CONSORT
Bruny Island Battery Trial

Project Final Report

Project Results and Lessons Learnt

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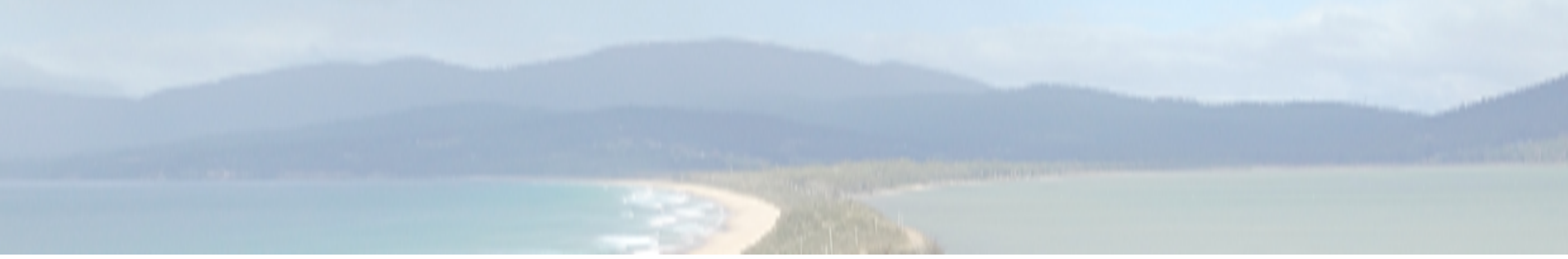
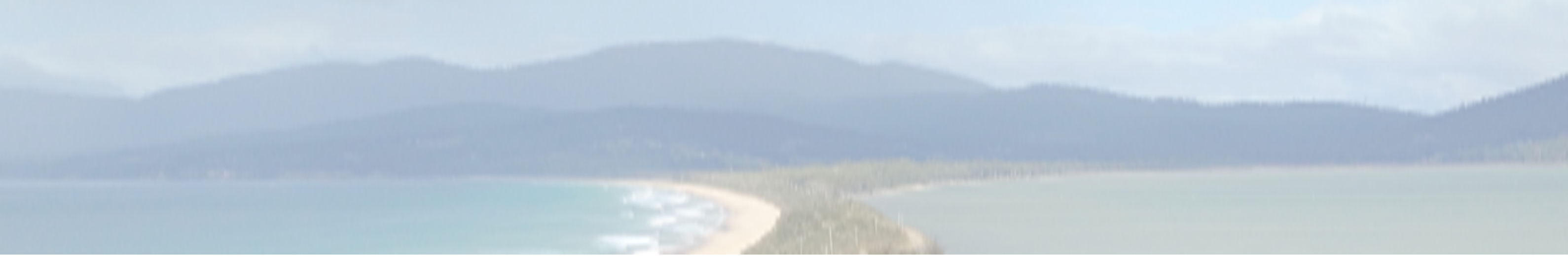
http://brunybatterytrial.org

CONSORT: "Consumer Energy Systems Providing Cost-Effective Grid Support" is a collaboration between The Australian National University, The University of Sydney, University of Tasmania, Reposit Power and TasNetworks. The Australian Government, through the Australian Renewable Energy Agency, is providing $2.9m towards the $8m trial under its Research and Development Program.



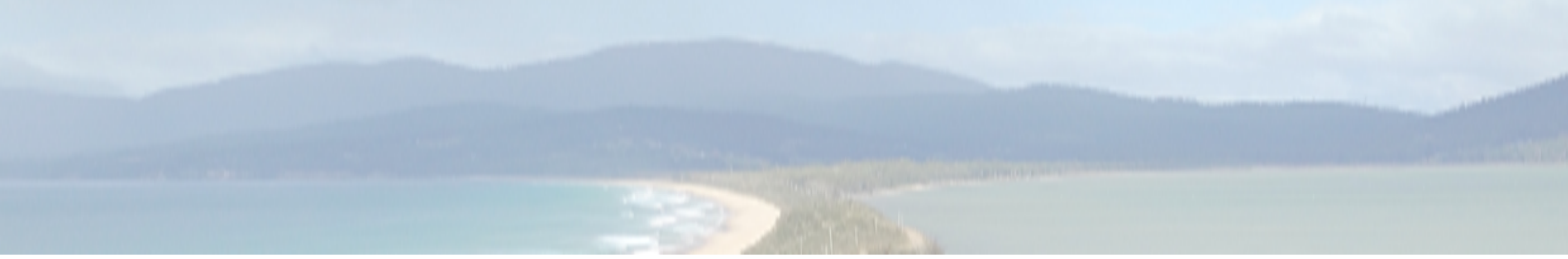


Executive Summary

Australia's high residential solar uptake is pushing our networks to their technical limits. Without alternatives, networks are faced with the choice of either limiting renewable uptake, or undertaking costly network upgrades, negatively impacting Australian householders. The CONSORT project aimed to develop and trial novel technologies allowing households to provide network support from their battery and PV system. At the same time, households would receive rewards and payments that properly reflect the value of this support, while continuing to enjoy the benefits of their system and the reduction in their electricity bill. CONSORT stands for CONSumer energy systems providing cost-effective grid suppORT. In CONSORT, the project team considered not only the orchestration algorithms underpinning network support from household systems, but also the pricing dimension of network support, as well as householder responses to the new technology. The technology developed was trialed on Bruny Island, Tasmania, where it contributed to reduce peak demand and diesel use.

At the heart of CONSORT is a platform called Network-Aware Coordination (NAC). The primary task of the NAC platform is to coordinate, in a non-intrusive way, the energy systems owned by prosumers. It meets network capacity and voltage constraints and achieves the required network benefits, at minimal cost. The NAC does this by providing appropriate price signals to the Reposit energy management system (Reposit box) located within people's homes, so the batteries are incentivised to support the network whenever problems such as congestion or voltage issues occur. This may sound simple, but at scale it is computationally very challenging and requires specialised distributed optimisation techniques to solve efficiently. Over the three years of the project, NAC has moved from a stage of basic research, to a world-first design robust implementation that runs in live network operations. NAC was able to reduce the expensive diesel requirements on Bruny Island by around one third by drawing on the 34 systems that were installed in the trial.

CONSORT also looked at ways to financially compensate householders for network support. This too is a challenging problem, because the value of each battery not only depends on the energy patterns and tariffs of the prosumer that owns it, but also on its location within the network and the actions of all other batteries over time. The team worked out a value-reflective pricing method for network support, to align with the policy shift towards cost-reflective network tariffs. The team successfully developed a method to reward consumers in a way that reflects the financial value of their battery-solar technology to the electricity network. We learnt that a method that initially appeared most promising in terms of finding a fair way to reward prosumers - the Shapley value - was computationally infeasible to use directly, so a principled heuristic was developed instead. We also tested how customers responded to receiving payments in advance of peak events, for the energy reserved in their batteries, or after the peak event, for energy used to support the network. Although customer preferences did not strongly favour either, technical difficulties implementing each approach were uncovered,



indicating it was simpler and more effective to reward for a battery's energy use for network support.

The CONSORT social research team generated rich new qualitative data on how householders respond to Distributed Energy Resources (DER), revealing important insights for future DER roll-out. We learnt that householder participation in DER is not certain; it cannot be assumed that householders are willing to participate, despite broad industry and government support for DER technology. Further, individual household responses varied, and DER program design cannot assume a uniform and predictable response. The households in our Bruny Island Trial are not typical early-adopters, and our findings therefore give a good insight into issues that might be encountered with DER programs elsewhere that similarly adopt a network area or geographical focus, that comprise a diverse mix of householders.

This public dissemination report gives an overview of the project, its outcomes, and the lessons learnt. it is accompanied with a number of more specific project final reports covering the details of particular aspects of the project:

- Trial Deployment[1]
- Network-Aware Coordination[2]
- Reward Structures[3]
- Participant System Financial Performance[4]
- Social Science[5]
- Commercialisation[6]

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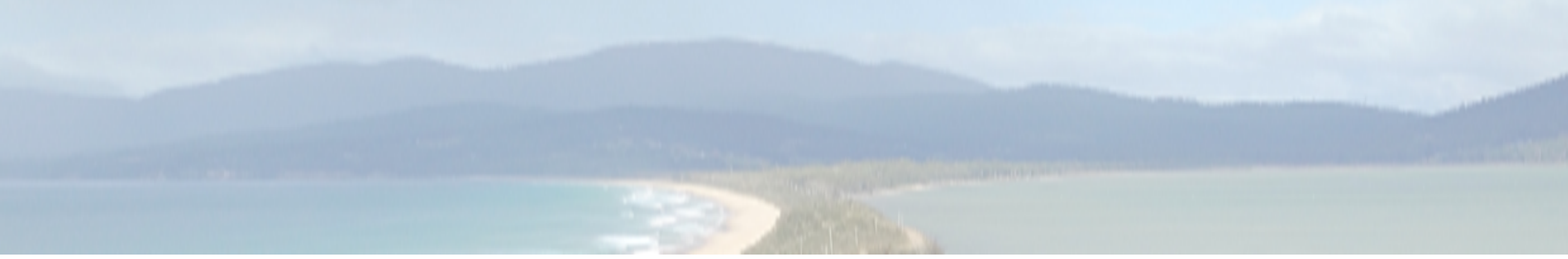
[1] Laura Jones, Evan Franklin, Andrew Fraser, and Alain Reid. Lessons Learnt during Trial Deployment, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019.
[2] Paul Scott, Dan Gordon, and Sylvie Thiébaux. Network-Aware Coordination, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019
[3] Archie Chapman, Sleiman Mhanna, and Gregor Verbič. Reward Structures, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019.
[4] Evan Franklin and Archie Chapman. Participants System Financial Performance, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019.
[5] Phillipa Watson, Heather Lovell, Hedda Ransan-Cooper, Veryan Hann, and Andrew Harwood. Social Science, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019.
[6] Luke Osborne. Commercialisation Plan, Final Report, CONSORT Bruny Island Battery Trial Project. April 2019.



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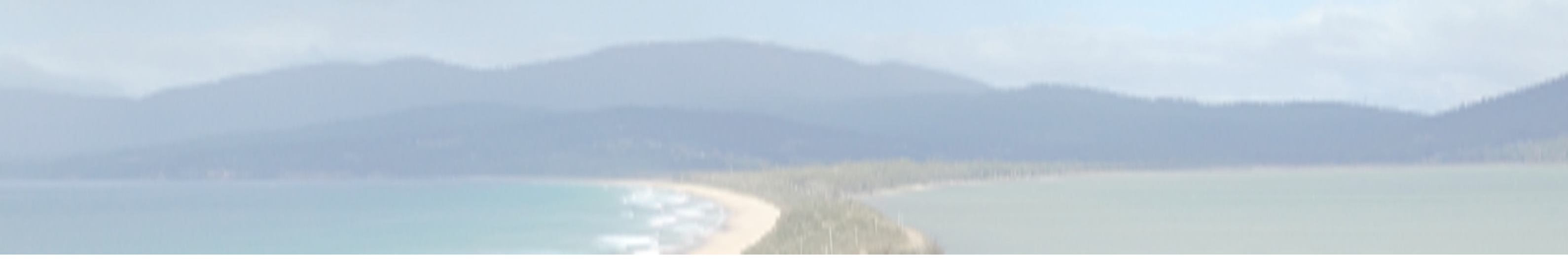

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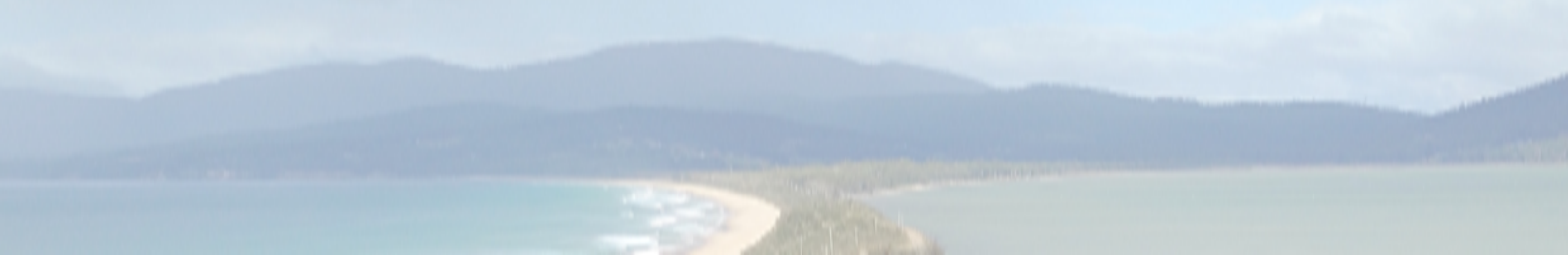


Project Overview

Project summary

The major planned outputs from this project occurred across 4 work packages:

Work package 1: Consumer Engagement, Hardware Installation and Baseline Solution Setup. We deployed PV-battery systems totalling 133 kW PV and 128 kW / 333 kWh storage equipped with the Reposit GridCredits system at selected participants premises on Bruny Island. This allowed for the collection of high frequency data, for solar shifting by GridCredits on behalf of the customers, and for a baseline manual control of the aggregated batteries during peak loading to reduce diesel consumption. Reposit's user interface provided consumers with real-time information about the status of their system and the financial returns from their services. An effort was made to replicate the installation process people would go through outside the trial and foster a proprietary attitude, by letting participants select their own installer and the hardware to be installed, and providing them with a generous subsidy complementing their financial contribution. This work package was led by TasNetworks.

Work package 2 Network-Aware Coordination (NAC). We aimed to mature and extend the distributed coordination algorithms developed by ANU team members, from a stage of basic research to a design and robust implementation that runs in live network operations. The NAC platform is "network-aware" in that it relies on a model of the network and explicitly enforces compliance with network constraints. These algorithms are designed to automatically and optimally coordinate a large number of batteries and other energy resources, in order to balance demand and generation and prevent capacity and voltage constraint violations across the network. They do so at the same time as allowing prosumers to make the most of their PV-battery systems to optimise their own energy bill (via shifting PV to better serve their own demand and deriving revenues from services provided to the network). This work package was led by the Australian National University.

Work package 3 Reward structures for network support. The aim was to explore and test designs for reward structures that pay battery owners in a way that reflects their value to the network and support the DNSP to achieve its goals. This work package brought the principled pricing methodology of the Shapley value from theory to practical deployment. The rewards structures that were developed satisfy principles of fairness and efficiency. In doing this, they generate prices that account for the value-varying effects of battery capacity and power limits, phase connection, network location, the household's load with the peak period, and other technical factors. Two reward structure computation methods were fully developed. The first is a light-weight form of reward structure that was integrated with the automated NAC processes, and a second for more detailed offline assessments of value-reflective reward structure design. During the trial, tests of customers' perspectives on pre- or post-peak event payments were also made. This work package was led by the University of Sydney.

Work package 4 Participant benefit evaluation. The aim was to identify and understand (participant) households' responses to the installed technologies and the new peak energy pricing arrangements. The research in work package 4 was guided by the question: 'How do householders respond to the combined PV-battery technology, and the new peak electricity pricing enabled by it?' This research question allowed examination of responses to the installed technology, for example household use patterns and acceptance of the technology, and key practices and attitudes that affect the ongoing use of this technology in the home. This work package was led by the social research team at the University of Tasmania.

Project scope

Australia has the highest residential solar uptake of any country, which is pushing networks to their technical limits. Networks are faced with the choice of either limiting further renewable uptake or undertaking costly network augmentation. Both options have a negative impact on Australians, who may prefer to leave the network altogether once low-cost energy storage is available. This motivates the question: how can networks and prosumers work together constructively to meet their individual needs and reduce overall costs?

Networks are obliged under the National Electricity Rules to manage the network for the least cost, and prosumers want a reasonable return on their renewables investment. The views appear divergent: Networks are limiting the further uptake; and Australians see moving off grid as a viable response. The CSIRO Future Grid Forum has shown this scenario as a more expensive future.

The deadlock can be broken with the advent of household level battery storage, but only if implemented in a way to increase the penetration of renewables on the network. CONSORT has addressed the question:

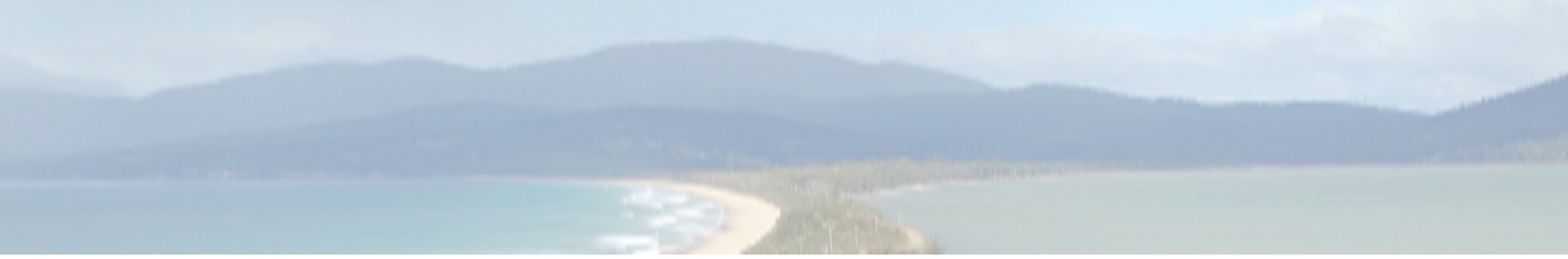
How do Networks and Prosumers combine constructively to meet their needs?

This problem has two elements:

1. How are batteries coordinated to achieve the desired technical outcome?
2. How are prosumers rewarded for the services their battery provides?

In order to answer these questions, CONSORT studied and demonstrated the use of householder owned batteries, network-aware control, appropriate reward for battery services and the required householder acceptance.

The CONSORT project team chose Bruny Island, Tasmania as a test site to undertake the research. Due to its remote location, Bruny Island faces an energy distribution challenge also experienced by other edge of grid locations. The underwater cable that links the island to the mainland's network is unable to cope with sharp increases in demand during busy weekend



and holiday periods in the cooler months. Since 2012, TasNetworks has been relying on a diesel generator located on Bruny to supplement energy needs during peak periods. CONSORT provides an alternative solution to upgrading the cable itself, which would be very expensive.

Despite the increasingly complex control algorithms, prosumers are likely to want a simple reward structure for their battery support. CONSORT has explored the use of reward structures conducive to uptake. Success ultimately depends on people accepting both the technology and the rewards. For this reason, the interdisciplinary CONSORT team has included a social science component to investigate the response of Bruny Island prosumers.

At its completion, CONSORT has demonstrated how networks and prosumers can solve network constraints, enable more renewables and be fairly rewarded for their efforts. By solving these problems, CONSORT has enabled a future where high renewable penetrations and other network constraints can be managed at a much lower cost than is conventionally possible.

Outcomes

Overall, the Bruny Trial achieved outcomes across all its intended goals. The batteries and orchestration algorithm were able to deliver a 33% reduction in diesel and completely avoid all diesel generation on one network peak. The Trial participants remained engaged throughout the whole Trial and continue to provide valuable insights. The reward structures team developed a new Shapley value based means of pricing network services. A summary of key outcomes include:

- 34 households with solar/battery systems equipped with Reposit Power battery controllers totalling 128kW/333 kWh
- An advanced battery orchestration platform, Network Aware Coordination (NAC)
- A means of pricing network services that reflects the value they provide to the network
- A map of the customer experience and insight into the suitability of future demand response and orchestration programs.

More detail on the outcomes is provided below.

The network's perspective

This trial was designed to be a model for the future. With this in mind, we carefully designed the process to replicate the process people would use to install a battery capable of providing grid services outside of a trial setting. We obtained valuable learnings about the householder experience and likely issues the industry would face as this technology is scaled. The process included:

- Participants maintained choice over as many parts of their install as possible, such as battery, inverter, solar system size and how the system is installed, and were paid a subsidy purely related to the size of the battery installed
- Participants chose their own installer from a list moderated by the CONSORT team and managed the install process themselves
- Participants were randomly selected from those that applied rather than based on network location
- Even though there was a large battery subsidy, the trial still paid customers for the services they provided the network.

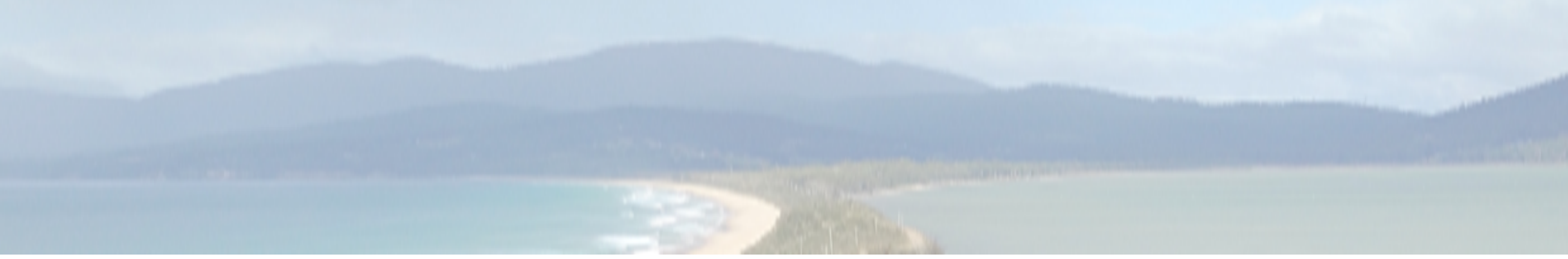
Ultimately, there were 34 participants who installed a system out of 46 offers made among a pool of 119 applicants. The average household financial contribution was $4,700. The lowest was $2,000 and the largest was $26,600. Only one participant did not receive the maximum subsidy for their battery size (i.e. the minimum customer contribution set the subsidy amount). All participants opted to install a 5kW/10kWh LG battery, but there was a mix of the high voltage and low voltage variant. Both these batteries peak discharge power is 5kW so attracted a $16,000 maximum subsidy. There was also a mix of inverter type, with SolaX, Sungrow, and SolarEdge inverters in use. Some of these inverters limited the battery discharge power capability below what the battery itself could sustain.

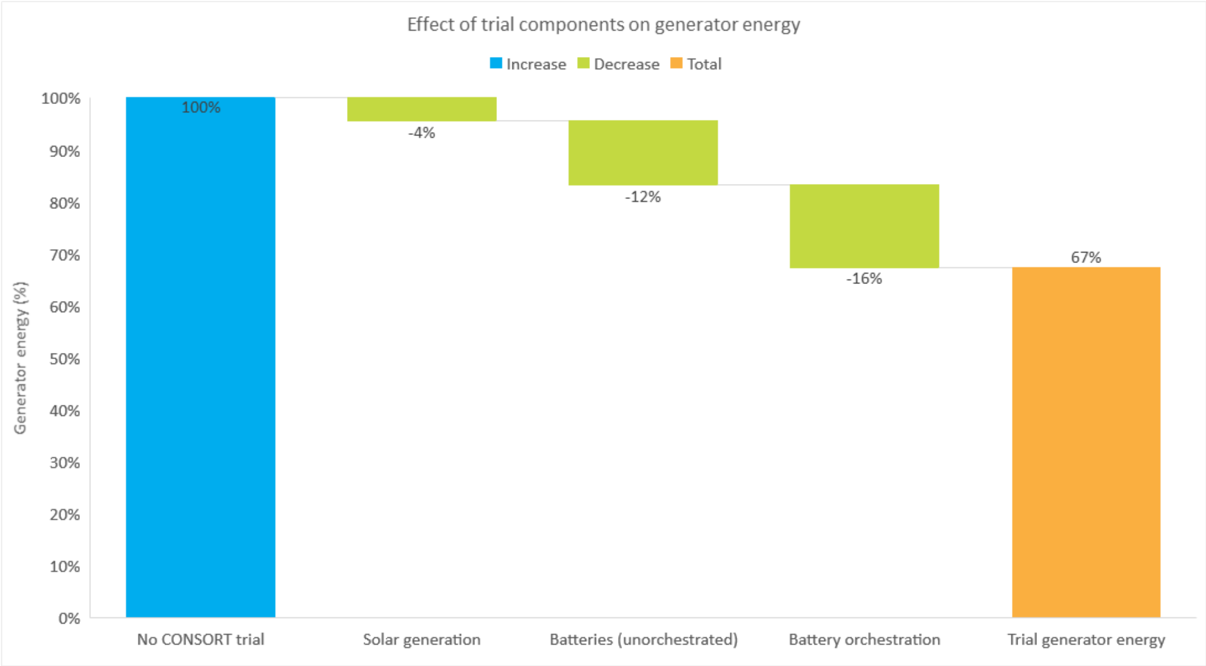
Diesel savings

There were several positive impacts on the Bruny electricity network from the trial. In 2018, there were 24 events where diesel would have been required if not for the trial. These occurred in Easter, the April school holidays, Anzac day, Queen's Birthday long weekend, and the July school holidays. The contribution of each component in reducing the diesel consumption can be seen by analysing modelled diesel use in the case where:

- there was no batteries or solar
- there is only solar generation
- the battery operation during periods when NAC was running is replaced with battery output of times when NAC was not running; and
- the actual island load.

A summary of this analysis is in the chart below:





This chart shows:

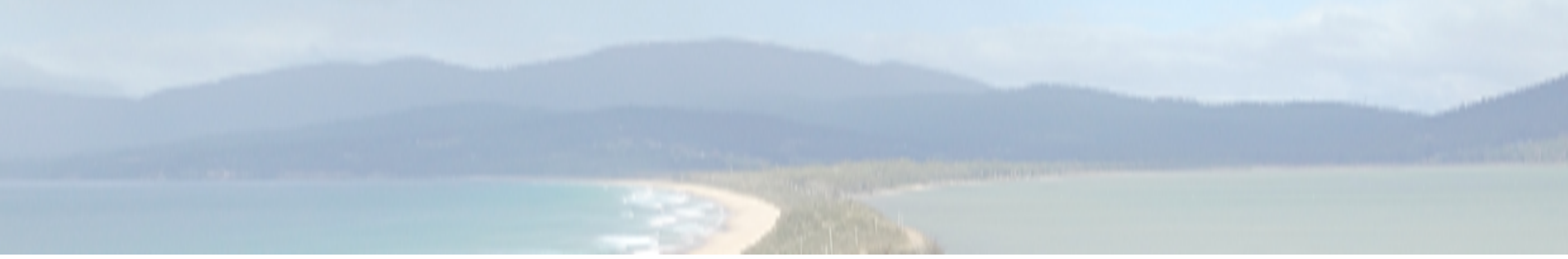
- Solar provides only a relatively small diesel reduction (4%)
- Batteries alone, optimising for customer behaviour individually, deliver a small but significant diesel saving (12%)
- Orchestration through NAC approximately doubles the value of the battery/solar systems in reducing diesel consumption.

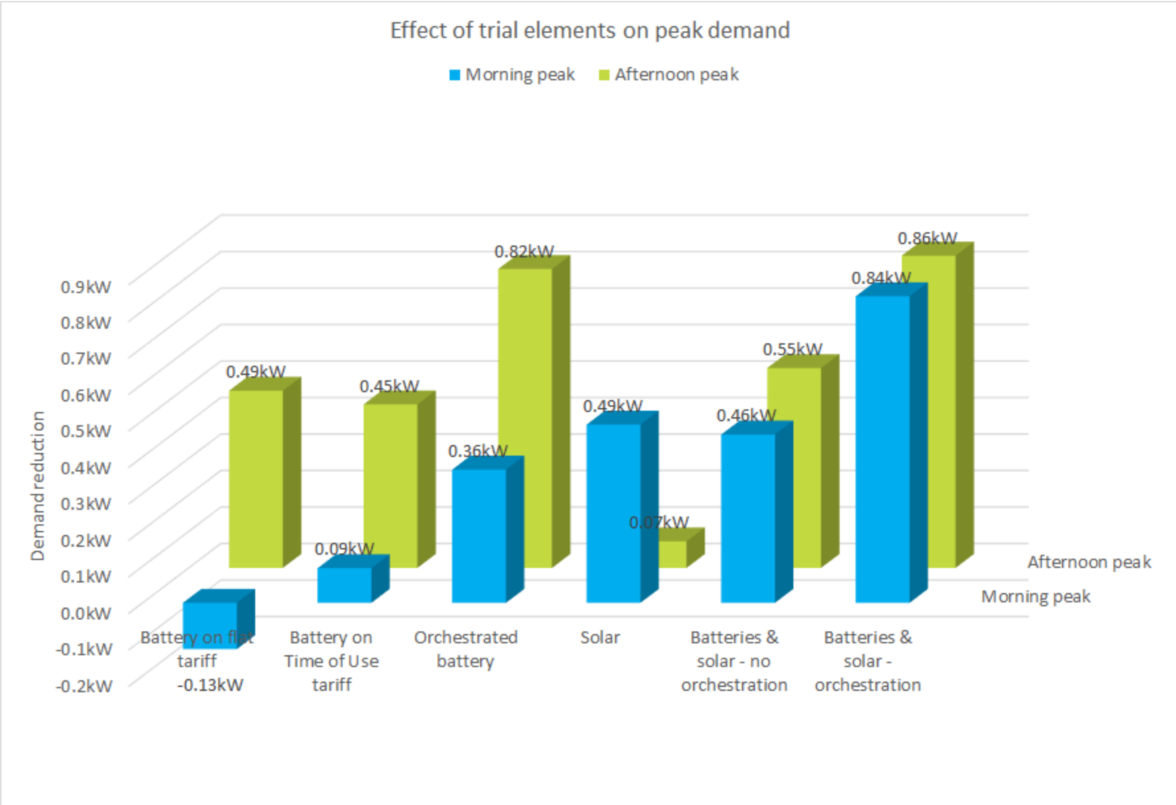
Peak load

Generally peak load is a good indicator of system strain. Bruny Island, like most cold-weather peaks, has two peaks per day - one in the morning, one in the afternoon. Either of these peaks can cause the diesel generator to start. Similarly to diesel use the impact of the trial components can be split into categories. As there is more available data the impact of more elements can be analysed:

- Solar;
- Batteries on a flat energy tariff;
- Batteries on a time of use tariff;
- Orchestrated batteries.

This is shown below.





From this chart we can see that:

- Solar generation provides some benefit in the morning, but little in the afternoon;
- For morning peaks, orchestrated batteries alone (without solar) are not as effective as orchestrated batteries with solar;
- The benefit of a battery is dependant on what tariff the customer is on - time of use tariffs significantly increases the value of the battery. Batteries on flat energy tariffs increase peak demand in the morning. This is a result of the battery either being flat or storing excess solar; and
- Orchestration again provides significant value.

The householder perspective

In discussions about the transformation of our energy networks, it is often assumed that householders are willing recipients of new technologies, receptive to new ways of running the grid, and are responsive to price signals. Yet, we do not currently have enough information and understanding of the role of householders in a changing, decentralising, electricity grid to make such assumptions. The CONSORT social research team undertook in-depth qualitative longitudinal research with all 34 Trial households on Bruny Island to better understand the feasibility of DER from the household (social) perspective through a combination of interviews (x3 with each household), focus groups (x2), energy diaries and observations of the technology as installed. Bruny Island successfully operated as a rigorous test case for new

DER interventions, because of its rural location, high proportion of holiday-house owners and non-average demographics.

The key overall lessons from our social research on the Trial, along with recommendations about how to respond, are as follows:

- Householder participation in DER is not certain; it cannot be assumed that householders are willing to participate.
- Householder responses to DER are diverse, and expecting that households will have a uniform and predictable response to any particular DER intervention is unrealistic. For example, some Trial households were responsive to price signals, others much less so; some households used the Reposit app regularly, others never downloaded it.
- The households in our Trial on Bruny Island are not typical 'early-adopters', and our findings therefore give a good insight into issues that might be encountered with DER programs elsewhere that similarly adopt a network area or geographical focus, with a diverse mix of householders.
- The combining of various technologies to create DER systems in homes has created a complex system that goes beyond information and knowledge available on any one technology.

Recommendation: be more cautious in projections about household sharing of DER and where possible substantiate projections and modelled scenarios with 'real world' social research data. Plus, consider the type of organisation likely to be able to provide knowledge support about the overall DER system.

A number of more specific lessons emerged from social research on the Bruny Trial. These lessons cover findings on the installation experience, and experiences of the technology, as well as views on pricing and financial rewards for network use of their battery:

> **Installation:** installation of the technology is an important moment for households, and a key lesson is to devote resources (people, time, expertise, money) to the installation of household DER technologies. Also, to consider having installers as a core part of the DER project/policy team, including at the design stage.
>
> **Householder experiences**: householder emotional responses to new DER technology (joy, enjoyment, anger, anxiety, frustration) are a central component of how households understand and respond to the new technology. Taking into account household emotions in DER programs is important because, for example, communication strategies that only focus on technical information could limit DER uptake, and some coping strategies used by households (e.g. disengaging) could mean that potentially hazardous technical faults are not noticed and reported.
>
> **Changes over time:** our social analysis revealed that changes in household energy behaviour (new practices, changing the time of practices, use of feedback) reported by

households soon after installation (c2 weeks post-install) tended to persist over time (12-18 months later).

Pricing: householders value financial rewards, but they do not necessarily trump other values. On Bruny Island, battery back-up at times of grid outages was seen as valuable by Trial households, and this might well be the case in other rural locations where outages are above average. Changes to Time of Use tariffs, although not strictly part of the Trial, were most visible to households, thereby making it harder to explore the specific Trial pricing interventions. A lesson is to carefully map out all household pricing interventions when designing a Trial.

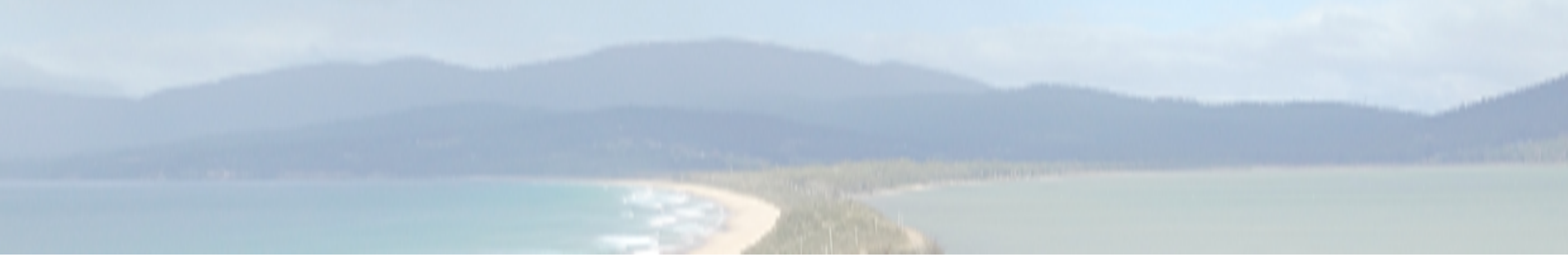
Our high level findings from analysis of householder experiences on the Trial are:

Technology Installations at our Trial households:

- The installation process was not a discrete, one-off event, but rather a diffuse process that for most households took some time and was not straightforward.
- The installation experience was an important moment for households, and one which had a strong impact on their ongoing experiences of the overall Trial, including their satisfaction with the technology and pricing.
- Installers varied greatly in terms of the level of education and support they provided for households. In most cases installers did not have the capacity to provide follow up support to households. Therefore Tasnetworks and Reposit had to provide support above and beyond what is likely to be feasible outside a trial situation.

Householder experiences:

- Householders' emotions formed a central part of our social research analysis because in situations where people lack critical information, or situations that are complex or uncertain, their evaluations tend to be based on affective (emotional) responses - particularly beliefs about trustworthiness - rather than only deliberate cognitive evaluation.
- Trial householders expressed both positive and negative emotions: 23 of 32 longitudinally-analysed households were overall relaxed and confident in the technology and the Trial, but experienced some level of frustration and confusion, and therefore had criticisms of the installation and the technology; 9 households expressed more negative emotions in regards to the technology and experience of installation such as anxiety, frustration, and anger.
- For those households experiencing negative emotions, coping strategies were used, such as: reframing the technology from something that needs their active input and understanding to a technology that can be seen as 'set and forget'; and taking control and keeping the perceived risk at bay by dismissing the technology (e.g. by considering opting out of network support).



Changes over time in household energy behaviours and use of the Reposit app:

- We examined the issue of change over time because there is some uncertainty in academic studies about whether household behaviour change is short-lived in response to a new energy technology (or other energy intervention), or whether it persists over the long term.
- Types of energy behaviour change reported to us were mostly to do with changing the timing of energy use activities, rather than stopping behaviours. Typical activities discussed by Trial households include clothes washing, dishwasher, showering, heating (space heating and hot water), and use of the oven.
- The key prompt for household energy behaviour change identified by households was the new Time of Use (TOU) Tariff.
- Our findings indicate that initial changes in behaviour and use of the Reposit app have persisted over the course of the Trial, for the majority of households.

Householder perspectives on system value

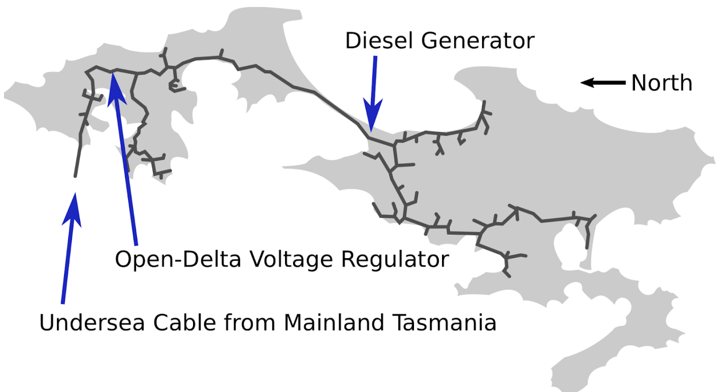
- Understanding motivations of Trial households with regard to pricing and preferences for using their installed CONSORT technology is important in order to test pre-Trial assumptions underpinning use of the Reposit software. The Reposit controller is designed to optimise against incentive structures that are represented in financial terms. To date, the only incentives exposed to the Reposit controller are to lower the household energy bill as much as possible. In effect this represents a scenario where finances hold critical sway in household decision making around energy. When householders were asked about third-party use of their DER, we found that financial considerations were important, but we also found a range of other issues and motivations to be important, such as battery backup, and community and environmental values. For example, a key tension in the Trial was the value householders placed on having back-up power available from their battery. In some households, the value of back-up appeared to be stronger than the motivation to trade energy and to receive a financial reward. The rural context of Bruny, with above average network outages, may be an important influencing factor.
- Most householders did not have a preference between the two types of network payment that were trialled: *Energy Reserve* and *Energy Use*. On prompting, those who did express a preference (5 of 30) all chose Energy Reserve due to a perception it would pay them more (as they observed more power would be reserved than would be potentially needed).
- A significant number of households did not change to the TOU tariff, despite preliminary analysis indicating they may have been better off financially to do so.
- The process of changing tariffs involved several steps, and was not straightforward, meaning a number of households were not certain what tariff they were on after installation, and even a year later.

- The change in tariff was a really key part of the Trial experience for householders, and was given more consideration by householders than other pricing interventions such as the network support payments.
- Awareness of the NAC platform was low amongst Trial households - it was generally not differentiated from Reposit.

Network-Aware Coordination

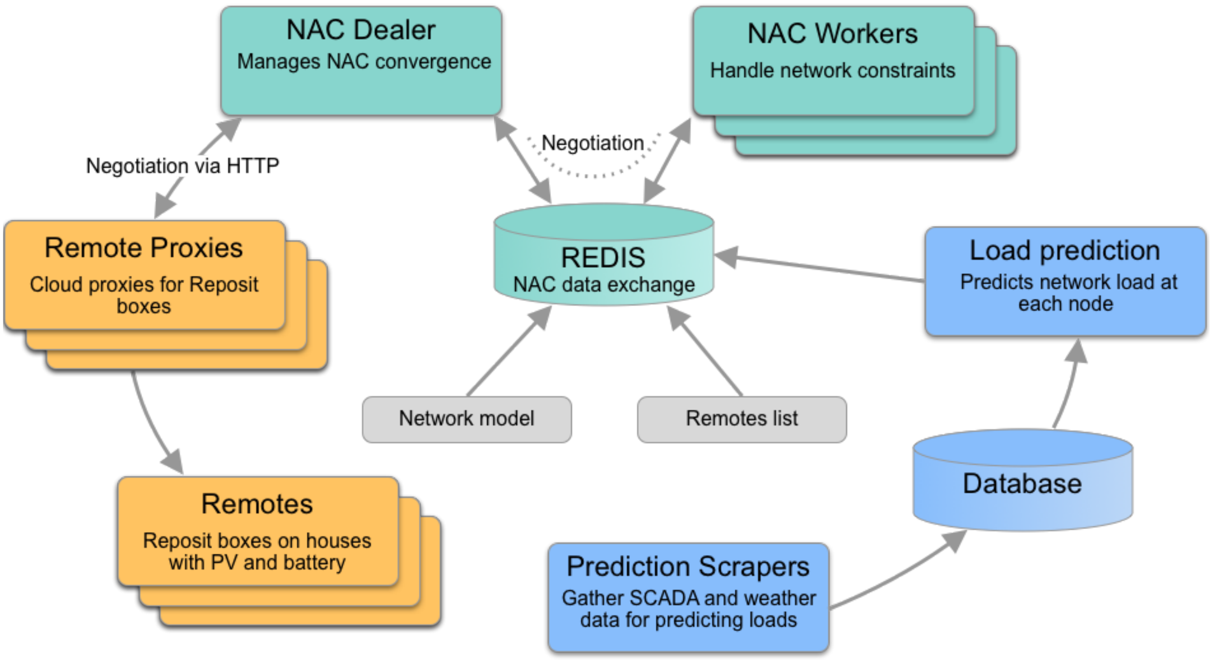
Network-Aware Coordination (NAC) is the key technical innovation at the heart of the CONSORT project. CONSORT has demonstrated how NAC can coordinate DER to manage network constraints at lowest overall cost to the network and prosumers. NAC has the following desirable properties:

- By explicitly modelling the physical and operational network constraints, the NAC finds an Optimal Power Flow solution for the network: a DER and generator dispatch that minimises overall costs within the network's constraints.
- It is a distributed algorithm. As more NAC participants are added, the calculation can be scaled up by simply adding more computational resources, and leveraging the existing resources of participants.
- It preserves the privacy of participants. The algorithm does not need detailed information about each participant and their DER, just where they connect to the network and their expected power consumption at their network connection point
- It provides the means for participants to have agency, in the form of their EMS acting in their financial best interest. NAC is not concerned with the details of the calculation by which each individual household energy management system (EMS) plans its battery discharge. This means that there is a clean interface between the NAC and the EMSs; each of these may be developed independently, and to participate in NAC, an EMS need only to be able to exchange some simple information, and to conform to some assumptions about the way the battery discharge is planned.



The Bruny Island 11 kV network, which is modelled by the NAC in order to optimally coordinate DER dispatch.

The architecture of the NAC and its interaction with other systems is shown in the figure below. The three colours highlight the NAC in teal, the battery energy management systems in orange, and the network-level load forecasting for non-participants in blue. The NAC Dealer orchestrates the negotiation between the NAC Workers, which model and solve network power flows, and DER aggregator energy management systems. This negotiation can be viewed as a distributed optimisation, which converges towards an Optimal Power Flow solution.



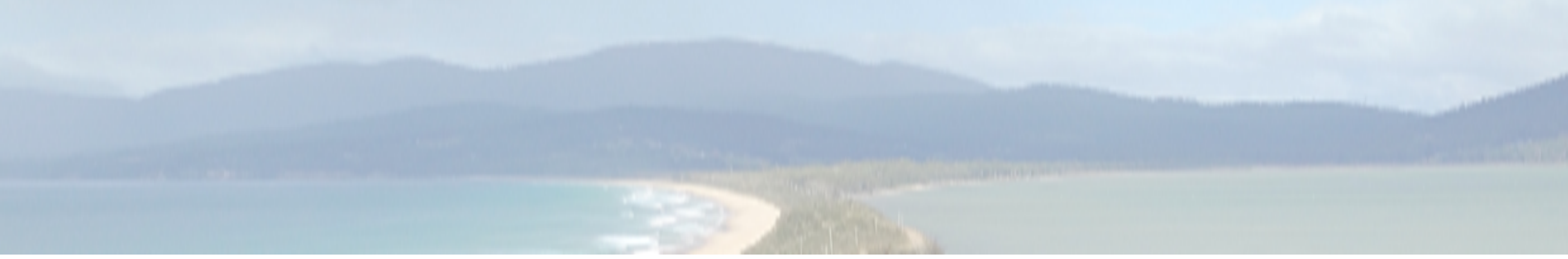
Detailed NAC architecture, as implemented in CONSORT. Different systems are highlighted in different colours: teal for the NAC, orange for the remotes, and blue for the load prediction.

Over three years of the CONSORT project, we have successfully implemented and tested NAC on Bruny Island. By the end of the project, we are able to run NAC on a routine basis, for periods of at least several weeks at a time, and have demonstrated a reduction in diesel usage during peak periods of around 33%.

For developing the NAC, the main purposes of conducting live trials were to:

- Demonstrate the viability of NAC for controlling congestion in the network. In essence, we wanted to demonstrate that the NAC was viable for solving Bruny Island's main network issue;
- Gain insights about the behaviour of the NAC algorithm when used in realistic circumstances;
- Provide a baseline and validation for simulations[7] designed to answer counterfactual questions like: What would have happened during the trials, if the batteries and PV had

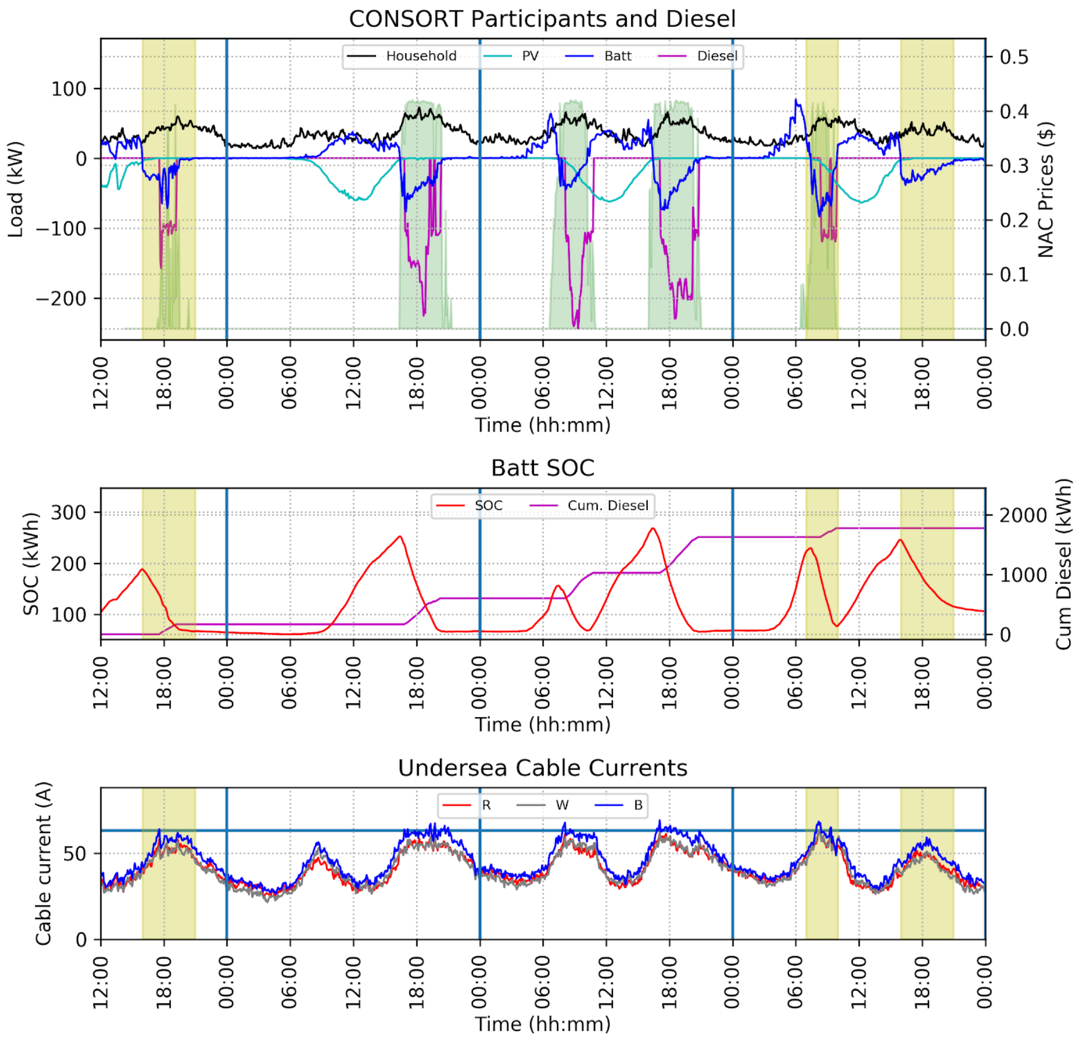
[7] Simulations using SmartGridToolbox https://gitlab.com/SmartGridToolbox/SmartGridToolbox/ were used to supplement the live-trial results. This simulation tool was also further enhanced as part of CONSORT.



been present but NAC had not been used? What if there were no batteries / PV? What would be the effect of adding extra participants?

- Study the performance and scaling of the NAC algorithms; and
- Study the use of NAC to control network voltages.

The live trials provided the research team with opportunities to refine the NAC and to demonstrate that the NAC does provide a more efficient way to coordinate DER compared to other options, and its potential as a means of controlling network voltages. The following figure shows time series results of NAC operating for 3 days over the Queen's birthday weekend in June 2018. This figure illustrates the dispatch of the batteries during network peaks to manage the nominally 63 Amp undersea cable limit.



Queen's Birthday long weekend trial. Top: aggregate participant loads, diesel load; negative = generation. Yellow bars are peak TOU tariffs. The pale green filled graph represents non-zero NAC prices. Middle: aggregate battery state of charge, cumulative diesel discharge. Bottom: current in the undersea cable. The horizontal line is the approximate upper limit to which the current is normally controlled by the diesel operators (63 A).

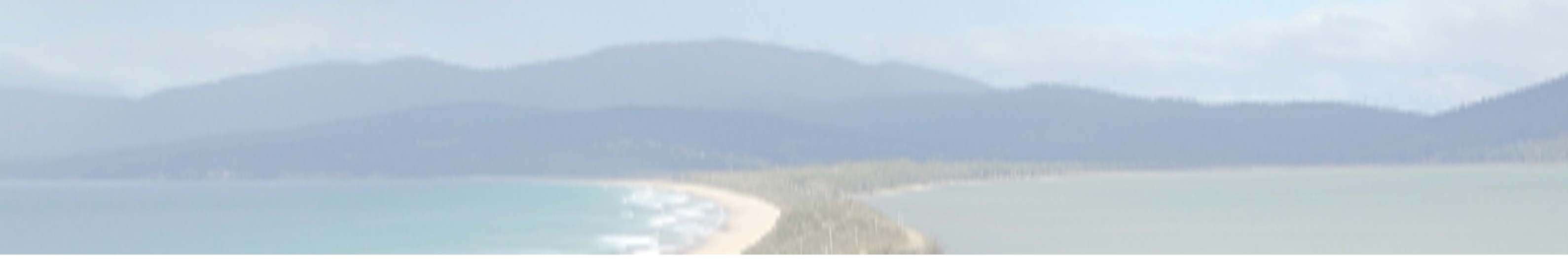
From the beginning, the NAC technology has been designed to not just solve the Bruny Island problem, but to also expand to a larger range of network conditions, to different types of DER including electric vehicles, and to enable load flexibility to the wider wholesale markets. Toward the end of the project, we investigated the use of NAC to control voltages. Similarly, NAC was designed to be able to interface with multiple DER providers, enabling it to adapt to a range of DER sources. The NAC is therefore applicable over a wide range of feeders or networks of various sizes, experiencing a range of existing or emerging issues associated with DER deployment. It provides the means for distributed renewable generation and other DER to be safely, efficiently and flexibly integrated into our distribution networks, improving the outcomes for network operators, DER owners and the wider NEM.

Reward structures

Reward structures refer to the design of payments to customers for the network support services that they provide. In the CONSORT project, we have developed reward structures that unpack the “value-stack” available to distributed energy resources. In keeping with recent microeconomic reforms to the electricity sector, these reward structures implement value-reflective pricing methods for network support. They are aligned with the move to cost-reflective network tariffs put in place after the AEMC’s Power of Choice review.

As a baseline, payments were made to the customers at a rate of $1/kWh for energy discharged from their batteries during the network support period. This was a flat rate across all customers, and was considered large enough to be salient in their decision making. However, a flat reward structure design does not accurately reflect the network support value of a battery, in the same way a flat retail energy tariff does not accurately reflect the cost of producing energy at different times of the day. Given this, the CONSORT reward structure trials considered two independent design considerations for the network support payments made to customers. The first major consideration regarded the timing of payments made to customers, and of peak event alerts sent to customers. In order to understand these effects, two treatments were developed and trialed: an 1) *Energy Reserve payment*, and an 2) *Energy Use payment*. Roughly speaking, Energy Reserve payments were computed on forecasts of the NAC's operation and communicated to trial participants via a text/email notification using the Reposit system before a forecasted peak event; while Energy Use payment were computed from actual NAC operation data and communicated to participants after a peak event. Ultimately, implementation difficulties, and a lack of overt preference from customers, makes the case for recommending Energy Use payment type over Energy Reserve payments.

A second major consideration was to find a value-reflective pricing methodology for the network support provided by customer-owned batteries, to replace the $1/kWh flat rate baseline. A solution was found in the economic concept of the Shapley value, which was used as a template of an ideal reward structure. The Shapley value provides a principled set of properties related to network support pricing, most importantly a form of fairness (equal



treatment to equal contributions and independent pricing of independent effects) and efficiency (full disbursal of the rewards available). However, since directly using the Shapley value reward structure in practice is computationally infeasible, the team developed various estimation and approximation methods. These were integrated with the NAC algorithms, and successfully deployed in the field (although participants were still paid the $1/kWh rate). Analysis of the payments computed by these reward structure methods indicated that they did indeed reflect the batteries' value to the network in principled ways, including accounting for battery capacity and power limits, phase connection, network location, the customer's load with the peak period, with useful findings for distribution network companies and retailers.

Despite these successes, the reward structure methods developed had varying degrees of success by practical computational metrics. One finding from the reward structures work package is that the exceptionally difficult task of calculating the Shapley value of a network support event makes it infeasible to use as a method of generating spot or even close-to real-time prices, unless severe approximations of the computation are made. Additionally, although they could be deployed in the CONSORT trials, the required approximations undermine the use of these reward structure for calculating customer payments in more complicated problems of sharing multiple DER value streams, for example, when simultaneously managing network voltages as well as thermal limits.

Nonetheless, a path forward to the use of value-reflective reward structures in paying for network and power system support services has been plotted based on the findings of the project. The methods developed can overlay any DER control scheme, regardless of its level of sophistication. In particular, the statistical analysis provided alongside the case study results present a path to using value-reflective reward structures for generating network and power system support services. Specifically, as an alternative to online "spot price" calculation, offline Shapley value computation, analysis and regression-based implementation may be a viable way to implement the Shapley value-based methods for pricing network support. The process could work as follows: Given a set of past network peak events, the Shapley value for each can be calculated offline (i.e. in simulation). The results would then be matched with appropriate input data, such as average in-peak load, battery use, or average voltage ratios. Regression of these inputs against the Shapley values would reveal the major contributing factors to the network support value, in simple to understand terms. Such a regression-based model could, ultimately, take the characteristics of a home as inputs, and return the resulting prices specified in simple, but tailored, $/kWh units. The development of this type of tool would help both DNSPs and customers understand the mechanics of implementing value-reflective pricing of network support services.

CONSORT Participants System performance and financial benefit analysis

In terms of specific financial analysis of the different components of the system, the team was able to perform detailed analysis on 19 out of 34 systems. Key findings from this analysis are:

- Average participant solar self-consumption was 41% without battery, and increased to 68% with battery.
- Participant’s batteries were utilised to shift daily an average of between 2.5 kWh and 6 kWh of load, with an average across all participants of 4 kWh.
- The total energy savings from all installed system sources ranged from $630 up to $1550 per year, with an average participant saving of $1100.
- The annual savings attributable to solar generation only, range from $380 up to $1230, with $750 being the average saving.
- The annual savings attributable to battery system (excluding Reposit optimisation and network support payments) were $60 up to $350, with $200 average.
- The savings attributable to the TOU arbitrage component of Reposit’s optimisation algorithm was ~ $0 for flat-rate tariff customer and for Time-Of-Use (TOU) customers it ranged between ~$0 up to $140, with $70 average. The TOU arbitrage component was the only part of Reposit’s optimisation algorithm that was analysed in arriving at these figures.
- Savings (benefit) owing to NAC-driven Network Support Payments (which spanned 16 separate peak demand events over 12 month period) were: $115 average across all participants. The cost of participation meanwhile, which is the lost benefit (or opportunity cost) as a result of having a battery act to support network peaks rather than to meet household load, was no higher than $7 for any given participant, with an average of $1.40 across all participants for the 12 month period.

There are a few bigger picture lessons that we learnt from performing this analysis. Firstly, calculating the financial benefits in detail in the way we have done is very complicated and unlikely to be possible for householders to do for themselves. This means if a system is not working at its optimum performance, it may be difficult for householders themselves to work this out.

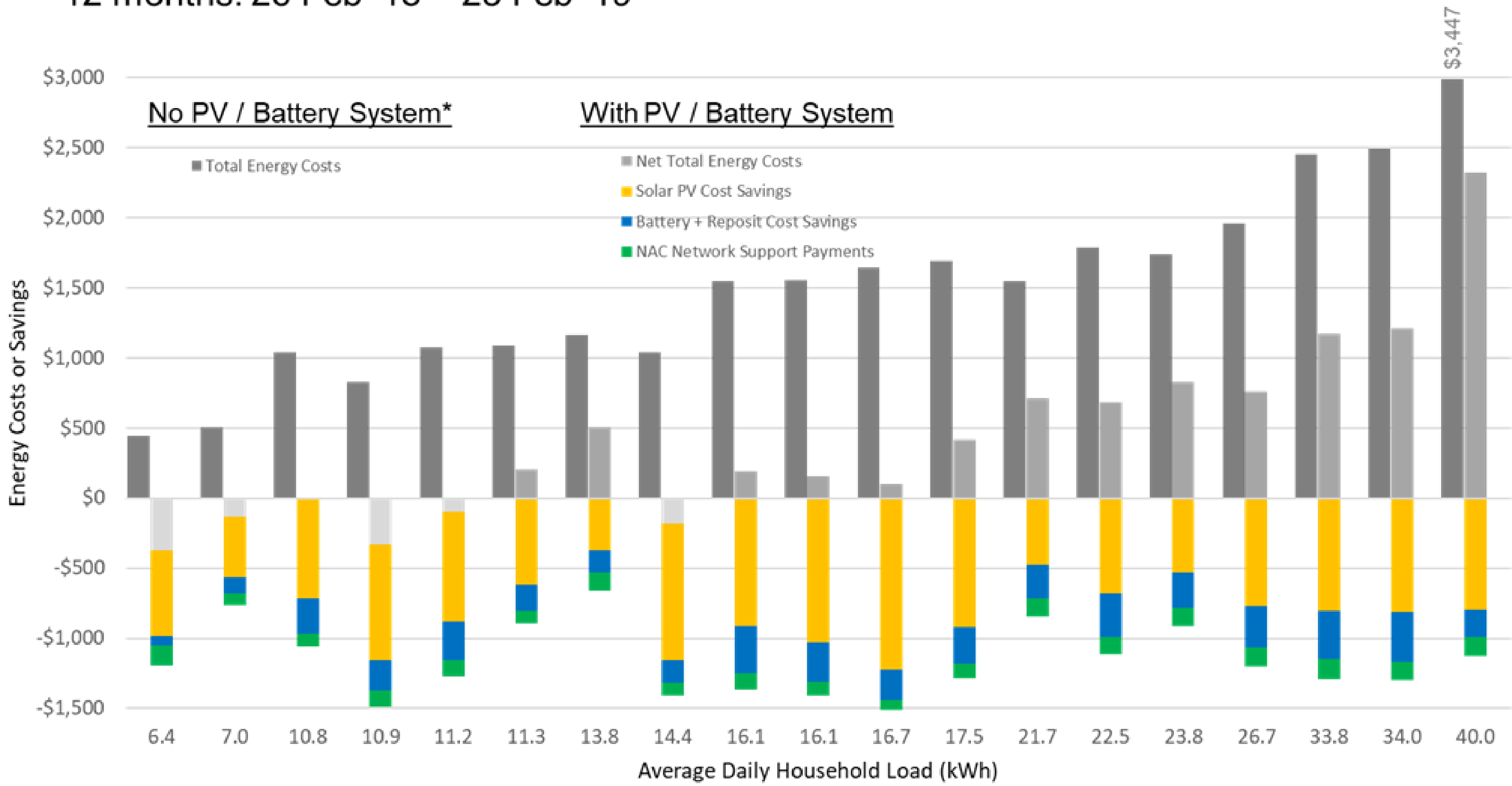
Secondly, there were large ranges between the different ends of the savings/benefits spectrum, which shows how important the factors of individual householder consumption, their system size and when they use energy are to potential savings. All this may be important, when communicating the potential ‘value stack’ of this kind of system.

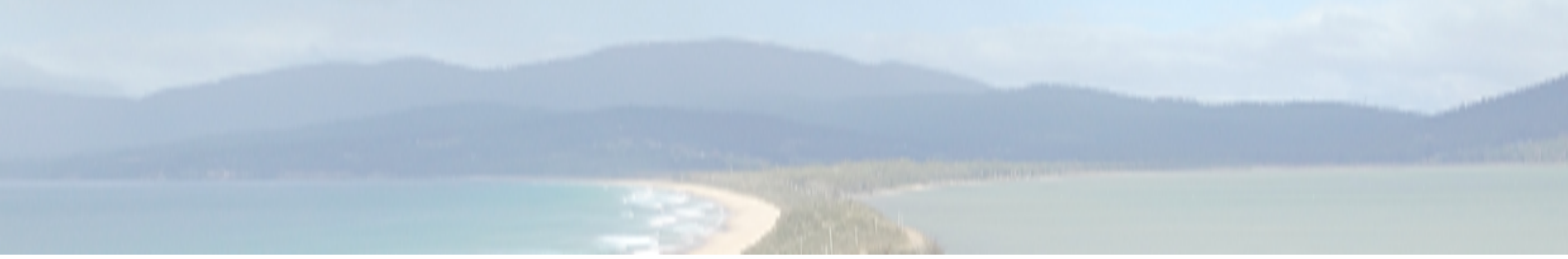
Thirdly, while the benefits associated with TOU arbitrage of the Reposit Box greatly depend on individual characteristics of customers solar battery systems, the network support benefits from battery orchestration can only be realised via such a system.

Finally, we found that the financial opportunity cost associated with allowing batteries to be used for coordinated, intelligent support of the network is very small, quite easily justifying monetary benefits associated with providing that support. While the net financial benefit of providing that network support was a relatively small part of the participant's savings in this trial, it could easily be a larger fraction for networks with more frequently occurring network constraints, and furthermore could be anticipated to increase with increasing penetration of DER.

The figure on the next page summarises: Total annual energy costs without PV/battery system installed (dark grey - modelled from observed data), and with system installed (light grey - observed data), and breakdown of energy cost savings by component - PV only (yellow - modelled from observed data), Battery plus Reposit box (blue - modelled from observed data) and NAC-driven network support payments (green - observed). Data analysed is for 12 months from 26 Feb 2018 to 25 Feb 2019, and is sorted by average daily household load.

Annualised household energy costs per year (excl. fixed charges, excl. load on T41 if applicable), 12 months: 26 Feb '18 – 25 Feb '19





Transferability

Scalability

Network Aware Coordination (NAC) is an award-winning technology, well-positioned as the marketplace for Australia's rapidly growing fleet of Distributed Energy Resources (DER). We know that DER is set to play a vital role in keeping our future energy system balanced while keeping electricity costs in check. However, it is very important that this 'prosumer power station' is well integrated with the existing wholesale market and respects the physical limits of the distribution grid. If DER is not well managed, the system will deteriorate; lowering reliability and increasing costs. The NAC is a superior technological solution integrating DER into our system. CSIRO and ENA found that a well integrated 'prosumer power station' will deliver the system a $100 billion benefit over coming decades.

It is no easy task to ensure the prosumer power station works well for householders, their retailers, networks, and our market simultaneously. Competing architectures are unlikely to successfully do this without severely restricting the 'peaking generation' role of DER in our wholesale market.

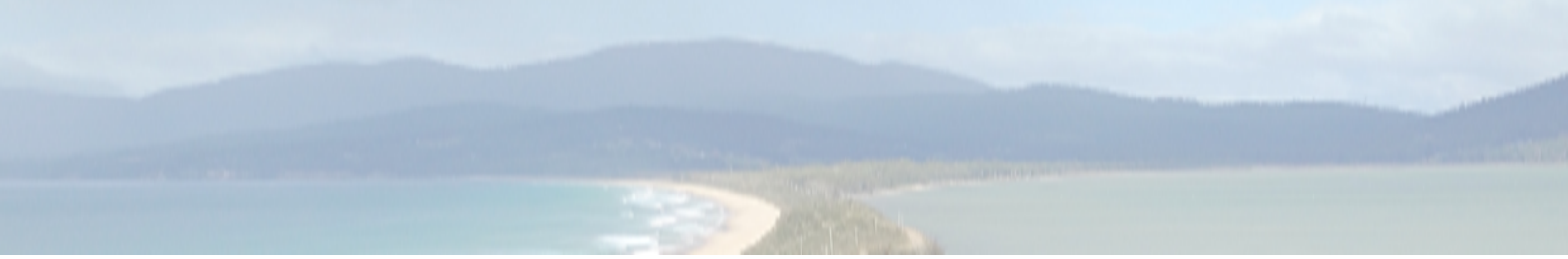
The Bruny Trial was focused on using price signals to solve a distribution constraint on an undersea cable. In the future we intend to use the platform to solve a much larger problem: integrating the 'prosumer power station' directly into our wholesale market. Our vision is for the NAC to automatically enrol DER into NEMDE's existing 'bid-stack', allowing the market operator to treat the DER resources like any other peaking generator. This in turn will make it easy for DER managers to access wholesale market revenues-and-savings without the cost of becoming an official NEM participant. In performing this market-linking role, the NAC will automatically respect grid constraints, allocating scarce capacity to the best economic use.

The next step for the NAC is to scale-up operations from the successful Bruny Island trial. Key activities for this next project would be to introduce a greater variety of DER, develop systems for bidding into NEMDE, and operate over a greater geographic range. In addition, further social science analysis work is required to explore how to overcome the institutional gaps and challenges identified by the social science research in CONSORT.

Knowledge sharing

Within organisation

The CONSORT team have been busy throughout the project, sharing project objectives and outcomes to audiences within their communities. Researchers within CONSORT published 9 research journal articles and 26 conference presentations/publications (some of these conferences were also attended by industry). TasNetworks have planned a 'deep dive'



workshop with Australian networks in April 2019 to focus on CONSORT learnings. Reposit, the industry partner within CONSORT have continuously applied key learning from CONSORT trial findings into their own business planning.

External knowledge sharing

In terms of knowledge sharing outside of the project partner's direct communities, the CONSORT team produced at least 50 media items which focused on the project across multiple media types. This included an article in *The Conversation*[8] which reached at least 17,738 people. This article was also re-posted in RenewEconomy. The CONSORT team presented the project to at least 12 forums across community and industry audiences. The team also made two public submissions (the ENA-AEMO Open Energy Networks project and the AEMC Approach Paper: Distribution Market Model). Finally, the CONSORT project attracted significant industry attention through winning 4 industry awards in 2018:

- *Energy Project of the Year*, The Electrical Energy Society of Australia;
- *Business Community Engagement Award*, Clean Energy Council;
- *Tasmanian Engineering Excellence Award*, Engineers Australia; and
- *Energy Networks Industry Innovation Award*, Energy Networks Australia.

Other relevant projects

Internationally there have been a variety of projects involving real trials of technology for managing DER[9]. On the technical front, the novelty in our project has been in solving Optimal Power Flow (OPF) on the distribution network via NAC, which achieves the highest value use of the DER while taking into account network limits. OPF is a computationally challenging problem which we have shown can be solved in a distributed manner in practice, and which can provide significant benefits over simpler alternatives.

Three relevant international projects are the Olympic Peninsula Project[10], the Pacific Northwest Smart Grid Demonstration Project[11], and the PowerMatching City project[12]. In order

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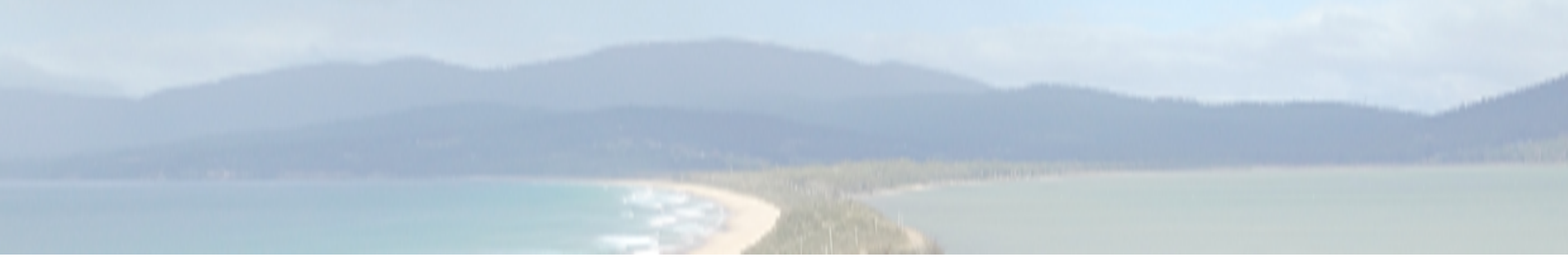
[8] Tesla's 'virtual power plant' might be second-best to real people power, http://theconversation.com/teslas-virtual-power-plant-might-be-second-best-to-real-people-power-90319

[9] P. Kohlhepp, H. Harb, H. Wolisz, S. Waczowicz, D. Müller, and V. Hagenmeyer, "Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies," Renewable and Sustainable Energy Reviews, vol. 101, pp. 527 – 547, 2019.

[10] D. J. Hammerstrom, R. Ambrosio, J. Brous, T. A. Carlon, D. P. Chassin, J. G. DeSteese, R. T. Guttromson, G. R. Horst, O. M. Järvegren, R. Kajfasz, S. Katipamula, L. Kiesling, N. T. Le, P. Michie, T. V. Oliver, R. G. Pratt, S. E. Thompson, and M. Yao, "Pacific northwest gridwise testbed demonstration projects: Part 1. olympic peninsula project," Pacific Northwest National Laboratory, Tech. Rep., 2007. [Online]. Available: http://eioc.pnnl.gov/research/gridwise.stm

[11] R. Melton, "Pacific northwest smart grid demonstration project technology performance report volume 1: Technology performance," 2015. [Online]. Available: http://www.osti.gov/servlets/purl/1367568



they solved a much simpler unit dispatch problem, traded energy between 27 nodes at the transmission level, and developed a market for agent bidding. In contrast we solved a full OPF that accounts for network losses and phase contributions down at the distribution network level, and that ensures network constraints are satisfied.

Three relevant ARENA-funded projects In Australia are the Decentralised Energy Exchange (DEX)[13], Evolve DER Project[14], and the Optimal DER Scheduling for Frequency Stability Study[15].

The DEX project has been developing a platform to enable DER resources to trade energy in markets. CONSORT's NAC can be similarly viewed as a market, where DER negotiate with the NAC over their operating point and the price for their services. The NAC negotiation is structured in such a way as to guide the outcome towards a lowest-cost solution which explicitly satisfies network constraints.

The Evolve DER Project is developing open interfaces between DER aggregators and networks, as well as trialling DER management techniques that convert hosting capacity into operating envelopes for DER, rather than seeking an OPF solution. The experience from the CONSORT project and interfaces developed between the NAC, network and aggregator, could prove useful for the development of the interfaces in the Evolve project.

Finally in terms of NAC relevant projects, the Optimal DER Scheduling for Frequency Stability Study is looking into extending the services that DER can perform into the area of frequency management. Part of the project is building on CONSORT's NAC so that it can jointly optimise DER to provide energy and FCAS services, all while preserving distribution network constraints.

Regarding pricing and reward structures, most technical projects, including those mentioned above, have some pricing elements embedded in them. Of more pertinence, ARENA has recently funded the Pricing and Integration of Distributed Energy Resources Study,[16] which is explicitly considering the value stack available to DER. The study will examine ways to value and provide price signals for the services that distributed energy resources (DER) can provide within the network and at customer sites. This is a consultative project, and CONSORT team members will engage with and provide feedback to the project investigators.

In terms of social research, internationally, there are still few other academic studies similar to the social research undertaken for CONSORT. However, in the past few years a number of Australian industry, government and non-government organisation prosumer studies have

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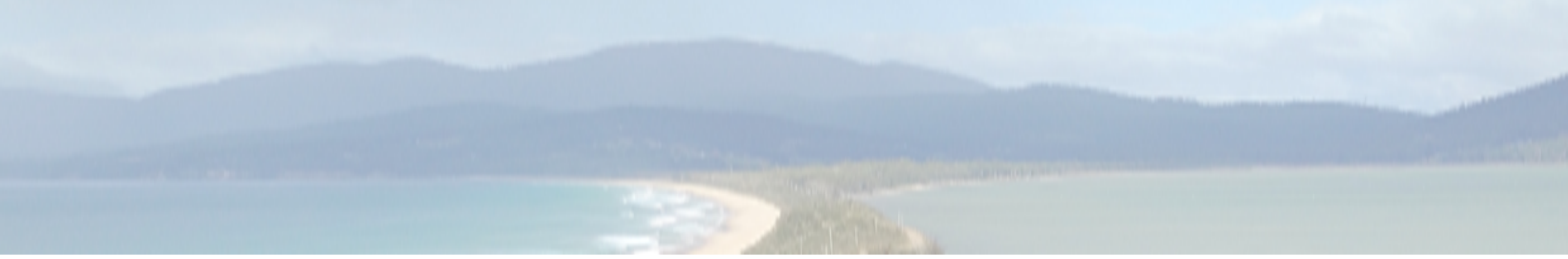
[12] F. Bliek, A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde, and M. Eijgelaar, "Powermatching city, a living lab smart grid demonstration," in 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Oct 2010, pp. 1–8.

[13] http://arena.gov.au/projects/optimal-der-scheduling-for-frequency-stability-study/

[14] http://arena.gov.au/projects/evolve-der-project/

[15] http://arena.gov.au/projects/decentralised-energy-exchange-dex/

[16] http://arena.gov.au/projects/pricing-and-integration-of-distributed-energy-resources-study/



emerged. The majority take an anticipatory approach - identifying trajectories and issues based on stakeholder and user perspectives - often using existing PV data and anticipating inclusion of batteries with PV. All of the studies anticipate increased future uptake and use of DER, based on analysis of householder perspectives and expert stakeholder understanding. Both the Clean Energy Council / Energy Consumers Australia study[17] and the CSIRO / Energy Networks Australia study[18] engaged on a notable scale with stakeholders from industry and governance organisations. However, to date there is only one published study, by Energex[19], that researched and engaged with householders using new battery technology and trading their home-based DER technology with the network. There are significant gaps in our understanding of household involvement with DER and energy trading with networks. More social research understanding will therefore greatly assist DER transitions, in Australia and internationally.

Conclusion and next steps

While the Bruny Battery Trial was a success, the story is not over. There were many learnings that can be taken from this project and applied to future activities in this space (several of these are outlined in the next section on Lessons Learnt). In terms of NAC specifically, the next challenge is to demonstrate operation at a larger scale, as well as build new modules, such as a NEMDE-compatible bidding engine. If the NAC technology can demonstrate superiority over alternatives, it has an excellent chance of playing a vital role in the future of our electricity system; helping to deliver a lower cost, lower emission, and more inclusive service to our economy.

Importantly, although not found by CONSORT to be practical for dynamic pricing, cooperative game pricing methods can be used as a benchmark method, to calibrate simpler network support tariff designs, or to assess the value-reflectivity of several network support tariff options.

Finally, notwithstanding the technical potential of NAC, customer engagement, management and retention will need to be considered explicitly in the design of future market- and network-interactive DER programs. A relatively smooth customer experience is critical for success, as they are the ultimate providers of the service the algorithm is orchestrating.

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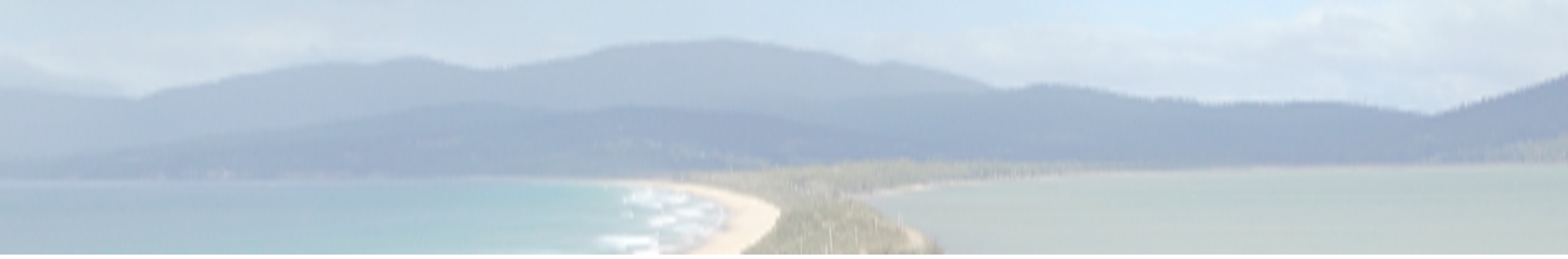
[17] Clean energy council (2019) Behind the Meter Code http://www.cleanenergycouncil.org.au/advocacy-initiatives/behind-the-meter-code , accessed March 2019

[18] CSIRO and Energy Networks Australia (2017) Electricity Network Transformation Roadmap: Final Report 2017-2027, April.

[19] Energex. (2017). Energex Battery Trials preliminary findings report. November.



Lessons Learnt

#1 Lessons Learnt Report: Short term load forecasting

Project Name: *CONSORT*

Knowledge Category:	Technical
Knowledge Type:	Network connections
Technology Type:	Storage
State/Territory:	TASMANIA

Key learning

Dispatching batteries accurately to manage network load requires a good forecast of the load in the immediate future. A poor load forecast will cause either over dispatch (network support when not needed) or under dispatch (missed peaks). This is particularly true for automated algorithms such as NAC.

Implications for future projects

Future distribution optimisation projects should consider load forecasting as a critical input and ensure adequate effort is assigned for development.

Process Undertaken

In the CONSORT project developed three methods of prediction:

1. Initially network support was manually dispatched based on operational experience
2. The first uses of NAC used a simple regression-based load forecasting engine
3. Later uses of NAC used an advanced transformer neural network load forecasting engine

The initial dispatches were relatively unsuccessful in offsetting diesel, Predicting peak days required significant over dispatch or the risk of missed peaks was too high. Similarly the regression based forecast required conservative settings to ensure response on all peaks, which resulted in over dispatch. The final forecasting engine delivered better performance, avoiding diesel generation successfully on one occasion.

#2 Lessons Learnt Report: Rewards structure methodology

Project Name: *CONSORT*

Knowledge Category:	Economics
Knowledge Type:	Pricing methodology
Technology Type:	Computation
State/Territory:	NATIONAL

Key learning

Rewards structures based on the Shapley value provide a principled approach to network support pricing, embodying a form of fairness (equal treatment to equal contributions and independent pricing of independent effects) and efficiency (full dispersal of the rewards available). However, the exceptionally difficult computational task of calculating the Shapley value of a network support event makes it infeasible to use as a method of generating spot prices, or even close-to real-time prices (e.g. day-ahead), unless severe approximations of the network value are made.

Implications for future projects

Calculating principled customer payments in even more complicated situations where multiple DER value streams are shared (e.g. when simultaneously managing network voltages as well as thermal limits) will be a challenge.

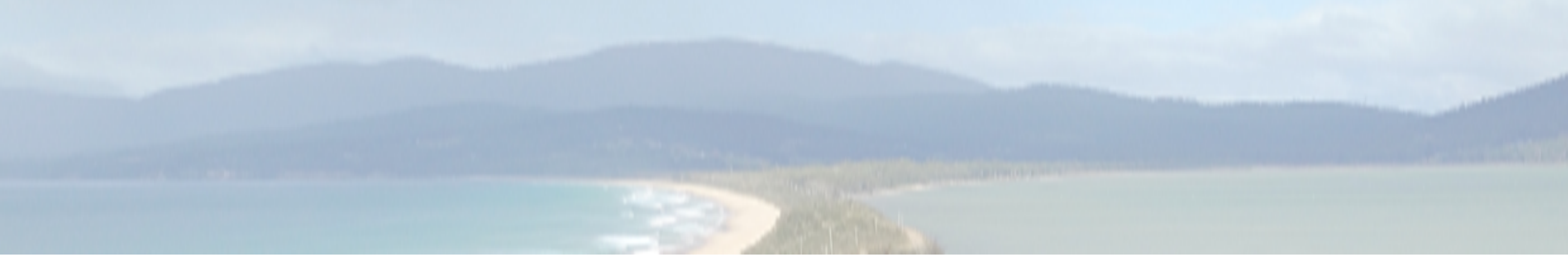
Knowledge gap

Offline Shapley value computation, analysis and regression-based implementation maybe a viable way to implement the Shapley value-based methods for pricing network support. Such regression-based approaches could take the characteristics of a home as inputs, and return the resulting prices specified in simple, but tailored, $/kWh units. The development of this type of tool would help both DNSPs and customers understand the mechanics of implementing value-reflective pricing of (potentially co-optimised) network support services.

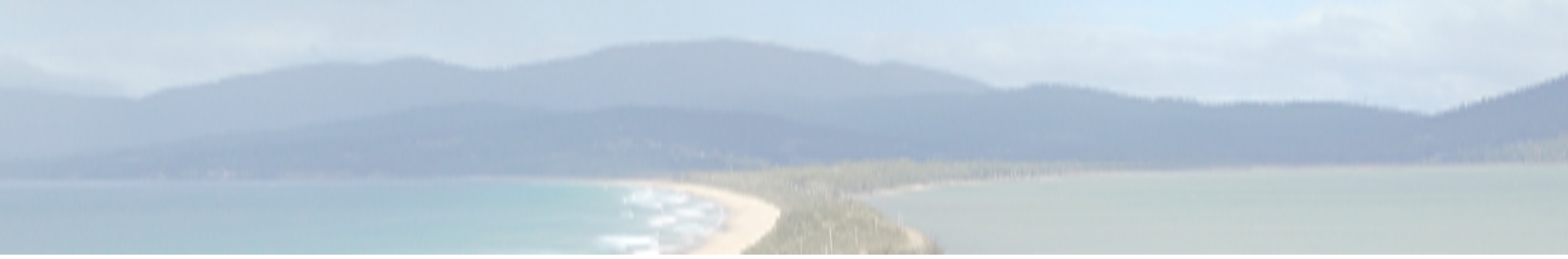
Process Undertaken

During the project, several computational approaches to calculating prices were trialed, and the two most-effective were

1. a sample-based Shapley value estimation of the customer's value-reflective prices, and
2. a Shapley value approximation heuristic.



These two methods have different use cases. The sample-based estimation method was found to be unviable as a method for quickly generating prices, due to the number of samples needed, each of which involve solving the underlying battery coordination problem. However, it may form the basis of a proposed regression-based approach to pricing, by providing training data for the regression analysis. The approximation heuristic was successfully integrated with other software developed in the project and deployed during the Bruny Island field trials.



#3 Lessons Learnt Report: Customer participation as part of orchestration and algorithm design

Project Name: *CONSORT*

Knowledge Category:	Social
Knowledge Type:	Network connections
Technology Type:	Storage
State/Territory:	TASMANIA

Key learning

The algorithms household battery systems must interact with as part of the CONSORT trial (NAC, reward structures, and the standard Reposit controls) are technically complex and make assumptions about how householders live and what they require from energy. The success of the algorithm, we have learnt, requires customer participation. When developing and implementing algorithms and related customer engagement strategies it is important to consider the overall context and technical system the algorithms exist within. In effect, the algorithms need to function in a way that fits in with how households use their systems and their energy loads. Householders may have need for additional, unexpected energy use on certain days that cannot be patterned by an algorithm, and emergencies may arise, like bushfire or floods, which may require intermittent and unusual responses from the system. Customer management, engagement, retention and participant numbers need to be considered explicitly in the design of the orchestration algorithms. It is easy to create an environment too complex for the customer to manage or that is misaligned with householder needs and priorities. This clash with orchestration of batteries may cause customers to become dissatisfied or opt out of participation.

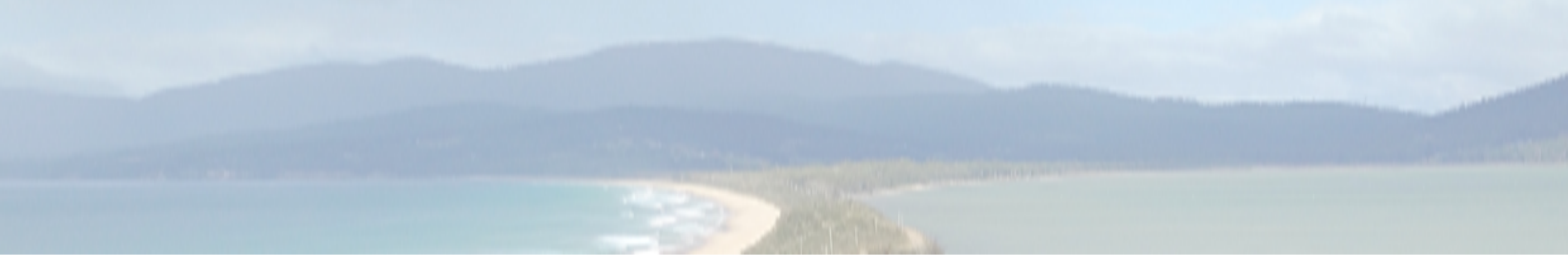
Implications for future projects

Customer engagement, management and retention need to be considered explicitly in the design of the orchestration algorithms. A relatively smooth customer experience is critical for success, as they are the ultimate providers of the service the algorithm is orchestrating.

Process Undertaken

Within this project this issue was managed across the project team:

- The social science team measured and reported on issues as they arose during the research (communicating on households' behalf where necessary or requested);
- TasNetworks resolved issues, provided information, and were first point of call for issues where responsibility was unclear;



- Reposit Power resolved technical issues for customers about the Reposit hardware and provided information and training on the use of their software; Installers resolved issues with installed hardware; and
- The rest of the project team provided information and guidance where required.