1-USO032 Plug and Play Solar

Project results and lessons learnt

Lead organisation:	Commonwealth Scientific and Industrial Research Organisation
Project commencement date: 7th January 2013	**Completion date:** 7th April 2017
Date published: 10th March 2017	
Contact name:	Chris Knight
Title:	Project Leader
Email: Chris.Knight@csiro.au	**Phone:** +61 2 4960 6049
Website:	www.CSIRO.au

Summary

The rationale for the Solar Plug and Play Project was to simplify the integration, accelerate the deployment and lower the cost of incorporating solar energy with more traditional non-renewable generation to deliver greater reductions in CO_2 emissions. These outcomes were particularly targeted at remote area power supplies (RAPS), but are equally applicable to any scale of off-grid or fringe-of-grid power.

The key pieces of technology to allow this to happen are reliable forecasting of expected solar output, a process to decide the appropriate response to any predicted variation in solar output, and linkages to integrate this decision with on the ground hardware.

What this means for the Solar Plug and Play project is the use of a skyward facing camera to capture periodic images of the sky, integration of algorithms to turn these images into a short term prediction for the next 15 minutes, and decision-support software to turn these predictions into sensible scheduling for any stored energy such as batteries, or energy production such as diesel generators. Linked with this are decisions to curtail output from solar generation as a means of smoothing any step changes in solar energy.

The project began in January 2013 and over the 4 years until December 2016 concentrated on 4 main activities. The first activity was the Plug and Play system design, definition and development, which culminated in the testing of various modules in the CSIRO Renewable Energy Integration Facility.

Activity 2 focussed on the grid management system, and included an evaluation of current commercial options in the grid management space. This activity culminated in a successful test phase of CSIRO control algorithms with solar forecasting signals, at the NREL test facility in Golden, Colorado.

Activity 3 was directed at developing and deploying a prototype system. This activity focussed on deployment at two Australian sites, supplementing laboratory testing at CSIRO and NREL. These sites were at Weipa in far North Queensland and Port Hedland in Western Australia. Deployments to both of these sites were completed in early to mid-2016 with testing continuing until November 2016. Both sites still have equipment deployed and data collection is ongoing to allow further model development. This activity led directly to the fourth activity which is the analysis of results of the two test sites.

Together, these two sites offered a great opportunity to test the performance of the CSIRO developed hardware. For example, analysis of data collected from the site at Weipa showed that a 97% reduction in the number of high ramp rate events can be obtained using CSIRO's solar forecasting algorithm, down from 490 events during the test period to just 13 events. This implies that a higher penetration of solar power can be achieved without the need to upgrade the existing diesel generator set to compensate for such high ramp rate events. A reduction in high output power ramp events of the existing diesel generators would be desirable as this may reduce the wear and tear on the generators leading to increased time between required maintenance, which can lead to financial savings.

Project Overview

Project summary

Hybrid renewable energy systems combine renewable generators, such as solar photovoltaics and wind, together with more conventional, non-renewable sources such as diesel or gas generation. Often some form of energy storage is also incorporated. This can take various forms, including intelligent building HVAC, ice storage, hot water storage or chemical systems like batteries. These integrated systems play an important role in the journey toward a lower carbon electricity system but they are subject to two key barriers: cost and technical complexity.

This project addresses these key barriers by developing a 'plug and play' (PnP) technology that allows more efficient use of key technical components like solar generation, energy storage, and traditional energy sources through dynamic configuration of the control systems. This will reduce the need for extensive retrofitting, ongoing expert user intervention which are costly and inconvenient. This problem is particularly pressing in remote area hybrid systems such as those in Western Australia, Far North Queensland and the Northern Territory where travel times and costs for people and equipment are significant, and fossil fuel supply is expensive, due to the large distances involved.
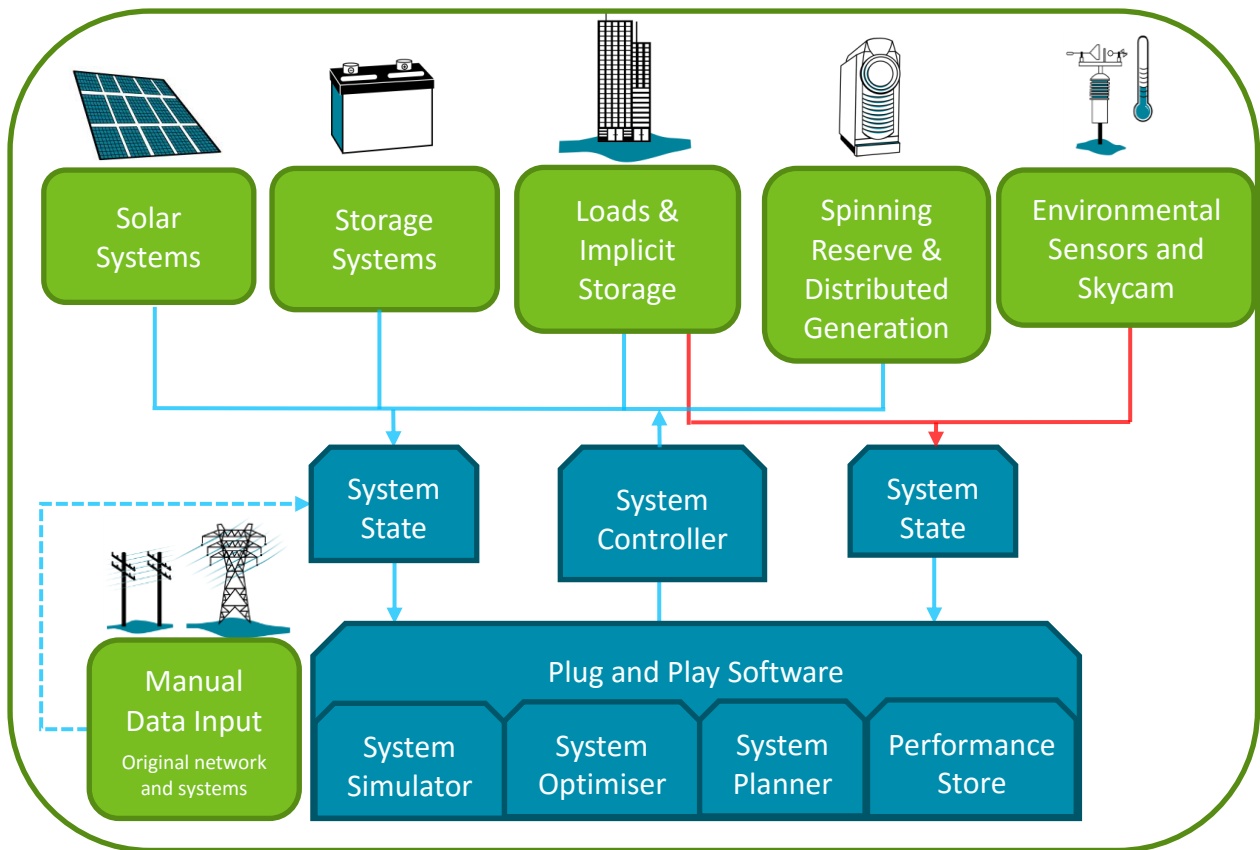
For this project, CSIRO collaborated with US research partner the U.S. National Renewable Energy Laboratory (NREL) and multinational engineering firm ABB. NREL has extensive experience in energy systems research, testing and the development of planning technologies to help grid designers and renewable energy proponents. This experience includes the development of the HOMER energy modelling software platform, a powerful tool for designing and analysing hybrid power systems. ABB is a multinational supplier of equipment and services to the global electricity industry and is a leader in developing power and automation technologies that enable utility and industry customers to improve performance while lowering environmental impact.

Hybrid distributed generation systems are those that incorporate renewable energy (such as solar power) in addition to conventional generation, typically where generation and load are co-located.

Often, these systems are considered in the context of remote area power systems (RAPS) but hybrid grids also include 'town size' solar-diesel and solar-gas systems and, increasingly, describe major electrical grids such as the National Energy Market (NEM) and South West Interconnected System (SWIS).

Concerns about solar penetration approaching or exceeding a grid's 'hosting capacity' have prompted grid operators to impose additional requirements on new solar PV systems. Such requirements need to be carefully developed to ensure they do not reduce the incentive to increase solar deployment in areas of greatest potential benefit - principally where the cost of supply is greatest.

The basic architecture of the Plug and Play system is shown in Figure 1. A variety of hardware is shown, and this is typically already part of the deployed system. The addition of the skycam hardware allows predictive forecasting of solar energy availability.

Figure 1. Solar Plug and Play architecture

The goal of many remote power system operators is to minimise the cost of conventional generation fuels while maintaining system reliability. A high penetration integration of renewables can help achieve this but is complicated by the intermittency of those renewables. There is a clear benefit to operators in reducing fuel costs, providing greater resilience in the face of sporadic fuel supply and improved CO_2 impact, if the predictability of renewables can be improved and this information integrated into the generation & load management systems.

In addition to this potentially 'transactable' value, solutions developed in this environment may very well be applicable to national grids as the amount of distributed generation increases and conventional grid generators become analogues of diesel and gas generators in hybrid power systems.

Key Project Technologies

As part of this project CSIRO has developed and integrated three key technologies; solar forecasting, load management and a planning tool for high renewable penetration power systems.

Solar Forecasting – Skycam technology

Solar power output has an intermittent character due to atmospheric effects such as insolation variability resulting from cloud movements. Variations also occur due to diurnal patterns and physical shading. Accurate solar forecasting is therefore a highly beneficial information source for the successful integration of large amounts of intermittent solar generation in Australian electricity networks. Accurate

solar forecasting enables variability to be managed and enables optimal matching of solar supply and electrical demand in applications employing energy storage or load control. System operators and planners already use load forecasting as one of the mechanisms to ensure infrastructure levels are sufficient to satisfy reliability standards and similarly, the introduction of solar forecasting potentially provides energy distributors, energy retailers and solar operators with an opportunity to achieve a better understand of Australia's solar resource and how to exploit it.

Load Management

In order to better understand load management requirements, CSIRO explored typical load profiles across different system sizes. Aggregate network loads for large systems can be reasonably stable and predictable, despite device switching and sporadic individual usage. When embarking on load management, loads can be broken into:

1. **Fixed loads** – the power consumption and time of operation of these loads cannot be changed – such as running a ventilation fan or watching a television show;
2. **Controllable Loads** – loads where there is some scope for changing run times and power levels in response to the needs of the plug and play system. This can include loads such as 'off-peak' water heating, air-conditioning and refrigeration where thermal energy storage exists. Pumping loads can often be shifted and rescheduled forward and back with reasonable flexibility however loads such as lighting and air-conditioning are often only adjustable up or down to reduce demand - through dimming, cycling or set-point changes.

The Network Planning Tool

CSIRO has developed proof-of-concept integrated decision support software for the design of high-penetration renewable systems. The software brings together leading energy systems design tool HOMER and the powerful OpenDSS power-flow suite to explore the network-level performance of potential energy solutions. The key technological advancement here is the development of interfacing systems that allow for the efficient translation of HOMER outputs into the OpenDSS platform – a process that would otherwise be laborious and manual. The result is an improved work-flow that enables a more rapid transition from initial high-level planning and to deeper network modelling that considers generation placement and network losses.

Project scope

This project sought to simplify the integration, accelerate the deployment and lower the cost of solar energy in hybrid distributed generation applications by creating technology which is capable of planning, optimising and operating these systems. The project's technology was developed to assist system developers, owners and operators by simplifying the process of implementing, expanding and operating solar hybrid systems and enabled a reduction in cost and complexity by reducing the requirement for on-site specialised labour, reducing connection time and associated outages.

The key problems addressed by the Plug and Play project were those associated with reducing system cost, enabling higher solar performance in hybrid grids and increasing the uptake of solar power. At the planning stage the developed software can help by reducing the need for complicated and protracted integration studies, commissioning and system modifications. During operations the

improved performance, both in terms of reduced fuel usage and reduced high ramp rate events, drives down the cost of onsite skilled labour and maintenance hardware costs. This problem is particularly pressing in remote area hybrid systems, such as those in Western Australia, Far North Queensland and the Northern Territory where travel times and costs for people and equipment are significant due to the large distances involved.

The key elements that the project sought to develop were around short term solar forecasting, diesel and battery scheduling, network planning tools, and load management. The integration of these elements allows a project to be planned with higher performance certainty with reduced project risk `in order to lower financing costs and improve capital availability – reducing system cost and increasing the uptake of solar power

The project was initially a partnership between the US National Renewable Energy Laboratory, ABB Group, HOMER Energy and CSIRO. In the last 12 months of the project, and continuing after the project completion, further partners were added as test beds for the technology. These were Energy Made Clean Pty Ltd and the Pilbara Meta Maya Regional Aboriginal Corporation (Port Hedland, Western Australia) and Weipa Solar Farm Pty Ltd and Rio Tinto (Weipa, Queensland). These two sites were used as test beds for the core solar forecasting hardware.

Outcomes

Project Outcomes were:

- A prototype plug and play technology system
- A configurable system for the real-time operation, optimisation and control of minigrid energy systems, utilising solar forecasting inputs and computational intelligence techniques
- Two operating prototype plug and play solar power systems in Australia
- A market potential report outlining next steps to commercialisation
- A research alliance formed between CSIRO and ABB to undertake this project
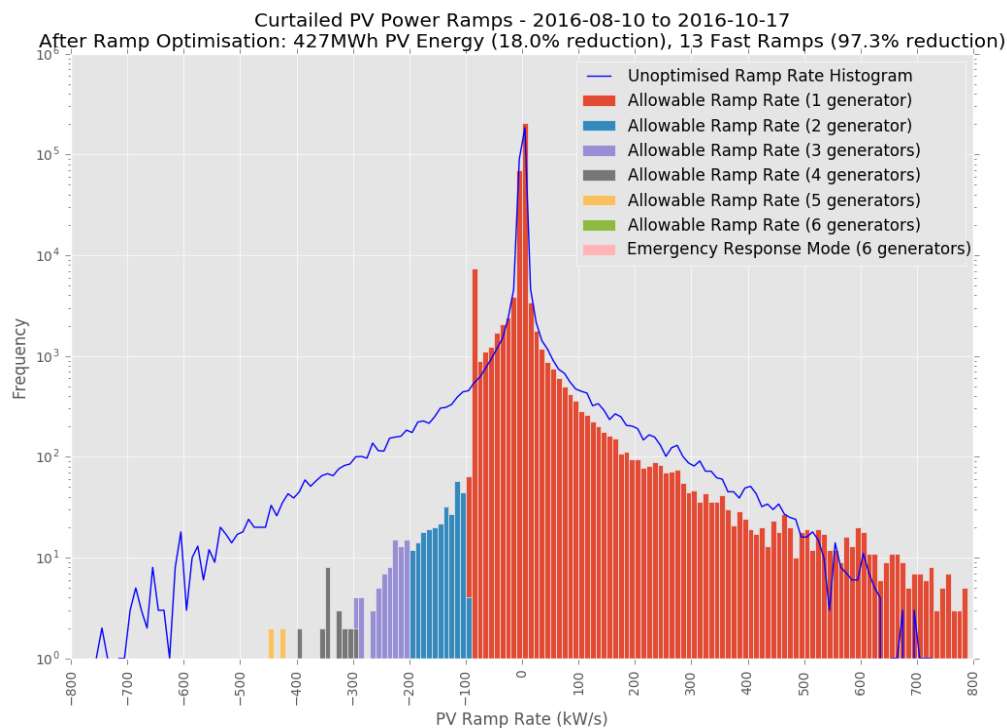- Significant research cooperation experience between CSIRO and NREL

The early part of the project consisted of system specification and analysis of existing hardware for control of minigrid components. This allowed a research alliance between CSIRO and ABB to develop. A number of components were tested, improved and further developed. These items were thoroughly tested in the CSIRO Renewable Energy Integration Facility (REIF), Newcastle Energy Centre. Further testing was also undertaken at the National Renewable Energy Laboratory (NREL), Golden Colorado. This testing allowed a significant research cooperation to develop between CSIRO and NREL, which has resulted in further collaboration on various projects.

As the testing moved to real world locations, we were unable to identify suitable test sites, with the specific hardware, in either Australia or the US. After further discussions with Energy Made Clean (EMC) and First Solar Australia, two test sites were found and our prototype hardware was installed.

This system collected solar and cloud data from the test sites in Western Australia and Queensland. This data was then analysed and predictions made of short term solar resource. These forecasts were then used to provide real-time operation, optimisation and control of various minigrid energy components, principally diesel and battery set points and solar PV output power settings.

The system performance testing in Australia, utilising the REIF laboratory, and in the US at the NREL facility, allowed an excellent opportunity for debugging and error checking the hardware and software interactions. This initial phase was critical in developing a body of knowledge for system operation. Onsite testing at Weipa and Port Hedland allowed collection of real world data which was then used to train the forecasting algorithms and set point decision systems. Both laboratory and in field testing of forecasting systems were critical in advancing the technology and improving system commercial readiness.

One of the surprising outcomes was how much our technology was able to reduce high ramp rate events. High ramp rates are seen in the diesel generators as they respond to rapid load changes and rapid solar energy changes. As should be expected, diesel generators have a maximum ramp rate that they can respond at. Additionally, though the generators *can* respond at that maximum ramp rate, there is a penalty in terms of both fuel consumption and increased maintenance due to these events.

Figure 2. Histogram of 10-second upward and downward solar ramp rates observed at Weipa, categorised by ramp capabilities of increasing number of generators, after optimisation by Skycam forecast ramp reduction algorithm.

As can be seen in Figure 2, the CSIRO algorithms were able to predict upcoming high generator ramp rates (due to solar generation decreases) and respond by pre-emptivly rolling off the PV output to reduce the magnitude of the event. Noting that the Frequency axis is logarithmic, the total reduction in the nominated 2 month period for high ramp rate events was 97% (from 490 events to 13).

As part of the project CSIRO contracted an independent industry analysis, Navigant Consulting, to prepare a research report on the likely impact of solar forecasting on microgrids. One interesting statistic out of their research was the impact of technologies like solar forecasting on aspects like fuel savings. As can be seen in Table 1, even with moderate impact of the technology the cumulative diesel savings to 2025 exceeds $330M.

Table 1. Cumulative Diesel Displacement, Solar PV Additions and Fuel Savings Impacts, Moderate and Aggressive Scenarios, Australia: 2017-2025

Australia	Cumulative Diesel Displacement (2017-2025)		Cumulative Solar PV Additions (2017-2025)		Cumulative Fuel Savings (2017-2025)
Units	TWh	MW	TWh	MW	($ Millions)
Moderate Impact	0.825	135	0.825	438	330.3
Aggressive Impact	1.651	269	1.651	877	660.6

(Source: Navigant Research)

Transferability

The key technologies created in this project are applicable to other sites. As this project was developing CSIRO took the opportunity to explore uses of the developed technology with other partners. Some of these discussions have developed to a deployment stage, with others at various stages of pre-deployment. We are confident that these will develop further and new opportunities will be found. The existing tests sites fully identified and with hardware deployed or nearing deployment are:

- Defence facilities
  - o The CSIRO have deployed technologies outlined within the Plug and Play project at two Defence facilities in the Northern Territory. The deployment sites area classed as running microgrids within Remote Area Power System (RAPS) environments.
  - o A further 3 Defence sites have been scoped for deployment in the future.
  - o The stage 1 aim of these deployments is to advise on battery storage and PV solar systems rollout and installation. Stage 2 is to implement the plug and play technology and manage and provide short term solar energy prediction to aid in the demand response algorithms controlling the installed hardware.
- Virtual Power Station 2 (VPS2) trial, Yarrabilba.
  - o The Virtual Power Station 2 trial is a co-funded CSIRO/ARENA project in the Lend Lease housing development in Yarrabilba, SE Qld. This trial site consists of 67 houses with a range of controllable hardware including air-conditioning, battery storage and PV solar systems. The Plug and Play project is installing 2 cameras on the site which will be used to provide short term solar energy prediction to aid in the demand response algorithms controlling the installed hardware.
    In this location accurate short term predictions will allow the VPS2 project to expand

on the useful output of the overlaying demand response trial and improve power quality in line with the new AS/NZ4777 Demand Response standard.

- A number of other sites that are in early discussion phase across Australia within minigrid and large scale solar farm environments.

As part of the dissemination strategy, CSIRO communications will be using our social networks, principally Facebook and Twitter, to communicate the key outcomes from a public perception view. In addition to these, there are technical and scientific communication activities. Some of these have been completed and others are planned for the early to mid-period of 2017. These include:

- **International Microgrids Symposium, Niagara-on-the-Lake, 20-21 October 2016**

This invite-only, international symposium is held annually, and for 2016 was held in Niagara, Canada. The symposium attracts researchers from around the world to present their work on microgrids. Two Solar Plug and Play project team members attended this conference. Dr John Ward presented on Australian Outback Microgrids, and chaired a session on challenges to a renewable energy based microgrid.

In his presentation, John outlined details of who CSIRO is, some background of Australian microgrids, and details of the Plug and Play Solar project, including preliminary results.

In addition Dr Saad Sayeef chaired a session on the challenges of solar intermittency remote microgrids, and introduced the location of the 2017 Symposium.

- **International Microgrids Symposium, Newcastle, November 2017**

In an excellent outcome for the industry in Australia, the location of the 2017 symposium was announced as Newcastle, NSW. This represents a great opportunity to present a number of outcomes from both the ARENA Plug and Play project, sky camera work, diesel optimisation results, and of course detailed results from both the Port Hedland and Weipa sites, which will have 18 months of data to work with. This is also a great opportunity to showcase and share with international microgrids research experts the progress and current status of Australian microgrids, considering the unique nature of our climate, electricity networks and population density.

In addition to this, the symposium local organising committee is made up of four Plug and Play team members, Saad, John, Dr Adam Berry and Tim Moore.

- **3rd Annual Remote Area Power Supply Conference, 22-23 March 2016, Melbourne**

Saad presented preliminary work from the Solar Plug and Play project at the 3rd Annual RAPS conference. His presentation was titled Bringing the Smart Grid to RAPS.

- **4th Annual Remote Area Power Supply Conference, 21-22 March 2017, Sydney**

Saad has also been invited to attend the upcoming 4th RAPS conference to be held in Sydney in early 2017. This represents another great opportunity to broadcast the outcomes from the Solar Plug and Play project.

As a final note, the Solar Plug and Play Project has been a major piece of work for CSIRO over the last 4 years. Although the project had no specific Knowledge Dissemination requirements it should be clear from the items above that ongoing presentations of the key outcomes of the project will continue.

Conclusion and next steps

After four years, the ARENA Plug and Play project has drawn to a close. The project was initiated to focus research and practical effort on maximising renewable energy, in remote area power supplies. It should be noted from the scale of the project's tests sites that the technology is also applicable to larger scale off-grid and fringe of grid applications.

Recent success in integrating large and increasing amounts of PV into fringe of grid applications has revealed problems in stability of those grids as solar intermittency impacts in short time frames. The approach explored in this project was to develop from existing CSIRO expertise a combination of network planning, solar forecasting and demand management tools.

CSIRO has developed decision support software for the design of high penetration renewable energy. Key to the success of this is the development of interfacing systems between the global standard for microgrid design, HOMER, and the powerful OpenDSS power flow software. The outcome of this is a fast transition from planning to network modelling.

The solar forecasting was completed using inexpensive hardware, based on sky facing cameras, coupled with highly optimised and developed algorithms to detect cloud edges and provide accurate and timely forecasts of impending solar energy changes.

Demand management tools were based on CSIRO developed algorithms initially deployed in the building heating, ventilation and air-condition space. This software use historical data, weather forecasts and learning algorithms to develop high level predictions of building loads, and optimised data for decision making.

These key technologies were integrated into hardware that was initially tested at the CSIRO Energy Centre, Newcastle. The Renewable Energy Integration Facility used its various power sources, including PV and gas turbines, and controllable loads, to test the developed hardware.

This same hardware was then put through further testing at the National Renewable Energy Laboratory (NREL), to evaluate the ability of the Plug and Play control system to provide stable and reliable operation of a microgrid, with suitable power quality at every source and load. The results of these two phases of testing revealed success in limiting or mitigating high ramp rate events, such as cloud shadowing of PV installations.

After this testing CSIRO was able to partner with two remote sites to provide preliminary real word testing of the system. The first site was in Western Australia at Port Hedland. This was at the Pilbara Meta Maya Regional Aboriginal Corporation office. That site has approximately 100kW of PV, a 110kVA diesel generator and a 77 kWh lithium battery.

The second site was a remote Queensland bauxite mine at Weipa operated by Rio Tinto, with an associated PV farm operated by First Solar Weipa. This site was much larger and had 1.7MW of installed PV panels and six 5.5MVA diesel generators. Together these two sites offered a great opportunity to test the real world performance of the CSIRO developed hardware. Due to the operational nature of both sites, we were not able to fully control the grids. However, the data collected during the trials has been used in this report to generate predictions of outcomes from the solar forecasting in energy production and grid stability.

Perhaps of all the outcomes, the reduction in high ramp rate event is the most revealing. High ramp rate events come about when the diesel generators are obliged to replace PV generated power on short notice. Typically this is due to shading events. The specification of the diesels provides a limit on how quickly the generator scan ramp up to replace the lost load. High ramp rates are hard on the mechanics of a generator and thus a reduction in these is of great benefit.

At Weipa, in the test period, there were 490 of these fast ramp events, our algorithms were able to forecast the incoming solar loss to an extent that reduced these ramp rates by more than 97% to just 13 events.

At Port Hedland, our analysis saw the potential for reduction in fuel consumption of up to 7.8%, as well as a reduction in the number of generator starts of up to 36.1%.

Lessons Learnt

Lessons Learnt Report
Optimising does not always reduce fuel usage

Knowledge: Technical
Technology: Solar PV

In order to properly evaluate the value-add of Plug and Play Solar control to the Weipa power supply system, we must be able to determine an approximate fuel consumption based on the expected operation of the diesel generators. MAN, the manufacturer of these generators publishes the expected fuel-oil consumption of a new unit at specific load-points. The best-fit polynomial for these parameters, based on fuel-oil consumed per unit time, can then be calculated.

While these parameters can only give a broad estimation of the fuel used by a diesel generator in dynamic operation, it is expected that it would suffice for the purposes of this evaluation. However as Rio Tinto was able to supply us with actual fuel consumption data it is of course worthwhile to validate this estimation algorithm against these values.

The diesel usage estimation algorithm was run over the full dataset of diesel data provided by Rio Tinto, resulting in the following:

- Total fuel used during the analysis period: 3,600kL (approximate)
- Fuel usage from estimation algorithm: 3,800kL (approximate)
- Over-estimation: 5.5%

While clearly not perfect, it is within the bounds of a reasonable estimate – as such it is acceptable to use this to estimate a likely change in fuel usage based on proposed control modifications. Note that at all times the diesel estimation algorithm will be used for calculating fuel consumed for both the 'control' and the modified operations, to ensure we're "comparing apples with apples".

Skycam based imagery was used to produce a 1-minute ahead forecast of solar power production by training a machine learning regression model using measured power produced by the Weipa solar farm during the first half of the 4-month data set available. The second half of the data was then used for validation and optimisation to mitigate the effect of fast downward solar power ramps on the diesel generators, which are required to ramp up to compensate but are limited in their ramp rates.

The ramp rate limits generator's operating manual for the generators in use, and specify the maximum upward (load acceptance) and downward (load reduction) loading per 10-second interval (to match the resolution of the skycam forecasts). Over the period examined, it was rare for fewer than three generators to be running simultaneously, so we considered a load acceptance rate for three or fewer generators to be desirable during optimisation. The optimisation process can be easily run with new figures for different operating conditions or for other sites.

Figure 3 shows an example of the skycam forecasts for a short period to illustrate the ramp-rate reduction algorithm. The Skycam forecasts are shown as a dark green line, which is surrounded by three confidence interval bands: 90%, 75% and 50% intervals shown as light, medium and dark green shading respectively. Two cloud-caused ramp events are shown, beginning at around 15:12 and 15:22, can be seen as sharp decreases in measured PV power (solid blue line). Both ramp events are detected with sufficient warning time to take action to mitigate the speed of the downward ramp in solar power production.

The action taken by the predictive ramp optimisation algorithm is to begin reducing the solar inverters' output an acceptable rate (slightly less than the maximum rated upward ramp-rate of a single generator in the genset) whenever the forecast predicts a downward ramp that exceeds the genset's ramp rate capabilities. This produces a new PV power setpoint that inverters can follow by pre-emptively reducing their output in advance of a cloud-caused downward ramp. This new inverter setpoint is shown as a dashed blue line in Figure 3.

The first event (at 15:12) is was predicted accurately, and the inverter setpoint was able to mitigate the ramp event very efficiently, by reducing output just in time, without curtailing more than necessary. The second event (at 15:22) was smaller than expected by the forecast, which meant that the inverter setpoint was reduced earlier than necessary, successfully avoiding the fast ramp event, but curtailing more power than necessary. This is caused by the algorithm having settings causing it to tend toward being more conservative – preferring ramp mitigation over maximising solar energy output. These settings can be adjusted to suit a particular site, and will change the level of trade-off between maximising ramp mitigation and maximising solar production. The results below are for only one of a range of possible customisable settings.
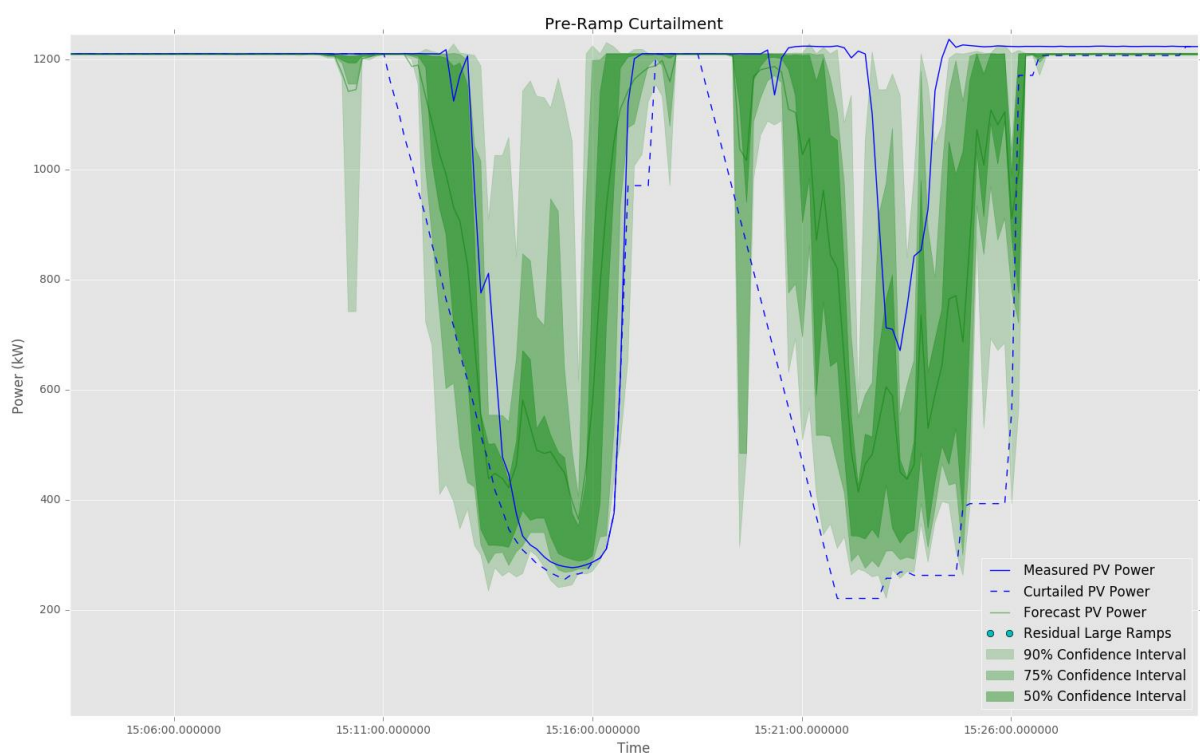

Figure 3 An example Skycam-based solar forecasts, with pre-emptive ramp-rate reduction.

Figure 2 shows a histogram of solar ramps for the same period, but after the PV output has been curtailed using the predictive ramp optimisation algorithm illustrated in Figure 3 and discussed above. The blue line shows the observed (unoptimised) ramp histogram for comparison. This result shows that the predictive ramp optimisation algorithm combined with skycam forecasts has reduced the number of large ramps (requiring 4 or more generators to compensate) from 490 to 13, a 97.3% reduction, with no ramps that were beyond the response capabilities of the genset remaining. This was achieved with only an 18% curtailment in solar energy production, which was reduced from 521 to 427MWh over this period. There was a slight increase in upward ramps because the optimisation algorithm does not yet implement any upward ramp rate limits, but these are still well within the rate capabilities of a single generator, and this can be easily corrected in future development. There was also an increase in downward ramps at around 95kW/s, as this was the rate chosen for the pre-curtailment PV power set-point, and is within the capabilities of a single generator.

The above curtailment is a clear improvement in terms of increasing stability, however it is important to determine the cost in diesel fuel (and hence fuel-cost). To calculate likely fuel costs, the diesel-estimation method described above was run on both the actual power profile of the diesel generators for the analysis period, and on the same data with any PV lost due to curtailment spread equally across all diesel generators currently running.

The above diesel-split calculation, combined with the fuel-estimation method described previously, was run over the curtailed-PV dataset to determine the additional fuel that would be consumed by pre-curtailing PV to reduce fast ramping. The results are shown in Table 2 below:

Table 2 Change in diesel consumption with pre-curtailed PV

Scenario	Diesel consumed (kL)	Increase in diesel usage (%)
Actual operation	3,000	N/A
Pre-curtailment	3,021	0.7

Given the scale of the reduction in high ramp events, an estimated increase of less than 1% of diesel fuel consumed is likely to be considered quite a worthwhile trade-off for improved stability.

Lessons Learnt

Lessons Learnt Report
Impact of Battery Sizing on System Operation

Knowledge: Technology
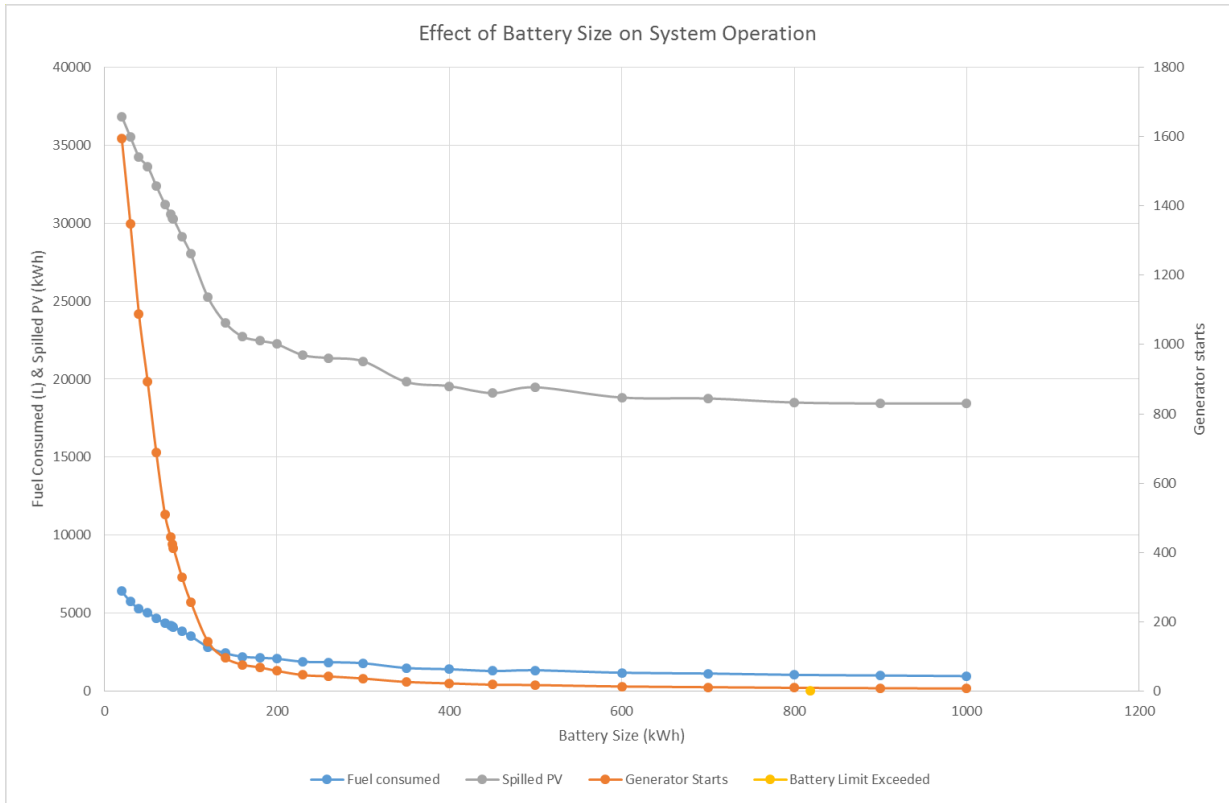**Technology: PV/Battery Systems**

The Energy Made Clean site in Port Hedland has a 77kWh battery. During the planning process for the site, various energy components were analysed to optimise the size of the generator, PV modules and the battery system. With the benefit of the data we collected it is worthwhile validating these decisions against the dataset to determine whether a different sized system may be more beneficial for the site. In particular the battery system is a key component to maximising use of solar generation, but is also a very substantial capital cost.

A number of simulations were performed with a range of battery sizes, to determine what impact the battery size has on the diesel fuel consumption, total count of generator starts, and amount of spilled PV; a broad subset of these results of this are shown in Table 3, with the full trend being shown in Figure 4. Each of these simulations used the 5-minute minimum run-time (with the standard hysteresis settings) as a baseline for comparison.

It is also noteworthy that the real system has been designed to minimise both diesel operation and capital costs in terms of battery sizing. This has resulted in a smaller than typical battery, but quite a large PV system. In practical terms, on days when solar resource is high, the battery may reach its maximum state of charge quite early in the day; at this point any additional solar PV excess to that required by the load is 'spilled', or wasted. As the cost of batteries is reducing substantially in recent years, an analysis has been performed to determine how much of an impact varying the battery size could have on both the amount of PV energy spilled and the operation of the diesel generator in terms of fuel consumed, number of starts and average run-time.

Table 3 Impact of battery size on Meta Maya system operation, Mar-Oct 2016 (also see Fig 6)

Battery size (kWh)	Fuel consumed (L)	Generator Starts	Excess PV spilled (kWh)
30	5,754	1348	35,521
76.8 (actual system)	4,214	444	30,568
100	3,540	258	28,034
140	2,439	96	23,610
200	2,088	59	22,246
300	1,802	37	21,152

Figure 4 Sensitivity of Meta Maya system operation to battery size

It can be seen that there is a general trend as battery size increases to utilise greater amounts of PV energy (and hence spill less excess), to consequently use less diesel fuel, and to need to start the generator less often (although understandably these runs would be for longer periods of time, in order to charge up the larger battery). There does appear to be something of a knee-point in both the PV-penetration and generator-start curves around 140kWh – further increasing the battery size beyond this appears to have a substantially reduced impact on these metrics.