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Evan Franklin

Peak Demand Management on Distribution Networks using Coordinated Behind-The-Meter PV / Battery Systems: The Bruny Island Battery Trial

Evan Franklin[1], Dan Gordon[1], Derek Jones[2], Paul Scott[1], Lachlan Blackhall[3], Sylvie Thiebaux[1]

[1]*College of Engineering and Computer Science, Australian National University, Acton, ACT, Australia*

[2]*TasNetworks, 1 – 7 Maria Street, Lenah Valley, TAS, Australia*

[3]*Reposit Power, 17/2 Yallourn St, Fyshwick ACT, Australia*

E-mail: evan.franklin@anu.edu.au

Abstract

We introduce the Bruny Island Battery Trial, a collaborative research project which will see around 40 photovoltaic and battery systems installed on Bruny Island in Tasmania by April 2017. This fleet of battery systems will operate via a coordinated optimisation approach featuring network constraint based price signals, to alleviate network capacity problems associated with peak-demand events, which are currently solved by on-island diesel generation. Battery owners meanwhile will benefit from two income streams, derived from time-shifting for local tariff optimisation and from network support. We show, via analysis of power flow data measurements over the preceding two-year period, that peak demand on the island is characterised by early morning and early evening peaks, and as such we demonstrate that PV systems alone will only ever have inconsequential impact upon peak demand mitigation. In contrast, we demonstrate that 40 residential-sized PV / battery systems spread across the island would have reduced peak demand over the two-year period by up to 150 kW, would have reduced the number of diesel starts from 43 down to 14 and reduced generator running hours and annual diesel energy production by up to 83% and 91% respectively. Furthermore we show, by modelling the network, the extent to which voltage is able to be controlled, particularly at the extents of the network, by such a deployment of batteries. We conclude that a fleet of behind-the-meter PV / battery systems, if coordinated with network requirements in mind, is an effective alternative to traditional network solutions in addressing peak demand and in addressing voltage issues.

1. Introduction

Australia is anticipated to develop one of the highest penetration rates in the world for grid-connected battery storage systems, with some predicting up to 20 GWh total installed energy storage capacity by 2035 (Bromley, 2015). The majority of systems will be behind-the-meter installations, typically having 5 – 15 kWh storage capacity and co-located with new or existing roof-top photovoltaic (PV) systems, equating to about 2.5 million systems across the NEM, or about one in five households. The driver for such rapid uptake is the large and growing gap between tariff paid by households to electricity retailers for electricity purchased from the grid, particularly at times of peak demand, and the tariff paid by electricity retailers to households for excess solar generation exported to the grid (Ren et al., 2016). Meanwhile, volatility in wholesale energy prices has provided some economic opportunities for utility-scale battery systems to participate in wholesale arbitrage only (Bradbury et al., 2014; McConnell et al., 2015) and more recently for residential battery systems to participate profitably in wholesale markets in addition to their primary function of time-shifting (Franklin et al., 2016; Reposit Power, 2016).

The potential for distributed battery systems to help manage peak demand on distribution networks has long been documented, a fleet of batteries being first proposed and implemented as early as 1888 as a means to reduce power generation and transmission capacity requirements in some of Europe's first electrical lighting networks (Crompton, 1888). In the contemporary context meanwhile, coordinated battery systems have variously been proposed as a means for tackling the problem of peak demand and/or peak photovoltaic system export on networks (Stetz et al., 2015; Bennett et al., 2015), thus avoiding or deferring augmentation or other costly conventional, network-based solutions. While there is certainly a recognition that residential behind-the-meter battery systems can provide valuable network management services, there has to date been, to the authors' best knowledge, no practically-implemented, systematic means by which collectively each of these distributed and independently owned resources can be coordinated to best achieve network outcomes by valuing fairly those service provided and incentivising battery system owners to act accordingly.

In this paper we describe the network management challenges currently faced by the operator of the 11 kV distribution network on Bruny Island, Tasmania, and subsequently provide an overview of our non-network approach for addressing these challenges: the deployment of a fleet of distributed PV / battery systems. Installation of these battery systems is planned for completion in early 2017, as part of the Bruny Island Battery Trial project, with behind-the-meter PV / battery systems being installed in households and businesses across the network. We briefly introduce our concept for coordinating the fleet of independently-owned battery systems to simultaneously achieve network goals while also maximising battery system owners' 'profits'. Using data collected via network monitoring, we utilise power flow modelling and data analysis techniques to investigate the expected improvement in network performance that the deployment of coordinated PV / battery systems will bring.

2. The Bruny Island Battery Trial and the Bruny distribution network

Bruny Island, a lightly-populated but relatively large island off the south east coast of Tasmania, is supplied by two 11 kV submarine feeder cables (shown in Figure 1). Owing to the configuration of the network, load cannot be transferred between these two feeders, with the vast majority of loads being served by the southern feeder cable. The island has about 300 permanent residential dwellings (Australian Bureau of Statistics, 2012) plus a small number of business premises, but experiences high peak power demand during weekends, public holidays and school holiday periods, when up to around 600 additional houses on the island become temporarily inhabited. At such times, the network operator is often required to deploy diesel generation on the island in order to ensure power flow on the southern feeder cable is kept below its rated capacity. Measurements are taken at a few strategic locations in the 11 kV network (highlighted in Figure 1), but otherwise there is currently little visibility of the 11 kV network or of the 415 V distributors to which customers are connected.

CONSORT, an Australian Renewable Energy Agency (ARENA) funded collaborative project between The Australian National University, TasNetworks, Reposit Power, The University of Sydney and University of Tasmania, will reduce considerably peak power demand and hence the reliance on diesel generation during these events, by installing and intelligently coordinating the operation of up to 40 PV / battery systems across the island. The project will allow battery owners to benefit from participating in network management by providing appropriate price signals to them based on the value of their participation. Using a distributed optimisation algorithm approach which we refer to as 'Network-Aware Coordination' (Scott and Thiebaux, 2015), individual battery system controllers subsequently make decisions on how best to use their battery capacity. Battery systems will, for example, store energy (either from local PV generation or via imports from the grid) in advance of anticipated peak demand occurrences so that they may be paid a higher price to discharge later in order to displace expensive diesel generation.

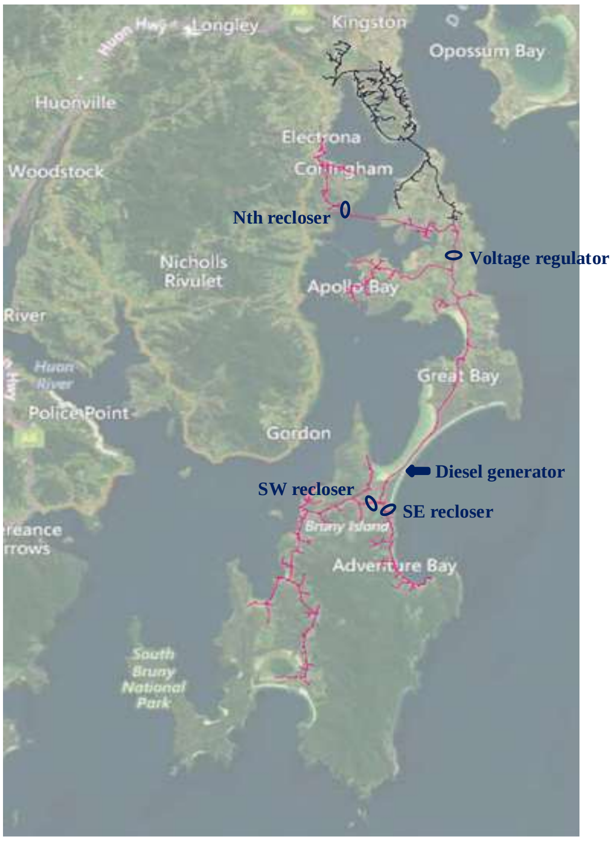

Figure 1. Satellite image of Bruny Island overlaid with the island's 11 kV distribution network. The feeder shown in pink and supplying the vast majority of the island includes the power flow constrained submarine crossing at the Northern end of the island. Current and voltage measurement points are indicated by the blue circles.

2.1. Analysis of Bruny Island demand characteristics and power flow constraints

In our analysis we use half-hourly instantaneous power flow data, measured at the network's 11kV reclosers and the diesel generation substation and collected by TasNetworks between 1 July 2014 and 30 June 2016, and interpolate between measurement intervals as required. We first investigate the demand characteristics of Bruny Island, and assess the current requirements for diesel generation to meet demand peaks. This same data forms the basis of our subsequent modelling of the impact that the planned deployment of distributed battery systems is expected to have.

Bruny Island demand can be characterised as a winter-peaking load, featuring both morning and evening peaks that are driven predominantly by heating requirements. Demand on the section of Bruny Island served by the southern, or main, feeder exhibits a minimum overnight demand of around 250 kW, reaches a normal winter peak of around 900 - 1000 kW, and averages around 520 kW across the two-year period. However, extraordinary peak demand events, which fall during holiday periods and occur throughout the year, typically see demand well in excess of 1000 kW, with a highest recorded peak of 1388 kW during June 2016. Network operators manually start the 550 kW diesel generator once the undersea cable demand increases above a pre-determined threshold, let the generator run at or above about a 100 kW minimum and then manually shut it down some time after the peak event has passed. The cable has a nominal thermal limit of 1200 kVA if carrying balanced currents, but we observe that phase unbalance results in operators typically starting the diesel generator whenever load approaches or exceeds 1050 kW. In our assessment of the benefits of distributed batteries on the feeder, we use this value as a target maximum cable power flow. Figure 2 shows a week of total demand data for the feeder region, including several large peak demand events.

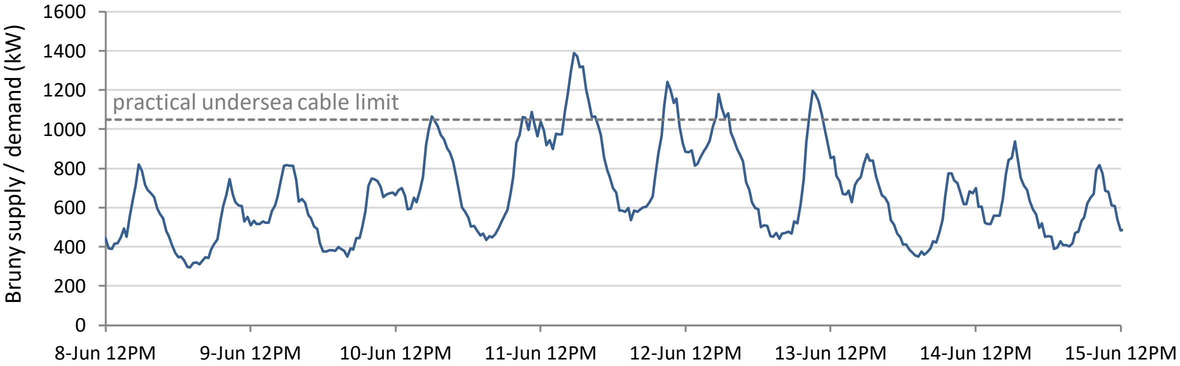

Figure 2. Total demand on Bruny Island main feeder at June long weekend 2016.

In the two-year period that we investigate here, diesel generation was required on 43 separate occasions for a total of 210 hours of run-time and 22.7 MWh of energy output, and with a maximum and average generation per run period of 388 kW and 224 kW respectively.

2.2. *Modelling the 11kV network*

We simulate the Bruny Island 11 kV network using an open-source C++ simulation library, originally developed by ANU researchers to support studies of optimization and smart grid technologies in power networks and referred to as SmartGridToolbox (Gordon et al., 2015), to solve the fully-coupled 3-phase power flow equations for the network. Distribution network data was provided by TasNetworks, with some additional un-recorded details (such as single-phase spur and transformer connections) determined via site visits. Load characteristics are handled by uniformly applying across all metered connection points in a network region the known, aggregate demand data from measurements for that region. We validate our model, by comparing the behaviour of simulated phase voltages and currents against measured voltages and currents at specific measurement points in the network. Figure 3, for example, compares measured and modelled line currents and line-line voltages at one location on the island, for a single day with high peak demand. While there is reasonable correlation for most quantities across the island, we do note the large apparent error in measurement data for one line-line voltage at this part of the island. Some discrepancies between measured and modelled values are not unexpected at this stage of the project, owing mostly to uncertainties in the measured data particularly that from the reclosers, and lack of information about load distribution within each region of the island. The deployment of PV / battery systems and their associated network monitoring capabilities will allow us to markedly improve network monitoring, to mitigate against likely measurement errors such as this and to enable us to improve modelling accuracy. Nonetheless, the simulated results allow us already to investigate the impacts that battery systems may have on the network.

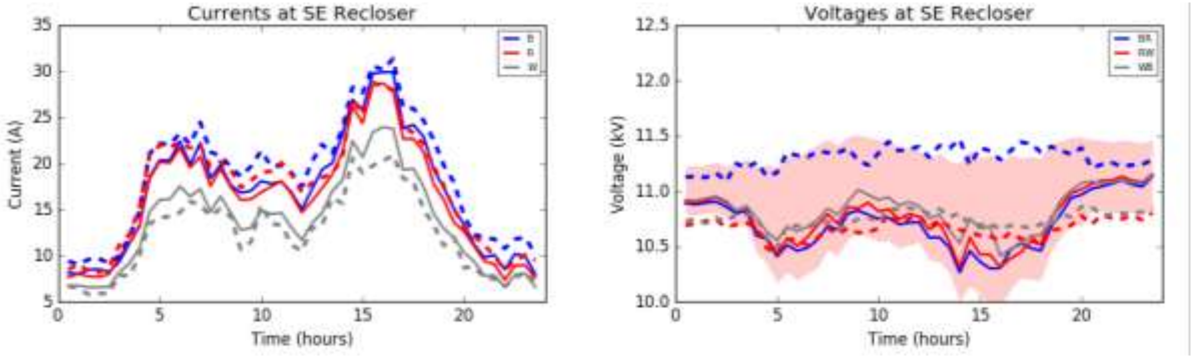

Figure 3. Measured (dashed lines) and modelled (solid lines) 3-phase currents (left) and line-line voltages (right) at the south-east recloser for a single 24-hour period where diesel generation was required. The shaded region represents the envelope of all modelled voltages observed across the entire 11 kV network.

3. Impact of distributed battery systems

For our modelling of distributed PV / battery systems on the network, we employ a total installed battery power and energy capacity of 150 kW and 300 kWh respectively, and a total installed PV capacity of 180 kW. This is consistent both with leading residential battery products currently being sold in Australia, and with the average Tasmanian PV installation size of 4.6 kW (Clean Energy Regulator, 2016). In absence of individual household load data (until the project commences collecting and analysing such data), we assume that total feeder load is uniformly shared amongst all dwellings, including those with PV / battery systems installed. More importantly, however, we assume that all batteries will be operated in such a way that they can always be called upon to discharge when significant peak demand events occur. This is a reasonable basis upon which to perform our analysis since it will be one of the primary objectives of the network aware coordination algorithm. In all cases where the diesel generator is required, a minimum acceptable generator output of 100 kW is applied. Finally, for purposes of examining more closely the outcomes for specific days, we use self-reported PV generation data from a north-facing, inclined and unshaded 5 kW PV system located at Margate, nearby to Bruny Island (PVOutput, 2016), applying the same generation on a per capacity basis to each system on Bruny; we recognise the inaccuracy that this introduces in terms of timing and exact quantity of generation, however since peak demand on the island has been observed to occur late or early in the day, the actual PV generation profile is of minor consequence. For our purposes, we consider this method to provide a reasonable proxy for on-island PV generation.

3.1. Network outcomes with PV / battery systems

The impact of coordinated battery system operation on the network can be illustrated by examining a specific peak demand day. Figure 4 shows measured total demand, undersea cable power flow and diesel generation profiles for one such day, both with and without PV and battery systems. In this case, typical of many other peak demand days observed over the two-year period, morning and evening peaks both currently require diesel generation. With battery deployment, the batteries can partially charge overnight via imported energy to enable the morning peak to be met without need for diesel generation, while they can be fully charged via excess solar generation during the day (or grid imports if required) to ensure that the evening peak is largely offset by battery discharge and the diesel generation is correspondingly reduced. The amount of energy supplied by the diesel generator decreases by about a factor of 4, from around 2000 kWh to 450 kWh. We observe that part of the reduction is due directly to battery exports offsetting diesel generation, while part of the reduction is attributable to the automatic battery dispatch allowing more efficient utilization of on-island generation resources by always operating the undersea cable at or close to the threshold during peak demand periods. Some diesel generation is still required since in this case both energy and power capacity of the batteries is insufficient for the size of the event.

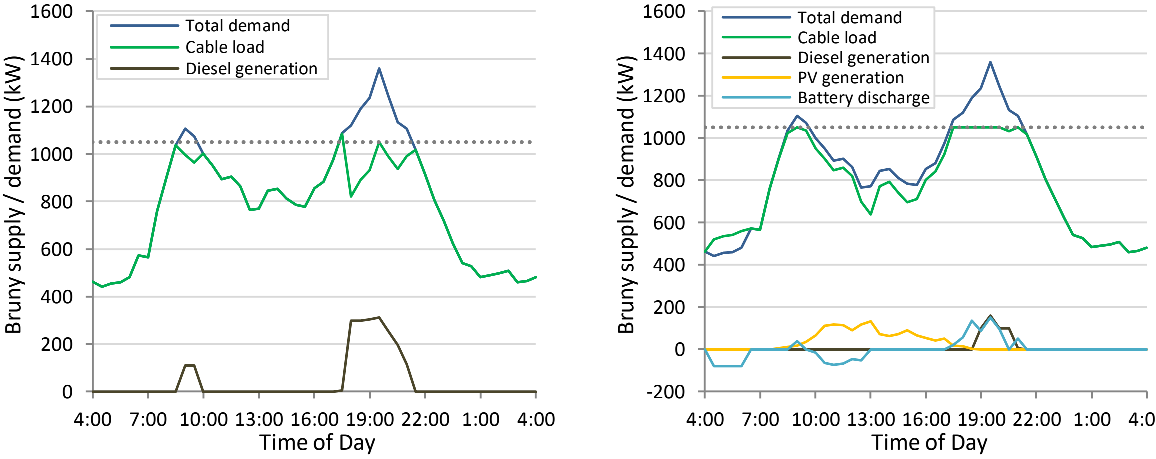

Figure 4. Plot of 24-hour Bruny Island total demand and source of supply, for a peak demand day (3 April 2015), both for case of no battery participation (left – measured data) and for case of PV / battery deployment operating to meet dual objectives of household retail tariff optimisation and network support (right – modelled data).

We proceed to apply the same modelling approach for all days where any significant peak demand events were observed over the two-year measurement period. As with any dataset obtained using measurement equipment in the field, we did observe several data points that were either missing or contained erroneous data. We determined for our dataset that all instances where this occurred were inconsequential except for one particular instance, where about three days of undersea cable power flow data is missing for a period including the second half of Easter 2015. This period is significant since it contains 6 diesel generator starts. In order not to exclude this period from our analysis, we estimate total island load by making the assumption that the generator was operated over the peak periods to effect the same net demand or undersea cable power flow profile as was observed on the highest demand day in the first half of Easter, and then recreate total demand accordingly. This is a conservative approach, and we find that all 6 peak events still required some diesel generation after battery deployment.

The overall impact of the deployment of 150 kW / 300 kWh of battery systems is summarised in Table 1. We find that the battery systems can dramatically reduce the requirement for diesel generation, with up to a tenfold reduction being possible. We additionally observe that the requirements of the battery to meet network peak demand are low, with the quantity of cycled energy being less than 1.5% of that normally cycled for day to day tariff optimisation operations (assuming an average of 1.1 cycles per day). To put the effectiveness of the 40 battery system trial size into context, we also test the scenario where the number of installed PV / battery systems is doubled (to 80); this results in some 98% reduction in annual diesel generation, yet still requires some diesel generation to guarantee peaks are always met.

Table 1. Summary of Bruny Island on-island diesel generation requirements, based on 2 years of data (July 2014 to June 2016), before (actual) and after (modelled) deployment of 40 PV / Battery systems on the island under the Bruny Island Battery Trial program.

	Before PV/battery deployment	After PV/battery installation	Reduction
Number of diesel generator starts	43	14	67%
Diesel generator run-hours	210	36	83%
Annual diesel generation (MWh)	22.7	1.96	91%

3.2. *Supply 'capacity firming' effect of battery deployment*

We make an interesting observation concerning an indirect benefit which is provided to the network operator by the presence of the distributed battery systems. Our analysis suggests that on up to 40% of occasions where the diesel generator is currently operated, the availability alone of battery capacity is sufficient to prevent diesel generator operation, even if batteries are not actually required to discharge at all (or perhaps in practice small amounts of discharge may occur to meet short time-scale peaks occurring within our measurement interval). This can be the case even if the diesel generator remains under manual operator control, as long as reliable information is provided to the operator about battery storage status. As total demand approaches the undersea cable thermal limit, the mere presence of battery storage in the system allows the operator to be confident of a higher supply capacity. This is a supply capacity firming effect (similar to the intermittent generation capacity firming effect usually associated with battery storage) which we illustrate by way of example in Figure 5. Without battery storage (left) the operator has little choice but to start the diesel generator as demand reaches the supply capacity limit (dashed line). When the instantaneous generation potential of battery storage is considered (right), the operator can retain a clear margin between demand and the total supply capacity and hence has no need to start diesel generation. Battery owners provide a valuable service to the network simply by having the batteries available if required.

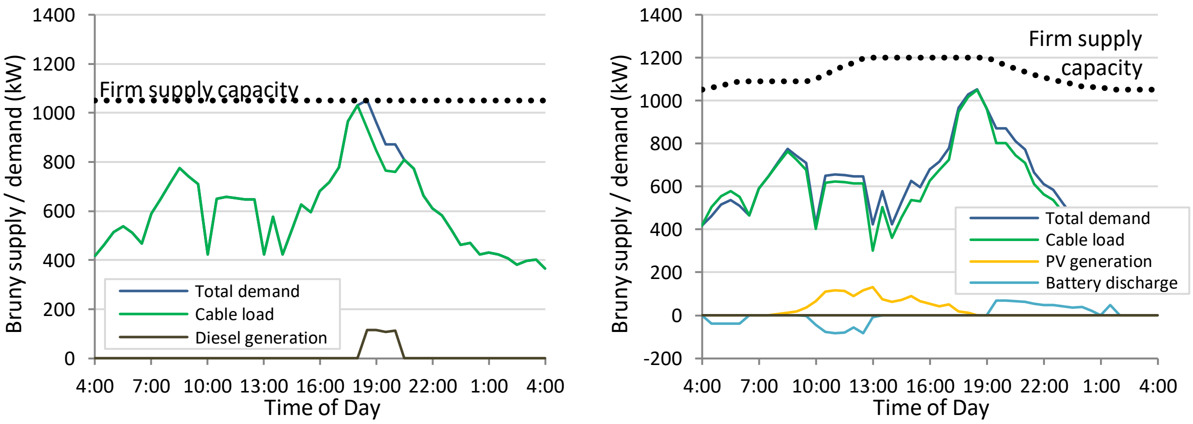

Figure 5. Reduced reliance upon diesel generation demonstrated via plots of total Bruny Island non-diesel supply capacity and demand for peak demand day (25 April 2015), prior to (left – measured data) and subsequent to (right – modelled data) deployment of PV / battery systems operating to provide capacity support.

3.3. Distribution network voltage management via distributed battery systems

We apply our full 3-phase network simulation approach in order to evaluate the potential for the fleet of distributed PV / battery systems to provide voltage support. Voltage drop along the 11 kV feeder will be most severe at times of high peak demand and so we again choose such a scenario to examine more closely. Figure 6 shows the modelled line-line voltage envelope for the entire network, for a day when diesel generation is required. With no battery systems deployed (red shaded region), we observe voltage dropping to a low of 9.9 kV (occurring at the southernmost extremities of the network), and around 10% below the nominal voltage and around 8% below the value observed for the same location during periods of light loading. Such a range would likely result in unacceptably low voltages at some LV customer connection points during peak demand events, although we do not yet have data to support this. We find that replacing some of the diesel generation with a uniformly dispersed deployment of 40 battery systems (green shaded area), each system injecting a constant 3.75 kVAr of reactive power, has little impact upon the minimum network voltage observed across a day such as this. This is partly due to the fact that the diesel generation is already injected at about a mid-point of the network and is replaced by injection spread across the entire network, and partly due to the fact that on days with high peak demand, the battery systems are only partially able to meet demand for part of the peak demand event period. For illustration purposes, we double the amount of systems injecting reactive power, with the blue shaded region in Figure 6 showing the voltage envelope for the scenario where 80 systems are deployed. In this case we can see more clearly the capability of distributed PV / battery systems in raising voltage across the network and throughout the day.

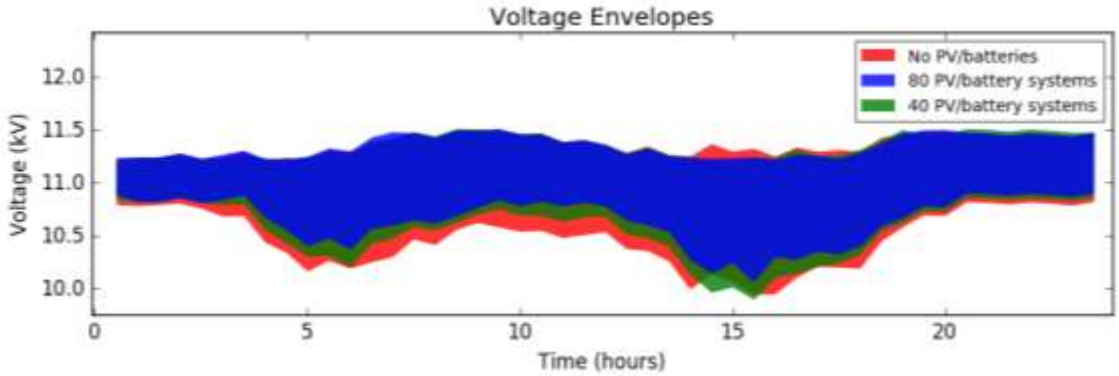

Figure 6. Voltage envelope plots for a high peak demand day with diesel generation only (red) and distributed PV / battery systems (40 systems – green, 80 systems – blue). In the PV/battery scenarios, the PV inverters inject a varying amount of real power and a constant 3.75 kVAr of reactive power throughout the day. Hour 0 corresponds to a local time of 4 am.

4. Conclusions

Australian distribution networks will see strong growth in behind-the-meter battery systems installations over the coming year, with individual systems operating primarily in tariff optimisation mode so as to maximise self-consumption from local PV generation. We have demonstrated, via an introduction of our Bruny Island Battery Trial project and via analysis of Bruny Island network-specific data from mid-2014 to mid-2016, that a fleet of distributed batteries can also be utilised effectively to firm supply capacity and to alleviate supply constraints. Specifically, we have shown for Bruny Island, which currently relies upon on-island diesel generation to meet peak demand over and above undersea cable power flow capacity, that the deployment of residential PV / battery systems with aggregate battery power and energy capacity of 150 kW and 300 kWh respectively will reduce the number of times the diesel generator needs to be started by about two-thirds, while reducing the amount of energy produced by diesel generation by around 90%. The requirements of battery systems to achieve this will be modest, with only a small number of occasions per year (about 20) where battery systems are required to discharge or be available to discharge in order to meet peak demand, and with a very small amount of energy being cycled for this purpose (1.5%) compared to that cycled during normal operation. We find that the nature of the Bruny network, the battery inverter hardware and the large peak demand events may potentially limit the effectiveness of battery systems in managing voltage on the network when deployed at this scale, although this requires thorough investigation once visibility of the network is achieved through system deployment, but we conclude positively that the deployment of batteries in this trial will enable very effective network capacity constraint management.

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