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VIRTUAL POWER STATION 2.0

Project results and lessons learnt

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Summary

The increasing uptake of both solar PV and battery systems poses a serious risk of exceeding the hosting capacity of many Australian distribution network segments. Large amount of uncoordinated solar PV and battery systems can result in so called ‘power quality’ problems, with unacceptably high and fluctuating voltages, an inability to export to grid at times, and restrictions placed on the proportion of energy sourced from PV.

Many existing energy-optimization solutions provide benefits to only one party: typically either the customer or the distribution network service provider (DNSP). The purpose behind the Virtual Power Station 2.0 (VPS2) project, by contrast, was to develop a moderately-priced solution that delivers balanced technical and economic benefits for all parties (customers, DNSPs and society). The solution leverages controllable PV, batteries, and loads (air-conditioners) to first optimise on-site electricity supply and demand and then aggregates customer-devices to deliver optimal solutions for the network as a whole.

Building upon CSIRO’s seminal Virtual Power Station (VPS) research, this project examined:

1. On-Site Supply & Demand Co-Ordination: Development of an integrated control system for coordinating major appliance loads, energy storage, solar export and reactive power within residential and small commercial sites.
2. Multi-Site Aggregation & Co-Ordination: Development of coordination algorithms that aggregate multiple sites to deliver distribution network benefits while respecting household needs.
3. Greenfield Demonstration: Development and demonstration of this integrated solution, at pilot scale, within a new residential development. The Lend Lease development at Yarrabilba, SE Queensland was chosen for this demonstration.
4. National Learnings Transfer: Diffusion of actionable VPS2 learnings to Australian DNSPs through development of an enhanced set of prototypical distribution feeder models. These allow assessment of how VPS2 and other control schemes can enhance Australia’s PV hosting capacity.

The outcomes from this project are a key building block for a technically and economically-sustainable distributed energy future. The project also capitalizes on Australia's global leadership in appliance demand response (DR) standards. The AS/NZS4755: *Demand response capabilities and supporting technologies for electrical products,* was released during this project, with major input from project personnel. This standard provides unparalleled capability for deploying DR and renewable energy load-matching across millions of residential appliances, particularly air conditioners, pool filtration, hot water systems and an increasing number of electric vehicles.

CSIRO would like to acknowledge the important support received from the VPS2 project partners:

- Ergon Energy
- Lend Lease Communities
- Selectronic Australia
- SMA Australia
- Tritium
- The University of Newcastle

Project Overview

Project summary

The major planned outputs from this project occurred across four works streams:

Work Stream 1: Modelling and simulation. Development of suitable network simulation models, based on the National Feeder Taxonomy Study (NFTS) to assess the performance of different electrical control strategies. At the beginning of the project CSIRO had completed work on a small subset of these models. By including all NFTS models into this research we developed the ability to assess Australia-wide impacts and benefits of the proposed solar management. These models were extended to incorporate representations of key controllable loads within customer sites. Baseline solar data for use with this simulation was initially from our existing experimental deployments. As the Yarrabilba site came on line this data was used to test and confirm the models. As part of CSIRO and ARENA's commitment to knowledge sharing, these models and data were made publically available to foster research on this problem.

Work Stream 2: Control system design (one site). In this work stream CSIRO developed a coordinated control system with both algorithms and early release commercial hardware, for managing loads, energy storage and reactive power at individual sites. Management of power quality and available renewable energy provides immediate financial benefit to consumers in constrained network areas. CSIRO's approach to this problem was to characterize the network impedance, at the connection point, then use both present and historic values of impedance, voltage, load and generation as functions of other environmental variables to provide forward estimates of these variables. Finally, controllable loads (air-conditioning and pool pumps), and energy storage (hot water and batteries), used in combination with reactive power control on the solar PV inverter, allowed the site impedance to be varied to manage grid power quality and showed the potential to increase the network solar PV hosting capacity.

Work Stream 3: Aggregator system design (multi-site). CSIRO developed coordination algorithms, suitable for use by energy service providers, allowed aggregation of multiple individual sites to provide reliable and location specific network services. These give DNSPs a viable third alternative to PV restrictions or distribution network upgrades. By enabling a market for locational specific network services, the project sought to facilitate better targeted and appropriately located solar generation and energy storage projects.

Work Stream 4: Pilot deployment. The pilot scale deployment offered the opportunity to test the proposed solutions from work streams 2 and 3. Initial testing was completed in the CSIRO Renewable Energy Integration Facility, where hardware-in-the-loop emulation is used to expose the system to a wide range of conditions, equivalent to networks from across Australia. Working in conjunction with Lend Lease, the Yarrabilba site was chosen as a testing ground for this work stream. The pilot scale deployment sought to enrol 50-100 households, and was successful in attracting 67 households. The Yarrabilba deployment collected high-resolution data from individual sub-circuits in each house for more than a year, and this was used to determine the impact of our developed software.

Project scope

Given improving economics, solar PV energy should continue to grow throughout Australia, providing consumers with local, clean energy that helps mitigate their energy bills. Existing and persistent operations of both distribution networks and consumer PV systems and household devices (e.g. air conditioning and energy storage) create an artificially low limit to the amount of solar power that can be safely and reliably integrated into a given portion of the network. This project sought to provide a balanced approach to operation of networks and consumer devices to enable the greatest possible solar power penetration at lowest possible costs without harming power system security.

The original thinking at CSIRO was that the ability to control numerous consumer devices like batteries, PV and loads should enable a power system with high levels of PV and still achieve levels of stability approaching, or even improving on, business-as-usual levels. Further, if the needs of both individual customers and distribution network service provider was sufficiently considered, a balanced outcome that appropriately incentivised both sides could be achieved.

The continuing large-scale uptake of solar PV poses a serious risk of exceeding the hosting capacity of many Australian distribution network segments. From a technical perspective, high penetration of solar PV commonly results in:

- unacceptably high and fluctuating voltages in some locations,
- the inability of PV systems to export to the grid at times - wasting energy and revenue, and,
- restrictions placed on penetration levels of solar PV installations, limiting customer choice and the amount of clean energy in Australia.

These effects are especially pertinent within residential network segments with low daytime energy demand, which exacerbates the problem.

These technical and economic challenges are often perceived as posing a threat to the economic viability of industry incumbents (often referred to as a 'death spiral'). In the absence of integrated solutions, it is unsurprising that mass-deployment of distributed solar PV is not always embraced by some network industry stakeholders.

In this context, VPS2 sought to provide Australian leadership for addressing a genuinely compelling global problem. While numerous energy-optimization solutions currently exist around the world, typically they provide benefits to only one party: either the customer or the DNSP.

By contrast, a commercially available and moderately-priced VPS2 solution provides:

- a reliable mechanism for better aligning local PV supply with household demand (to simultaneously optimise network benefits and customer utility), and
- an enabling platform for unlocking and sharing economic benefits between all parties (customers, DNSPs and society), potentially as part of a more 'transactive' energy future.

This capability is a key building block for a technically and economically-sustainable distributed energy future. It will also capitalize on Australia's global leadership in appliance demand response

(DR) standards, including AS/NZS4755[1]. This standard provides the capability for deploying DR and renewable energy load-matching across millions of residential appliances (particularly air-conditioners, pool filtration, hot water systems and, increasingly, electric vehicles).

The VPS2 project had the following objectives:

1. Develop an integrated control system (algorithms and prototype hardware), for coordinating loads, energy storage, solar export and reactive power within residential and small commercial sites.
2. Develop coordination algorithms that aggregate multiple individual sites to provide location specific network services, while respecting local demands. Our unique approach has led to the development of reduced-order analytic models for stochastic dynamic processes, greatly reducing the computational complexity of this control.
3. Develop, in close collaboration with our collaborators, a pilot trial to test and demonstrate the proposed integrated control system and coordination algorithms within a new residential development.
4. Enhance the feeder models developed through the CSIRO National Feeder Taxonomy Study (NFTS), to provide publically available datasets and models that will allow assessment of how this and other control schemes can enhance the Australia-wide network hosting capacity of Solar PV.

Outcomes

Recruitment and Installation

Early stages of the project were spent outlining requirements from manufacturers for the various components of the testing hardware. These included the batteries, PV inverters, battery inverters, data acquisition hardware and demand response controllers. In addition, Lend Lease, a project partner, identified a suitable development site to test this hardware. The Yarrabilba land development is approximately 30 minutes south of Brisbane and was a complete new build land development. This allowed us to have a consistent quality of housing stock, built to new energy rating standards.

After identifying Yarrabilba as the test site, CSIRO and Lend Lease approached residents with a proposal to join the trial. We found a very receptive group of engaged households willing to assist us. Of course, much has been in the media in the last few years about increasing levels of energy cost, and our volunteers felt these impacts as much as anyone. The trial allocated five 10kWh battery energy storage systems on a first come, first serve basis; unsurprisingly, the systems were acquired quickly. In addition, households with existing solar PV systems were given the option of installing an SMA inverter. Many took the offer, resulting in a total of 29 PV inverters under control, with 25 SMA, three Fronius and one Sungrow inverter.

In terms of controllable loads, we approached Energex (now part of Energy Queensland) to supply single channel Demand Response Enabled Devices (DREDs) on air-conditioners. The DRED is the hardware that receives the demand response signal from the DNSP (Energex) enabling remote control

[1] AS/NZ 4777:2015, Grid connection of Energy Systems via Inverters

of the air-conditioning unit. For our trial, there were 53 air-conditioning units allocated to a single unique communication channel provided by Energex. Having all units on one channel had the advantage of being able to control a large block of energy without being interfered by (or interfering with) other Energex control signals. On the other hand, allocating all air-conditioners to the same channel disables the control of individual air-conditioning loads, or even the control of groups smaller than 53. In subsequent modelling we were able to simulate the impact of group sizing, as discussed later in this report.

Hardware installs began on time in late 2016 with the installation of the data acquisition units, shown in Figure 1. These monitors allowed access to each of the sub-circuits of the households with data collected every minute and live data streaming for selected houses. CSIRO has experience across a number of different trials with these units and the installs went smoothly.

Figure 1. An example of the ecomon energy monitor installed in volunteer households.

The five battery energy storage systems (Figure 2), including the associated inverter, were installed next with a slight, but not time critical, delay. The batteries have been very well received by our participants. Some minor issues after setup were noted, principally around charge cycles. The main cause appeared to be time zone dependant as the batteries are charged on off peak power if solar is not available. These issues were solved in a timely manner. Installation began in December 2016 and was completed in January 2017 and have been running continuously since.

As noted above, some households elected to upgrade their inverter to an SMA branded unit; some elected to stay with their exiting inverter. Importantly, all PV and battery inverters met the most recent version of the Australian and New Zealand standard on inverters, AS/NZS4755, which allowed CSIRO to control the power flows from individual units.

In addition to household hardware being installed, another ARENA project, Solar Plug and Play installed a CSIRO Solar Forecasting System[2], for short term cloud monitoring, and a local weather station in Yarrabilba to gather fine grain data that can be used to improve the efficient operation and control of both air-conditioners and solar PV systems.

Figure 2. The first VPS2 LG-Chem Battery and SMA Battery Inverter Installation

[2] The Solar Forecasting System has a sky facing camera and on board computer vision to provide local solar energy forecasts.

On-site tests

Control of air conditioning load

A number of tests were completed with the installed hardware. A direct load control test was conducted in June 2017 in Yarrabilba to validate the communication of load control commands and assess the magnitude of the response of air-conditioning loads to demand response mode (DRM) commands while operating in heating mode. The test consisted of three sessions during which a sequence of DRM commands were sent to the air-conditioners. A morning session was conducted on each day between 4am and 7am. An evening session was conducted between 7pm and 10pm. The participants were asked to keep their air-conditioners turned on with a room temperature set-point no lower than 21°C.

One significantly interesting result was the disparity in response to demand response modes by specific air-conditioner models. In some cases, the air-conditioner responded to a DRM3 (75% rated power) as if it was a DRM1 (compressor off- that is, don't heat or cool). The cause of the problem appears to be an ambiguous wiring diagram in the installation manual. This has been noted in other states and was bought to the attention of Energex and the wiring fixed. The problem was not dangerous but did mean spurious results were seen and suggests a need to improve air-conditioning installations to ensure the demand response functionality enabled by the AUS/NZ 4755 is not compromised. Specific details on this issue are in the Lessons Learnt section of this report.

In addition, as the only mandatory demand response mode under the standard prior to 2014 was DRM1, some air-conditioners did not respond to testing of DR modes 2 and 3. This highlighted that there seems to be some confusion amongst the manufacturers of these units on whether to use rated power or current required power. While the requirement changed in the 2014 update to the air-conditioning standard[3], it has not necessarily been enacted by some manufacturers.

Control of PV output

AS/NZS 4777 DRM control was tested on the PV inverters in the Yarrabilba Pilot on July 10, July 14 and July 25, as illustrated in Figure 3.

On July 10, DRM5 was tested on a single inverter at VPS005, enforcing a 100% curtailment of PV active power output for 5 minutes. The device is a 5kW SMA inverter, tested compliant with AS4777. The inverter response implemented DRM5 at a ramp rate of 16% of the inverter rated capacity per minute, ramping down from 1.1 kW to zero in 2 minutes, and ramping back up from zero to 1.2 kW in 2 minutes when DRM5 was released. The test revealed the 16% per minute power ramp rate set up by default in SMA inverters, which is an obstacle for applications requiring fast control action, and prompted resetting ramp rates in SMA inverters for future tests.

On July 14, DRM5 and DRM6 were tested on 18 inverters. DRM5 was activated for 5 minutes, producing a temporary reduction of 48.6 kW in the aggregate PV capacity. DRM6 was also activated for 5 minutes, reducing the present aggregate power output by 50% to 27 kW. The default ramp rates of 16% power capacity per minute were also observed in these tests.

[3] AS/NZS 4755:2014 Demand Response Capabilities and Supporting Technologies for Electrical Products.

On July 25, DRM7 was tested on 18 inverters to reduce active power output by 75% and sink reactive power to enforce a 98.5% inductive power factor. DRM7 was active for 5 minutes, producing a reduction of 9 kW in aggregate PV power output, and a temporary reduction of 0.5 V in average on the voltages at the point of connection of the sites under test.

These tests validated communications and inverter compliance with AS/NZS 4777, demonstrating the ability of PV installations with such inverters to be controlled in a variety of ways that bring about a more flexible grid.

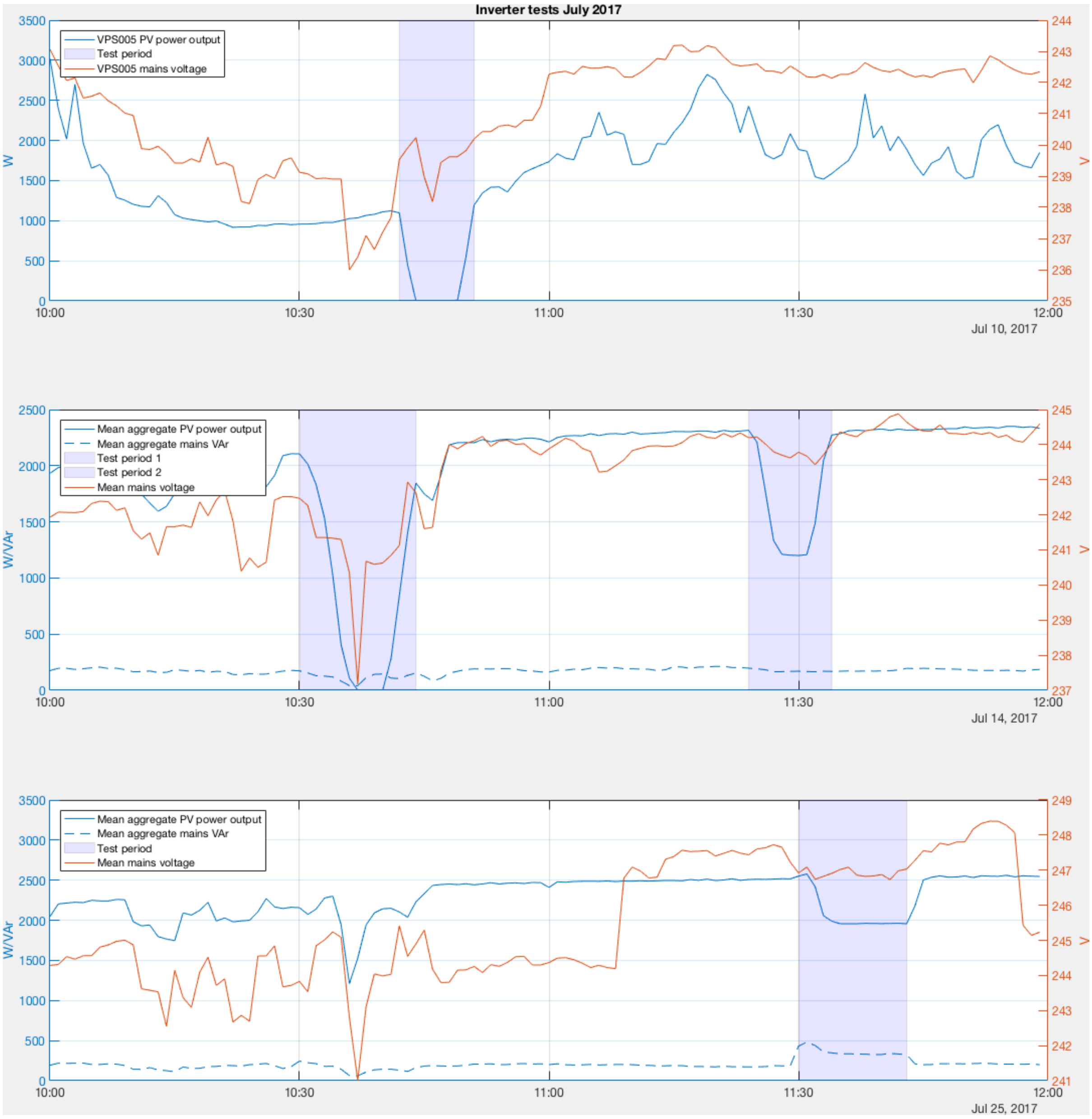

Figure 3. Inverter tests of AS/NZS 4777 DRMs

Control of air conditioning load based on sky camera observations

A number of tests were conducted on October 25, 2017 to assess the ability of AS/NZS 4755 DRM control of air conditioning load to follow rapid fluctuations in PV generation due to passing clouds. A CSIRO sky imaging system was installed on site, which provided images and 5-minute ahead predictions of solar irradiance. These images and predictions, were monitored in real time by CSIRO in Newcastle, based on which the activation of various AS/NZS 4755 DRMs was requested on the phone to Energex Load control Centre in Brisbane, where the DRM commands were transmitted through the network as Audio Frequency load Control (AFLC) signals.

Figure 4 shows the results of these tests on aggregate air conditioning load. Requests to activate DRMs were aimed at lowering air conditioning demand synchronously with drops in irradiance as predicted by the CSIRO sky imaging system, as may be appreciated from DRM requested test periods and mean PV generation shown in Figure 4. Note, however, the delay in the drops in aggregate air conditioning load, which should be expected given that the activation of DRMs was by verbal request on the phone to Energex staff at the Load Control Centre. Besides the impact of a human in the communication loop, there appeared to be intrinsic delays in transmitting the AFLC signals through the network and in the air-conditioners to respond. *This appears as a clear area for improvement in future trials.* AFLC signals or DRM commands would be more effective, especially for fast demand response applications, if they were automatically transmitted directly from the computer that processes the stream of irradiance predictions.

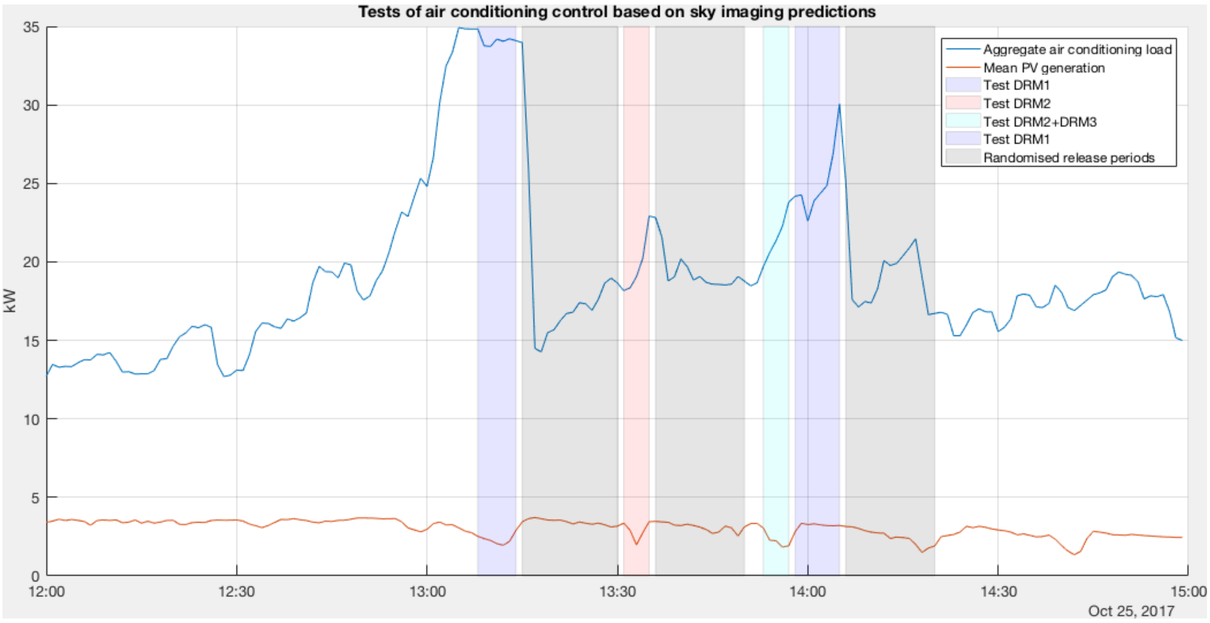

Figure 4. Air conditioning load control based on local sky imaging observations. The release of each DRM was followed by a randomised release period of 15 minutes (illustrated in grey), which was pre-programmed by Energex in the installed demand response enabling devices (DREDs). DRM activation was triggered with an aim to lower air conditioning demand whenever PV generation dropped.

It is also observed that the 15-minute randomised release period programmed in the DREDs following the release of DRMs, while convenient in slow demand response applications (such as peak demand shaving) to prevent undesired surges in demand following a prolonged period of air conditioning curtailment, is an obstacle to fast demand response applications (such as load balancing of PV fluctuations).

Control of air conditioning load, energy storage, and PV systems

On November 15 and 16, 2017, two series of tests were conducted to coordinate simultaneous control of air conditioning load, PV generation, and energy storage in Yarrabilba. As in previous tests, air conditioners were controlled using AFLC signals transmitted through the power network from the Energex Load Control Centre to trigger AS/NZS 4755 DRMs in the air conditioners in Yarrabilba. Inverters connecting energy storage systems and PV generation were controlled using AS/NZS4777 DRMs over TCP/IP communications via an application programming interface (API) developed by Australian company SwitchDin. At this time two CSIRO Solar Forecasting Systems were installed and operational in Yarrabilba. Sky images and a 5-minute-ahead data forecasts of solar irradiance produced in real-time by the forecasting system were monitored by CSIRO in Newcastle. These were used to request the activation or release of DRM commands on the air conditioners, and to transmit DRM commands to the inverters. These tests aimed at simultaneously lowering air conditioning load, gently reducing PV output at a controlled ramp rate, and increasing power exports from the energy storage systems at cloud events detected 5 minutes in advance by CSIRO sky imaging systems.

The tests included direct activation and release of DRMs in PV and energy storage system inverters in Yarrabilba through SwitchDin's API from a computer located at the CSIRO Energy Centre in Newcastle. Default ramp rates for inverters were reset from the default value of 16% capacity p*er minute* to 10% capacity *per second*, which enabled fast responses required to mitigate high ramp rates in PV generation due to passing clouds based on short-term sky imaging forecasts.

The tests proved that the full coordination of these systems can be effectively used to mitigate network power and voltage swings with small impact to end-use functions. The monitoring and control technologies tested are mature for a fully automated implementation, which, for example, could be implemented by centralising and linking sky imaging feeds and decision and control systems for inverters to Energex's Load Control System.

One of the key knowledge sharing activities for the VPS2 project is around design, testing and public release of reference controllers for both single site and multi-site coordination of distributed controllable loads, rooftop solar PV generation, and battery storage systems connected to a low voltage electricity distribution network. These controllers may be used to manage the balance of controllable loads and generation and support power quality at either a single site, or at multiple sites with distributed resources connected to the same local network.

Substantial work has been put into this process by CSIRO and recent publications go into some detail on various aspects of controllable elements of the low voltage grid. CSIRO work focused on modelling and control of thermostatically controlled loads (TCLs) – a class of flexible loads that includes electric water heaters, air-conditioners, and fridges, and offer important opportunities for demand-side services such as network load/generation balance and regulation. This study shows that the aggregate response of a population of variable output compressor air-conditioners (prevalent in Australia) differs in significant ways from the response of a population of on/off air-conditioners (prevalent in North America). Simulated step responses using the models of both types show that while their responses share some characteristics, most prominently the occurrence of damped oscillations after a common signal change, the oscillation period is significantly larger and the amplitude significantly smaller for variable output compressor air-conditioners. Moreover, their aggregate demand was found to be more sensitive to changes in signal and parameter values, in particular when cooling output saturates due to a minimum or maximum capacity limit. Based on these findings, the main conclusion is that models existing in the literature for the aggregate demand response of ensembles of on/off air conditioners may not adequately describe the response of a population of variable-output compressor air-conditioners, which require a different model structure.

As grid sited controllable loads began to include both solar PV and batteries CSIRO extended this research into more complex models. This work presented the reference controller designs for the coordination of air-conditioner load, solar PV generation and battery storage in a virtual power station electric network. The approach is a model-based predictive control strategy that optimises the balance between loads and generation to achieve control objectives defined in an optimisation cost function, which may be customised. The study illustrates the application of the proposed strategy by controlling air-conditioner load to follow PV generation assuming a short-term PV generation forecast is available. The proposed strategy manipulates the demand of air-conditioning using control commands consistent with the demand response capabilities specified by the AS/NZS 4755 standard. Namely, the commands can control air-conditioners to reduce their energy demand to 75% (DRM3), 50% (DRM2), or to switch off their compressor (DRM1). The performance of the proposed strategy is illustrated in balancing fluctuations in aggregate PV generation by controlling the demand of air-conditioning. This strategy may be applied through a single DRM signal channel to control demand in a single site, or at multiple sites. When more DRM signal channels are available, the strategy can control the population subdivided in clusters, each of which is associated with one DRM signal channel.

The underpinning structure of the reference controller has been recently published in the IEEE Transactions on Smart Grid[4], where the authors adapted the formulation of the model-based predictive control optimisation to produce demand response control signals implemented as small offsets to the air conditioners temperature set-points.

From a project delivery point of view, all of the planned outcomes were achieved, and from an experimental perspective, the pilot successfully demonstrated the ability of the deployed hardware and software to effectively control devices enabling greater deployment of solar power. Of course, as in any project the team would have liked to have done more. In research data is always useful, and with the hardware remaining in the volunteer's homes there is a great on-going opportunity to continue collecting data.

In addition, the trial results have revealed that individual control of air-conditioning loads is not required. Rather than controlling a group of air-conditioners as a single block, breaking this group into just three groups would allow sufficient control of power quality. Our research has shown that with

[4] Model Predictive Control of Distributed Air-Conditioning Loads to Compensate Fluctuations in Solar Power, Nariman Mahdavi, Julio H. Braslavsky, Maria M. Seron, and Samuel R. West, IEEE Transactions on Smart Grid, VOL. 8, No. 6, November 2017

minimal additional hardware, like cloud forecasting, fine grained control provides even better power quality results.

Transferability

The knowledge generated by the VPS2 Project was disseminated through articles in the scientific journals Renewable Energy, Automatica, and the IEEE Transactions on Smart Grid; through international conference papers presented at the IEEE Conference on Decision and Control, the IEEE Multi-conference on Systems and Control, the International Symposium on Smart Grid Distribution Systems and Technologies, the Australian Control Conference, the Asia Pacific Power and Energy Engineering Conference, and the International Conference on Modelling, Identification and Control; through presentations at the Energy Networks Australia Conference and Exhibition; and through technical reports published in the CSIRO Research Publication Repository.

The research fostered by the VPS2 Project has led to further engagement with domestic DNSPs, and further international collaboration with leading research groups in the area of load modelling and control, such as the University of Michigan Power and Energy Lab, and the Pacific Northwest National Lab (PNNL).

The core idea behind VPS2 is the use of distributed energy resources to help solve grid issues whilst providing value to customers. There are a large number of projects in Australia and internationally that use distributed resources to provide "grid services", with the vast majority of such projects focused on using demand-side resources to provide capacity or non-spinning reserves for wholesale markets through demand response. VPS2 is distinguished from such projects in three primary ways: first, it use variable controls to gradually increase or decrease the power supply or demand from devices, rather than simply turning devices on or off; second, it focuses on providing grid services to the distribution network, rather than the wholesale market; and third, it includes both load (air-conditioners), generation (solar PV) and storage (batteries). While no other technology project or tool includes all three of these features, many include one or two aspects.

In the United States, there are a number of related projects. The PNNL Transactive Energy project involves the creation of a price-like incentive signal to which distributed resources, or loads, like air-conditioners, respond by changing their electricity consumption. Accordingly, the project includes variable control of loads, but does so primarily with an eye on wholesale market issues – energy supply and capacity – rather than distribution network problems. At least two projects in California have integrated and aggregated battery storage and solar PV to lower customer bills and solve grid issues, primarily at the wholesale level. One project was managed by Sunverge and run in partnership with the Sacramento Municipal Utility District[5] and another combined technology from Tesla and Green Charge to help Pacific Gas and Electric and its customers.[6] Tesla is currently working with

[5] http://energystorage.org/energy-storage/case-studies/smud-and-sunverge-demonstrate-potential-aggregated-distributed-energy

[6] http://energystorage.org/energy-storage/case-studies/smud-and-sunverge-demonstrate-potential-aggregated-distributed-energy

Southern California Edison on a project quite similar to VPS2 that includes storage, PV, and controllable thermostats to demonstrate capacity, reactive power support, frequency regulation and reserves.[7]

In Australia, a number of companies, including EverGen and Redback, include technology that dynamically control solar PV, battery storage, and loads (including air-conditioning), but at present their technology only optimises for customer bill savings, and provides no explicit grid services.

Conclusion and next steps

The CSIRO – ARENA Virtual Power Station Project began in 2015 and completed research across four main work streams. The first was development of suitable network simulation models that extended our previous work and allowed assessment of national impacts and benefits of solar management. These early models were extended to incorporate representations of key controllable loads within customer sites.

The second work stream developed single site control algorithms for managing loads, energy storage and reactive power at individual sites. This work was then extended to multiple sites in the third work stream. This then allowed control by energy service providers as an alternative to PV restrictions or network upgrades.

The final work stream then brought this all together for a pilot deployment at the Lend Lease development, Yarrabilba, SE Queensland. In this trial 67 households were recruited and their hardware (solar PV, batteries and air-conditioners) were controlled in a cooperative manner to maintain power quality in the grid.

The results of this work has shown that a viable third alternative to electrical network upgrades or limits on roof top solar can be found in smart deployment of hardware and software to effectively control devices enabling greater deployment of solar power.

To continue the path towards wide-scale adoption of the VPS2 approach of optimising the use of distributed energy resources for both customers and the grid, a number of next steps are required. First, continued development of the communications infrastructure underlying the core control technology is required to provide more granular control of all devices at homes – solar, batteries, and loads. Additionally, the team is considering adding electric water heaters as another controllable device that could meaningfully improve customer bills and network operations. This would require the development and testing of more fine-tuned water heater control.

Further, additional validation of the fundamental approach is needed both from a technical and a commercial perspective. On a technical level, CSIRO needs to demonstrate the ability of the VPS2 approach to actually impact distribution operations in the field; to date, we demonstrated the ability to impact individual connection points and modelled impacts on distribution operations. Another technology pilot that allows the VPS2 approach to be showcased on a relatively "weak" distribution circuit with sufficient volume of controlled devices would meet this requirement. On the commercial

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[7] https://www.tesla.com/sites/default/files/pdfs/en_US/Tesla_SCE-Powerwall%20Case%20Study-2017.pdf

level, we must come up with incentive schemes and approaches to ensure sufficient uptake of the proper inverters, storage, and controls to actually lead to deployments that cost-effectively meet alternatives for solving the grid issues that arise from increased levels of solar PV.

We could make meaningful progress on all of these next steps through one or two additional pilot programs, providing they are located within the right types of grids that enable the actual demonstration of such benefits. The commercial viability of the approach ultimately depends on the development of markets that allow distributed energy resources to provide grid services. While no such markets exist yet, we are buoyed by the recent announcement of the Demand Management Incentive Scheme[8] and discussions between the Australian Energy Market Operator (AEMO), Energy Networks Australia (ENA) and others on the consideration of a Distribution System Operator role being assigned, which would provide a platform for the eventual trading of such services by distributed resources.

Overall, the VPS2 project was a success – it demonstrates the fundamental ability of the underlying technology. In the coming months and years, we must find ways to further demonstrate the power of the technology by allowing it to solve real-life grid issues on the back off cost-effective incentive schemes.

[8] See for example, https://www.aer.gov.au/taxonomy/term/1337

Lessons Learnt

Lessons Learnt Report
Australian Air-Conditioning Standards

Knowledge: Technology
Technology: Demand Response of Air-Conditioners

During testing for the Yarrabilba trials each of the air-conditioning units in our trials were sent a series of demand response mode commands. Demand Response Modes (DRM) are used to assert a particular level of energy consumption or power setting, depending on the version of the standard being used. The particular standard is AS/NZS4755.3[9] and has a 2012 version and a 2014 version. As can be seen in Table 1 there was a minor wording change to the standard that has a significant impact on the operation of compliant air-conditioning units.

If the standard has been implemented in the particular air-conditioner, the main difference between the two versions of the standard is that under the 2014 version, a response to DRM2 and DRM3 should be observable under any operating condition with the compressor active. In contrast, under the 2012 version, the air conditioner would only respond to DRM2 or DRM3 if their load is above 50% or respectively 75% of their rated capacity. Sufficiently oversized units will typically not respond to DRM2 or DRM3 except under extreme ambient conditions.

To put this in real terms suppose we have two identical households, with modern design and insulation. On even the most demanding days, the total power required to heat or cool the house is 5kW. The first household have installed a large air-conditioner, a 12kW capacity unit. The second household has installed a better matched unit, with a capacity of 6kW.

Under the older version of the standard (2012), the first household, with the 12kW unit, will not ever see a demand response mode. When the DRM2 command is sent, to decrease the power to 50% (6kW) of the rated power, the house is only requiring 5kW to cool. For the same conditions, the second house will have their air-conditioner limited to 3kW.

Compare this with the newer version of the standard (2014). When the DRM2 command is sent, to decrease the power to 50% of the required power, both households will see a reduction in power to 2.5kW. This is 50% of power currently required to cool the house, assuming that due to the ambient conditions house required 5kW to cool.

[9] AS/NZS 4755.3.1 Demand response capabilities and supporting technologies for electrical products - Interaction of demand response enabling devices and electrical products - Operational instructions and connections for air conditioners

Often the energy supplier has incentive programs to encourage people to join these demand response schemes. The home owner gets a small amount, typically $100 - $400, and in return they agree to have their air-conditioner controlled by the energy supplier. These events are quite rare: for example at Energex (Energy Queensland), since 2014 there have been just 3 events per year, and all but one have been DRM3. The last time (as of 8th January 2018) a demand response mode command was sent[10] was 13th Feb 2017.

Table 1. Definition of DRM modes according to AS/NZS 4755 (differences in bold).

Mode	AS/NZS 4755.3 (2012)	AS/NZS 4755.3 (2014)	Compliance
DRM1	Compressor off	Compressor off	Mandatory
DRM2	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed **if operating at the rated capacity in a half hour period.**	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed **in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.**	Not Mandatory
DRM3	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed **if operating at the rated capacity in a half hour period.**	The air conditioner continues to cool or heat during the demand response event, but the electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed **in a half hour period during normal operation under the same temperature and humidity conditions, and the same user settings.**	Not Mandatory

What is interesting from the VPS2 trials at Yarrabilba is that at least some of the air-conditioning manufacturers seem to be unaware of the subtle definition changes in the 2014 standard. As all of the houses in our trials were built after 2015, all of the air-conditioners should have had 2014 Standard responses. Of course it is worth reiterating that the effected demand response modes are not mandatory, and that all of the air-conditioners in our trial responded to the mandatory modes as required.

[10] A log of events for the Energex grid can be seen at: https://www.energex.com.au/home/control-your-energy/managing-electricity-demand/peak-demand/peaksmart-events

Lessons Learnt

Lessons Learnt Report
Multi-Site Control of Demand Response Loads

Knowledge: Technology
Technology: Demand Response of Air-Conditioners

On the Yarrabilba site, control actions were implemented using the Demand Response Modes (DRM) defined in the standards AS/NZS 4755 and AS/NZS 4777.

The control of a population of air conditioners based on the broadcast of small offsets to the air conditioner thermostats offers greater load controllability than that provided by AS/NZS 4755 DRMs, and the key advantage that the impact of demand response control to households (conditioned room temperatures) is tracked through the amplitude of the control signal. In contrast, the control provided by AS/NZS 4755 DRMs is simpler to implement and can deliver the desired load curtailment without need of a mathematical model. When implemented through a single control communication channel, as has been the case in the Yarrabilba Pilot, AS/NZS 4755 DRMs can provide effective load control to mitigate peaks in demand on high temperature days.

For faster demand-side services, such as load regulation to follow local PV generation output and mitigate network power swings due to passing clouds, at least two communication channels should be used to implement AS/NZS 4755 DRMs. CSIRO has shown in a simulation study that the proposed reference controller implemented through AS/NZS 4755 DRMs on three control communication channels can achieve a reduction in PV output fluctuations comparable to that achieved through thermostat control[11], with up to 94% reduction in PV output fluctuations. Figure 5 shows the result of these simulations for a population of 60 air conditioners, which are controlled in three clusters of 20 air conditioners. The 20 air conditioners in each cluster receive the same AS/NZS 4755 DRM command, which is not necessarily the same sent to air conditioners in a different cluster. The use of three independent communication control channels expands the effective control resolution of the three AS/NZS 4755 DRMs (four including no DRM) to 64 different levels of aggregate power load control, illustrated in the bottom plot in Figure 5. Figure 6 shows how this aggregate is decoded to the AS/NZS 4755 DRMs control signals for each of the clusters. These plots illustrate how a modest increase in the control communications infrastructure can greatly enhance the effectivity and network services from load control based on AS/NZS 4755 DRMs.

[11] Technical Report EP175736, Single-site and multi-site reference controller designs, July 2017 (Revised January 2018).

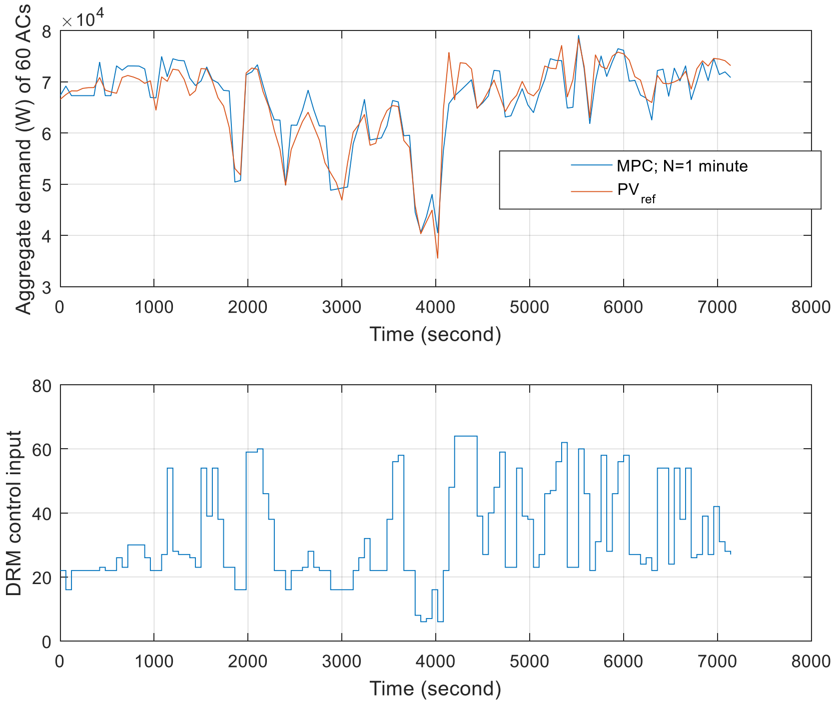

Figure 5. Controlled air conditioner load tracking fluctuations in PV generation. The top plot shows close tracking of PV generation based on 1-minute ahead irradiance predictions. Air conditioners are grouped in three clusters, each independently controlled using AS/NZS 4755 DRM commands. The bottom plot shows the aggregate control signal, which is decoded in the cluster control signals shown in Figure 6.

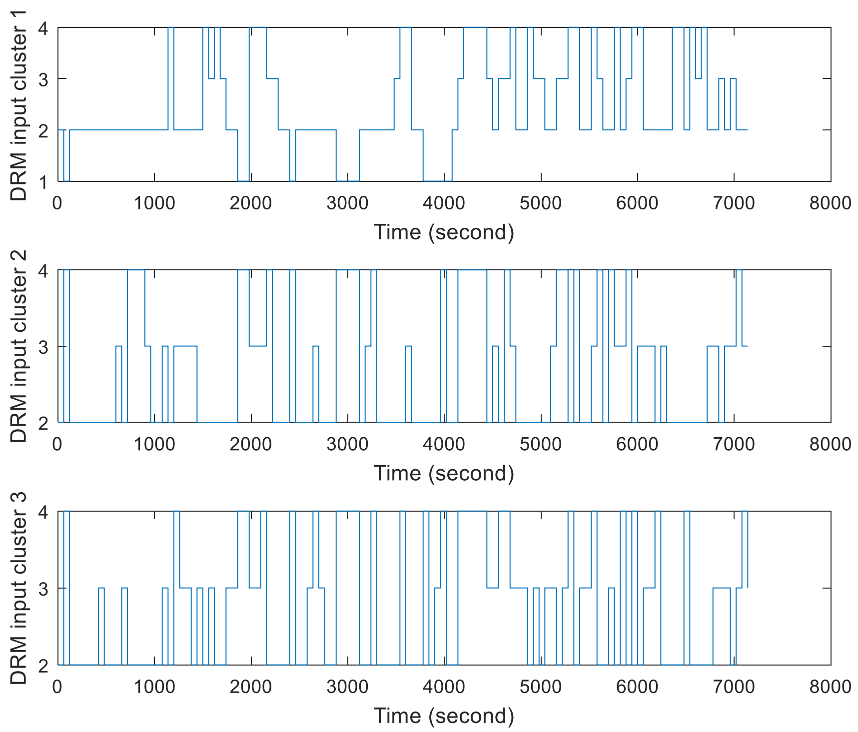

Figure 6. Air conditioner cluster control signals implementing AS/NZS 4755 DRM commands for PV output tracking.