration of PV into such systems – creating a PV-Diesel hybrid mini-grid system – is of increasing interest to both the public and private sectors in Australia as a means to reduce operating costs and fossil fuel use, while also improving the sustainability of existing electricity access given the potential for future load growth (IT Power 2013; ARENA 2014).

In the Northern Territory of Australia, Power & Water Corporation (PWC) provide utility services to 72 remote indigenous communities, while being responsible for 53 isolated mini-grids (CONTEF 2013). The large distances between communities precludes connection to the grid; and due to the historically high cost of renewable energy, the energy source mix for these mini-grids has been dominated by diesel. In 2013 TKLN Solar[1], in conjunction with PWC, commissioned three PV-Diesel Hybrid systems (Ti Tree, Kalkarindji, and Lake Nash – collectively referred to as TKLN) - using a novel Power Purchase Agreement (PPA) business model (PWC 2013). These systems incorporated almost 1MW of PV and are designed to operate at instantaneous solar penetration levels up to 80%.

Many prior studies have used computer modeling software (e.g. HOMER) for predicting the potential for PV to enact fuel savings at new or retrofitted sites (see for instance Ngan & Tan 2012; Shaahid & Elhadidy 2007). There has, however, been far less research undertaken to

[1] TKLN Solar is a renewable energy company privately owned by Epuron Solar which develops solar power stations, and is the owner of the 1MW Uterne Solar Plant near Alice Springs

analyse the operation of such systems once they are built. In light of this, the paper presents analysis of one year's operational data from one of the TKLN sites – quantifying the outcomes of PV integration in energy terms, fuel consumption and generator run hours. The paper introduces ASIM, a time-stepped modeling tool developed by PWC which is freely available for download from their website[3]. ASIM can accurately simulate the complex control systems of such a hybrid system, and as such is used in this study to firstly establish necessary baseline data for analysis as well as simulating scenarios to assess project outcomes, and explore alternative options. The paper begins by providing some background and context on the TKLN projects (Section 2), before discussing the analysis of recorded operational data in (Section 3). The use of ASIM to build a reference case and then alternative scenario with no PV contributions is then described (Section 4). In light of the results, adjustments are made to the generator selection and operating strategy and the simulation and the impacts of this discussed in Section 5.

2. Background on TKLN

State funding was awarded to PWC to undertake the three TKLN projects, and the solar plants' designer and owner, TKLN Solar[4], secured a federal grant under the former Renewable Remote Power Generation Program (RRPGP) program. Consultant CAT Projects was subcontracted by the Northern Territory Government (NTG) to undertake an EOI and tender process. The three communities were selected due to their comparatively large size and recent load growth. To ensure the most economic result, the Request for Proposal (RFP) did not specify the system configuration or even choice of generation/storage technology, so a variety of solutions were presented to PWC.

The tender was awarded to Epuron, a privately owned renewable energy company and project developer. The design nominated a conventional fixed tilt PV array with a short term storage device to smooth PV output, referred to as the Grid Stability System (GSS), which utilizes an SMA power reducer and adapted control strategies. A 20 year PPA was agreed upon, with a site specific annual minimum (take-or-pay) obligation in kWh. The final PPA also includes methods for accounting for system performance where either of the PV or the diesel systems impacts on the other.

The total renewable energy plant capacity installed across TKLN communities exceeds 1MWp, consisting of 992kWp of PV (Kalkarindgi 402kWp, Ti Tree 324kWp and Lake Nash 266kWp) and a further 45kWp of wind turbines at Lake Nash. The works also coincided with a replacement of an existing diesel power station at Lake Nash, which had reached end of life, along with PWC communications upgrades for remote monitoring at all sites. The projects began operation in January 2013. Further background and qualitative information about the risks encountered and lessons learned through the implementation are available from PWC and the investigators' prior publications (Airen 2013; Hazelton, Bruce, Macgill, et al. 2014).

3. Operational Analysis of Ti Tree Data

Ti Tree is a roadside community of 170 people, located approximately 200km north of Alice Springs. The power station configuration includes the 3 original diesel generators (450kW Gen A, 520kW Gen B and 720kW Gen C) that were in service prior to TKLN roll out, along with 324kWp PV/GSS system.

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[3] For full documentation and download link see http://www.powerwater.com.au/solardiesel

[4] A wholly owned subsidiary of Epuron Solar

3.1. Instantaneous 10 minute data analysis

The first stage of analysis utilized a database of 10 minute instantaneous samples for the Ti Tree site across the entire 12 months of 2013. Recorded data fields available for this analysis included the respective Load, Generator and Solar5 kW measurements. The median load for the community was 333kW, and the annual demand profile is shown in the frequency distribution of with the positive skew attributable to increased cooling demand in the hot summer months6. A typical 7 day load profile, along with the generation source is shown in

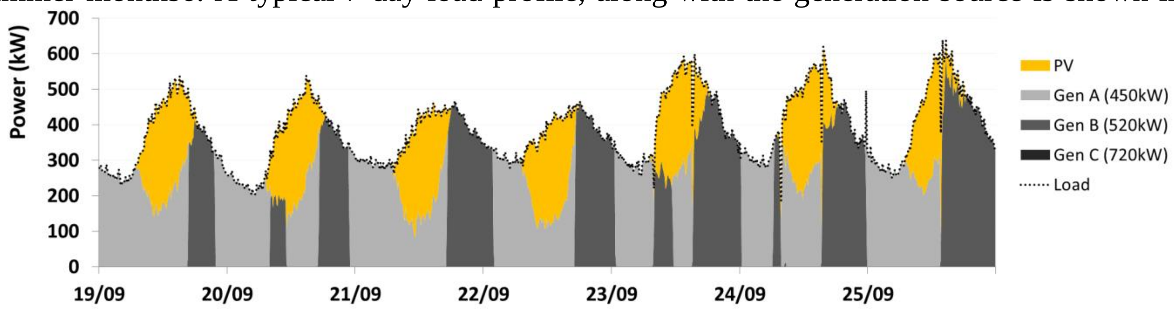

Figure **2**. It is apparent the PV output is well suited to reducing the peak load of the system. It's also evident the smallest generator, Gen A, is meeting the loads in the low demand early morning periods, during the times the solar is active, with Gen B coming on for the early evening.

Integrative methods were used to convert instantaneous power measurements to approximate energy generated, as illustrated in

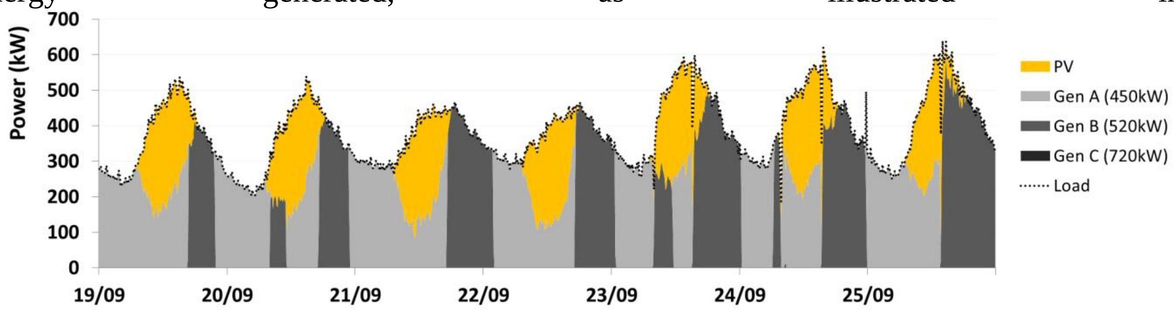

Figure **2**. During the analysis period, it is estimated PV system contributed approximately 542MWh during the year, equivalent to 18% of the annual energy demand. The annual peak instantaneous PV penetration (output as a percentage of load) was 77%. The capacity factor of the PV/GSS componentry was 19%, a relatively low figure for a utility scale system with a strong solar resource[8], but attributable to curtailment in the control system (see Hazelton, Bruce, Macgill, et al. 2014 for further details).

[5] Note that since the data was sourced from PWC - without visibility of the Epuron dataset - the PV-battery - power reducer are treated as a single component. In essence this means that the PV readings have already passed through the Grid Stability System.

[6] The maximum recorded load 725kW occurred just before Midday on the 22^{nd} of October

[8] Capacity factors calculated of flat plate PV farms have been reported in the range of 16-28% , and will depend on a number of variables (see OpenEI 2014))

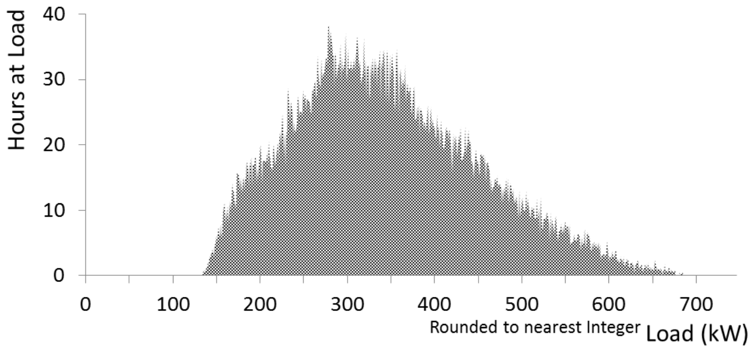

Figure 1 – Ti Tree Load Distribution 2013

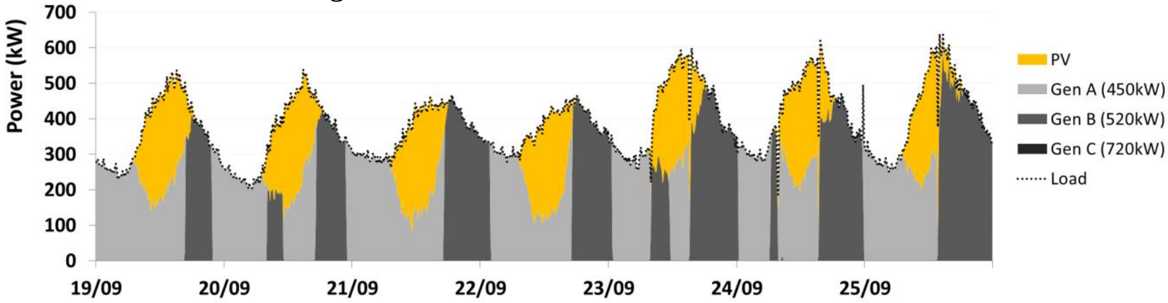

Figure 2 –Recorded data: Generation by Source at Ti Tree over 7 days.

4. ASIM Analysis – Quantifying the impacts of PV

PWC developed an open source modeling tool, called ASIM, to allow highly customizable and variable time step analysis (down to 1 second steps) of generator, PV and battery operation. The two elements of ASIM (an Excel interface and C# power system model) enable the user to conduct a fast simulation run based on user defined control algorithms and input parameters and then analyse and interpret the data within a spreadsheet. ASIM is designed to be complementary to the widely used HOMER micro-grid optimization tool, originally developed by NREL and now a commercial product (Homer Energy 2014). One advantage of ASIM is that it allows more detailed input data (e.g. 1 second as opposed to 1 hour) essential to model and refine control strategies, and as such can offer a higher precision of analysis to assist some aspects of control and complement aspects of Homers economic modeling, most notably fuel consumption. Besides the uses described in this paper, ASIM can also therefore find application for a range of other functions including asset management, investment planning, whole of life financial analysis PV/diesel hybrid systems and spinning reserve and PV set point optimization (PWC 2013).

4.1. Developing a baseline model

As there was no available baseline dataset before the PV integration at Ti Tree, ASIM was utilized to simulate how the power station would have run as a diesel only system, to allow for comparison to the current PV-Diesel system. The first step was to develop a reference case which accurately modeled the generator control strategy at Ti Tree. This was done by using the measured load and available solar generation as time series inputs into ASIM. Control system variables such as spinning reserve, hysteresis bands, sampling rates and outage schedules were initially provided from PWC assumptions, but on comparison with the measured data set, these were found to require some iterative tuning until the reference case generator behavior closely matched the recorded generator behavior such as in Figure 3. The simulated data presented is based on inputs of instantaneous 10 minute samples, and therefore will have slight differences from the recorded data, as in practice the control system is working in real time. In addition, while major outages greater than 24 hours were factored into the model, the smaller outage events that add up during the year and are not accounted for. The resulting slight variations can be seen by comparing Figure 3 to

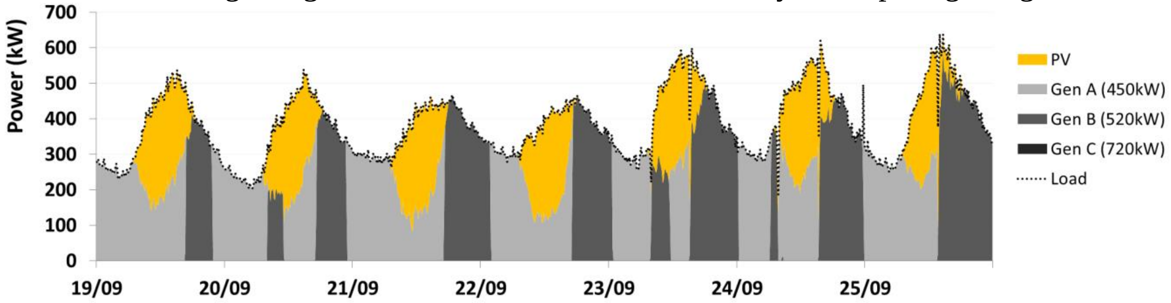

Figure **2**. An indication of how well the simulated data matches the measured data across a full year of data is available by examining the generator run hours presented in Table 1.

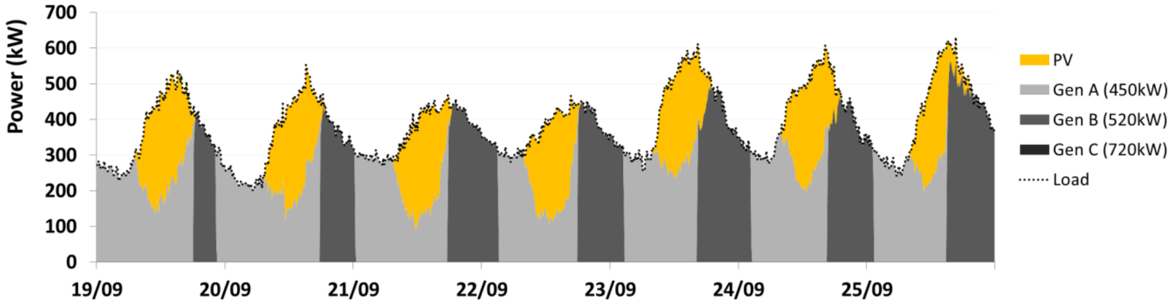

Figure 3 – Simulated Data: Reference case, PV and Load as actual

4.2. Diesel Only Case

Once the reference case had been developed and shown to be representative of the recorded generator control strategy, other scenarios could be modeled. Figure 4 below shows the case without the PV input (i.e. diesel only). It is apparent that in comparison to the previous graphs, in this 7 day period, Generator B is running more during the daytime, and Generator C is called upon for the highest load spikes. By comparison, in the cases with PV (both simulated and actual), the need to run the two larger generators is reduced due to the contribution of the PV in meeting the load. Analysis of the results from the ASIM simulations with and without PV allow quantification of PV impacts on fuel consumption, generator run hours and generator starts for the entire year.

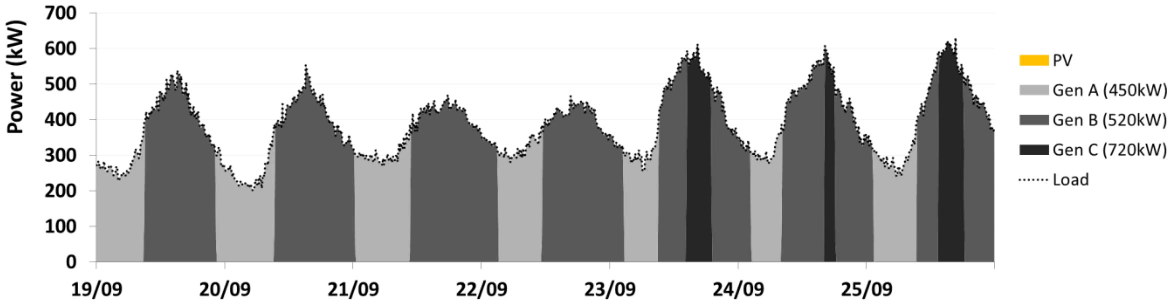

Figure 4 – Simulated Data: Scenario of No PV, same load

4.3. Estimating reduced Fuel consumption

Time series fuel consumption was calculated using 10 minute power data and fuel consumption curves for the generators provided by PWC. Using the recorded data, the estimated fuel consumption for the year 2013 was 536kL. For simulated data, the reference case gave 537kL, a result satisfactorily close to actual, and for a simulated case without PV the fuel consumption was 617kL. The estimated fuel saving attributable to PV is therefore approximately 81kL, or 13% of the Diesel only case.

4.4. Generator Run Hours and Operating Ranges

Since the diesel gensets are used to establish the grid frequency, a single generator will always be running. This then leads to the conclusion that in this case at least, overall generator run hours will be similar. As run hours are a primary determinant of maintenance requirements, there is unlikely to be any reduced maintenance costs as a result of overall run hours. However, benefit may instead be realized via a reduction in run hours of the larger more expensive generators. In Table 1, the ASIM simulations were used to explore this benefit in more detail.

Table 1 - Generator Run Times (as % of 2013 year) with and without PV at Ti Tree

Scenario	Gen A (450kW)	Gen B (520kW)	Gen C (720kW)
Actual Performance with PV *From measured 2013 data*	64%	35%	4%
ASIM Reference case *Using actual PV and Load as inputs, to verify the accuracy of the model. (Ideally this would be close to recorded data.)*	68%	31%	2%
ASIM model of system without PV *Using the load profile for 2013, but without any PV/battery contribution/input*	50%	45%	6%

With the integration of PV, modeling indicates that runtime on the smallest generator would have been 28% higher in relative terms for the year, while the two larger generators B and C would have each had their runtime reduced by 28% (814hrs p.a.) and 37% (200hrs p.a.) respectively.

The area below the curve in Figure 5 is indicative of operating time. With the incorporation of PV we see the largest generators - Gen B and Gen C's - operating time decrease, with an accompanying increase in runtime for the smaller Gen A. Also of note is that with the inclusion of PV, all profiles are moved down the kW operating range, indicating that the larger generators are not only running less, but are running at lower load. For instance the median operating power for Gen B in moving from a no-PV case to a PV case went from 77% to 70% of its rated power. It is therefore likely that over the life time of the systems, the larger more expensive generators will not need to be replaced as often. While lower loading on a generator is generally a good thing for fuel consumption and wear, this has its limit, with most generator manufacturers recommending generators not be run below 30-40% in order to reduce wear and maximize operating life (see Hoadley 2011 for more details of potential negative implications). As shown in the simulation the unfortunate consequence of the PV integration is the now-inappropriate sizing of the existing generators on site. It is evident from the measured data in Figure 5 that Gen A is being pushed slightly lower than it's ideal operating range. The median operating power for Gen A in moving from a no-PV case to a PV case went from 59% to 49% of its rated power.

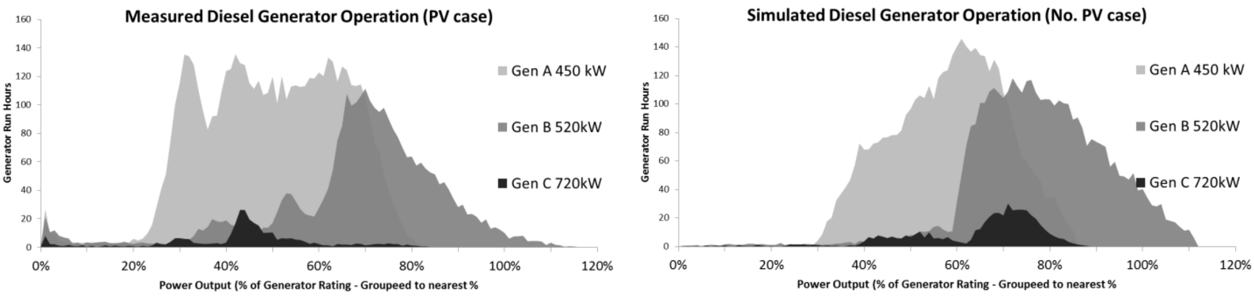

Figure 5 – 2013 Generator Operating Ranges by hour (with and without PV)

4.5. Generator Starts

Another important determinant of wear in diesel generators is the number of generator starts. The simulated datasets also provided the possibility to analyze this, and the results are shown in Figure 6. It's evident the actual data has a much higher number of starts then the simulated data. This is likely due to the differences between simulations based on ten minute sampled data, and actual data, which observes external events and higher resolution real time control problems. The sampling rate creates a degree of uncertainty in interpreting the results of the simulations. Nevertheless, in comparing just the ASIM simulated cases, it is observed that the PV would theoretically reduce Gen B and C's start counts, at the expense of Gen A It is suggested that the method be applied to a data set with a time sampling with frequency greater than 10 minutes in order to confirm this result.

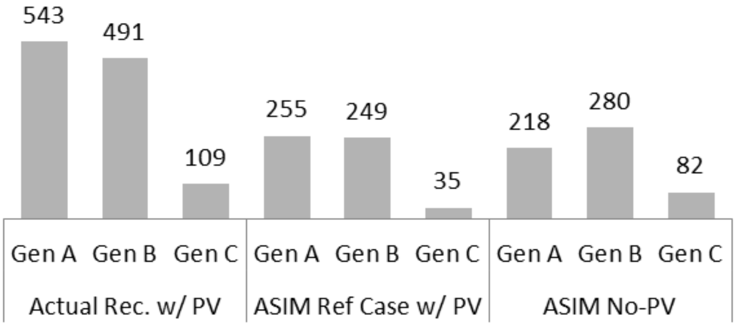

Figure 6 – Generator Start Counts for different scenarios

5. ASIM Analysis – Alternative scenario: Additional 320kW Generator

The operators are aware of the impact of low generator operating ranges presented Section 4.4, and the cause is having similar mid-sized generators (Gen A and Gen B). The ideal solution to be considered would therefore be the installation of a smaller generator. With this in mind, ASIM was used to determine the expected fuel consumption and operating range impact if a fourth smaller generator Gen D of 320kW was added to the system, with the view of covering the remaining load during times of high PV penetration. Modeled operation for the 7 days simulated previously for the existing generators is shown in Figure 7 and the resulting improved operating ranges over the full year shown in Figure 8. Using the same methodology as above and utilizing manufacturers specified consumption rates (MTU Onsite Energy 2008), the fuel consumption was calculated. The simulation gave a total fuel consumption decrease of ~1%, as compared to the actual and reference cases. As to be expected, with Gen D now running 24% of the year, a tangible reduction of run hours was observed in the simulation for Gen A only, ~33% reduction relative to actual.

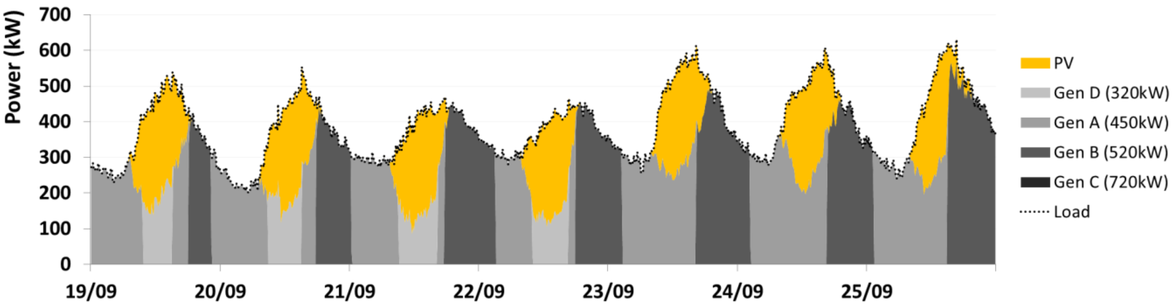

Figure 7 – Simulated Data: Additional Generator D to cover minimum loads

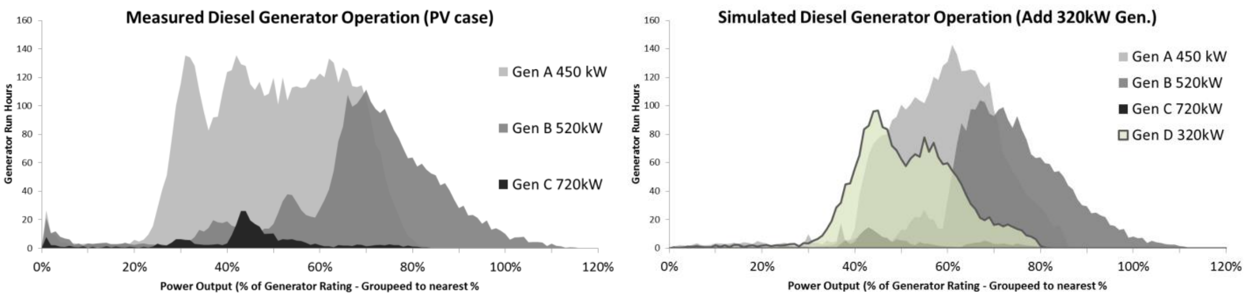

Figure 8 – Comparison of Operating ranges (Measured vs. Additional Gen. Simulation)

6. Discussion of Results

Beginning with the analysis of the recorded data, it is interesting to note that a moderate annual energy contribution of 18% from the PV would result in instantaneous PV power penetrations of up to 77% PV relative to load. While this is in part possible due to the GSS (the short term storage and power reducer in the Epuron PV plant), it highlights the design challenge and importance of suitable hybrid control strategies that will be required in some PV/diesel retrofits to attain even moderate annual PV energy contributions.

The recorded data identified the unexpected impact of low operating ranges for Gen A after the integration of PV, which has led to occasional set points below minimum loading. This suggests that for cases where substantial PV is retrofitted on existing diesel systems, smaller diesel generators should always be considered as part of the project works. The case for retrofitting PV into existing diesel mini-grids is currently a focus of the public and private sectors; this finding highlights the need to fully understand the whole of system impacts in order to prevent unnecessary wear on the original equipment. Designing standalone mini-grids to meet a particular load it is often akin to hitting a moving target so it's worth reviewing whether the existing diesel mini-grid is well sized to what currently is required and the of course in the alternative scenario, the impact of substantial load growth[9].

Most studies of the impacts of PV on mini-grids have used economic modeling software such as HOMER, which is useful at a very high level but does not allow detailed study of the operation of the diesel generators. Other studies typically depended on calculating PV output based on solar resource rather than actual measurements from an operating system. In this study the use of ASIM has enabled us to generate and accurately compare different scenarios where measured data from the alternative configurations are unavailable, and there was no prior years of diesel only operation to compare it to. It is also worth acknowledging ASIM's usefulness in other cases for its ability to verify alternative scenario's under the exact same operating conditions, which is useful for reporting, future project development and planning. Had there been, for example a 2012 data set of the operation with a Diesel-only source - a direct comparison of fuel consumption might give indicative results of fuel savings, but would be dependent on the loads of 2012 and 2013 being closely matched. ASIM could therefore be of use in tracking benefits, even if comprehensive fuel consumptions records exist before the retrofit. The next stage of the research is to conduct economic modeling, comparing results with that from Homer and combine the investigators prior published work to allow a detailed cost-risk-benefit analysis of the projects.

7. Conclusion

This research has presented operational analysis of the Ti Tree PV-Diesel mini-grid system over the calendar year 2013. The results showed that even a moderate annual energy contribution from the PV (18% of annual demand), led to a high instantaneous power penetration, with a recorded maximum at 77% of load. The paper also demonstrated the use of ASIM's time stepped analysis to create alternative cases for comparison. This allowed comparison to the Diesel-only case and derivation of annual fuel savings (81kL or 13%), and quantified the impact on generator runtime (Gen A +21%, Gen B -28%, Gen C -37%). The addition of a smaller, 4th generator was simulated as a potential solution to the current issue of

[9] Load growth is often identified as one of the main risks in deployment internationally see referenced examples in Hazelton, Bruce, and MacGill 2014

lower operating ranges for the existing Generator A. The subsequent operational impact of such a scenario was improved operating ranges and additional benefit being a small decrease in fuel use – due to the optimized sizing.

Acknowledgements
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