Project FALCON
Energy Storage

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FALCON

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Executive Summary

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), and the introduction of new demand technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas.

WPD's Project FALCON has examined a range of innovative alternatives to conventional reinforcement that might be used to mitigate the impact of such energy usage. This was undertaken firstly through physically trialling four engineering and two commercial techniques. Secondly, innovative alternatives where examined through building and operating a software tool. This tool: models the real network under a range of energy use scenarios out to 2050; identifies network constraints that arise over time; employs the studied techniques to mitigate constraints; and assesses impact and benefit.

This report is one of a series describing the engineering technique trials, and focuses on energy storage within networks. The five energy storage units (converter with battery module) were connected at existing substations on a single 11kV feeder from Fox Milne Primary substation. Each site contained a 50kW/100kWh energy storage (sodium nickel) battery (with battery management system) and a 100kVA rectifier/inverter unit.

High level results from the ES trials are that:

- Peak-shaving at individual sites was repeatedly achieved, and combined ES systems discharge also reduced the peak at 11kV feeder level over successive days of high winter demand periods;
- Manufacturer set-points of 50kVAr resulted in limited measurable voltage response impact on LV voltage;
- ES was found to increase losses in aggregate (considering both feeder I^2R losses, and ES system losses);
- Frequency response was demonstrated (for both above and below 50Hz);
- PQ was improved at one site (highly circumstantial), though not at the other more representative monitored site;

Whilst energy storage has been shown to improve network capacity headroom over peaks, the experienced costs within the trial are high. In view of the reductions that have already occurred in energy storages prices, and that further reductions are anticipated, it is recommended that technology tracking in this area is carried out, to monitor for key changes in: capability/cost; practice of connected customers downstream of the meter; and development in market practice (including second-life batteries). A follow on project investigating the interfacing, metering, control and energy management of multiple customer battery units operating to provide capacity headroom at a feeder in conjunction

with frequency support (to provide an income stream outside of this) would assist with accelerating remaining operational issues of energy storage within the grid. However, in view of the changes in technology, it is recommended that this is undertaken in conjunction with a mixed set of battery technologies, so that impacts of different battery chemistries can be investigated in regards to energy management and aging in multiple operating modes.

SECTION 1

Project Introduction[1]

[1] This introduction to Project FALCON (Flexible Approaches for Low Carbon Optimised Networks) is common to all the engineering technique Final Reports.

With the growth in all types of low carbon generation, such as wind and solar photovoltaic (PV), coupled with the introduction of new technologies such as electric vehicles (EVs) and heat pumps, Western Power Distribution's (WPD) electricity network is expected to see unprecedented swings between peaks and troughs of energy usage in localised areas. This expected change in nature of customer demand and electricity generation will have an impact on networks nationwide and globally, and provides a significant challenge to WPD, and all electricity network operators.

Part of Western Power Distribution's (WPD) approach to this challenge has been to look at new and more flexible ways to design, optimise and manage the network in the future. Project FALCON (Flexible Approaches to Low Carbon Optimised Networks) is designed to help answer these questions and is focussed on the Milton Keynes area 11kV network.

In the past, network operators have used conventional reinforcement to deal with constraints. However, this approach can lead to the solution being over engineered to meet only peak demands; it can also be expensive, disruptive and inefficient. In project FALCON, WPD and its partners trialled alternative techniques and assessed if they were more flexible, more cost effective, quicker to deploy and more effective at managing these new demand requirements than conventional reinforcement. The techniques are:

- Dynamic Asset Ratings – Using prevailing weather conditions to run an asset at a rating potentially higher than its name plate to take advantage of, for example, cold temperatures.
- Automatic load transfer – load is redistributed between 11kV feeders.
- Implementation and operation of a meshed (interconnected) 11kV network.
- Deployment of new battery technologies allow the flow of power on the network to be changed as the battery is charged or discharged.
- Demand Response services - the use of localised smaller generation and load reduction services that can be provided in the event of a local constraint.

Central to the project is the Scenario Investment Model (SIM) - a new piece of software being developed to assist long term network planning. The SIM performs load flow analysis for the network for 48 half-hourly periods during the day for different days of the week and different seasons of the year. Predicted load patterns extend as far as 2050. A network planner will operate the SIM to help with planning based on load forecasting. When a network planner is running the SIM and a voltage or thermal problem is found, the SIM will select the techniques that could help resolve the problem and determine how they could be applied to the network. The best solution can be selected using a weighted metric that combines elements such as installation and operating costs, network performance, losses and disruption to customers.

This report presents the work undertaken through project FALCON on the addition of energy storage to the 11kV Network.

SECTION 2

Introduction to Technique Trial

2.1 Presentation of Learning

Learning Objectives originally associated with this technique are listed in Appendix B Throughout the document, key learning is presented in a box as follows:

LP #	Brief description of learning.

Each piece of trials feedback is referenced as a Learning Point (LP) with a unique number.

2.2 Overview of technique

The Energy Storage trial looked at understanding the implementation and operational capability of installed battery energy storage connected at existing substations on a single 11kV feeder from the Fox Milne Primary substation. The potential benefits that may be expected when considering energy storage within an electricity distribution network include:

- Improved capacity margins,
- Increased penetration of distributed generation,
- Deferring network reinforcement by reducing peak loads in branches of the network (above the point of battery connection), where the unmodified peak loads would ordinarily have approached or exceeded effective circuit capacity,
- Power quality and phase balance improvements through active filtering that counters harmonic distortion, and prioritises output to more lightly loaded phases,
- Provision of frequency response and other ancillary services by utilising the stored energy outside times of peak load (primary purpose).
- Improvements in control of voltage at the point of connection;

However, batteries in particular have specific operational drawbacks and limitations that include:

- Any reduction in the peak circuit loading is heavily dependent on the prevailing shape and duration of load peaks (e.g. short sharp peaks vs. long relatively flat peaks), the power rating and capacity of the energy storage system and the strategy used to trigger the start of energy output;
- Worsening of network power quality due to the connection of power electronics;
- An operational life that is dependent on the pattern of usage (e.g. repeated high depth of discharge operation).
- Provision of land;
- Operating noise;

- Overall system efficiency;
- Construction costs; and
- Operating costs (maintenance, plus the net cost of electricity for commercial services)

The aim of the trial was to operate a trial 11kV feeder with battery/inverter units installed at five LV substation locations and explore:

- Baseline operation of the LV substations and HV feeder without operation of the energy storage units;
- Peak lopping and trough filling using demand forecasts;
- Voltage response;
- Frequency response;
- Impact on power quality;
- Specific operational circumstances, for example, response to circuit fault/disturbance.
- Reliability and degradation

Additional objectives included

- Investigating optimum charge and discharge windows
- Available triggers for charging regime
- DNO connection requirements for ancillary grid service operation
- Best placement of storage on the system
- Changes to battery condition over the course of the operational trials
- Integration of ESSs with existing control environments
- Improvements for equipment specifications
- Support for UK-wide Good Practice Guide

The documented learning objectives from the design phase of the project are catalogued in Appendix B.

In order to undertake this trial investigation the following activities were undertaken:

Operation of the assets within the trial consisted of a series of periods with the system operating in key functional modes, these highlighted and examined: basic charge and discharge operations (including audible noise, and weekly maintenance/calibration); peak-shaving functionality, both at the local Distribution substation and on the host 11kV feeder; reactive power/voltage response; real power/frequency response; and impact on power quality. Predominately these operations were conducted remotely via Microsoft Remote Desktop Connection to the (Windows-based) ES Site Controller, over the FALCON Trial Communications Network.

Modelling and validation activities mainly consisted of analysis and charting spreadsheets linked to a database of measured data. These were developed throughout the trial operation, for example a simple Excel tool was developed to estimate the required peak-shaving threshold setting.

Impact assessment involved analysis of monitored output of the energy storage systems, both individually and in combination, with comparison to local and feeder indications (for example power, voltage, and power quality). Conclusions were drawn from these results and analysis.

SECTION 3

Design, Construction and Commissioning

3.1 Overview of as-installed equipment

The installed equipment comprised of five energy storage units (converter with battery module) connected at existing substations on a single 11kV feeder from Fox Milne Primary substation. Each site contained: a 50kW/100kWh energy storage (sodium nickel) battery, with battery management system; a 100kVA rectifier/inverter unit; site controller (providing user interface and control functionality); G59 protection connection circuit breaker; and fused connection to the LV distribution network at the adjacent Distribution substation.

Figure 1 to Figure 3 show selected images characterising the Energy Storage trial and associated equipment. Figure 1 shows a picture of the installed arrangement at the AWA Middleton site; Figure 2 an electrical schematic of the ES systems and Figure 3 a view of the Princeton Power Systems' rectifier/inverter unit.

Figure 1: Installed arrangement at the AWA Middleton site

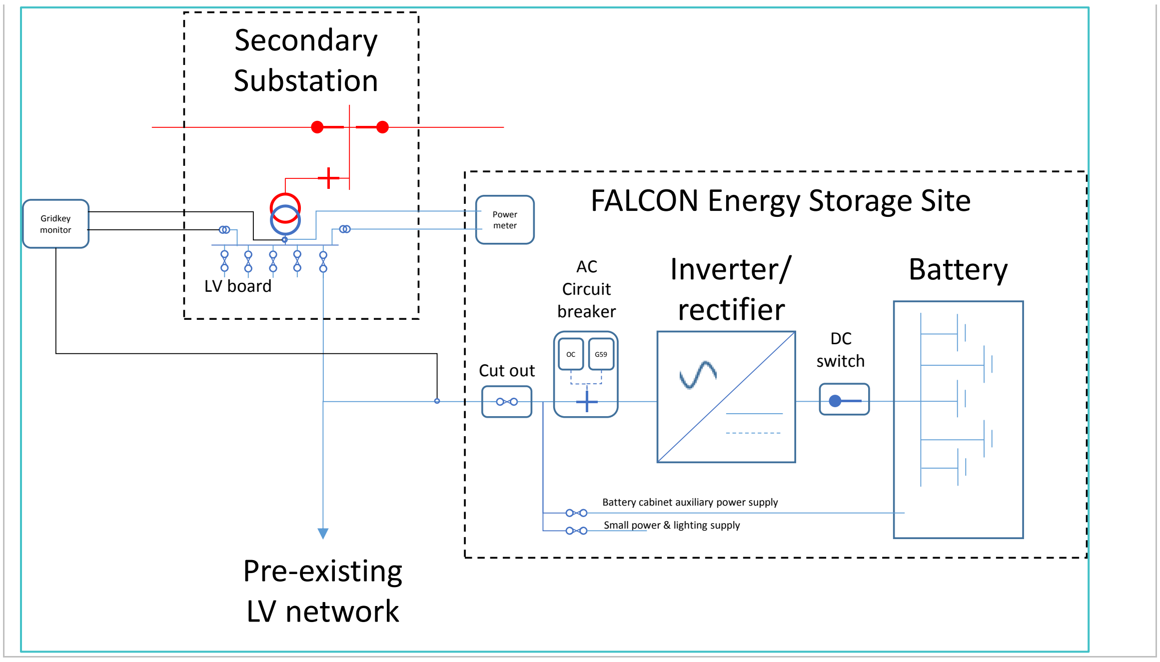


Figure 2: Electrical schematic of the ES systems

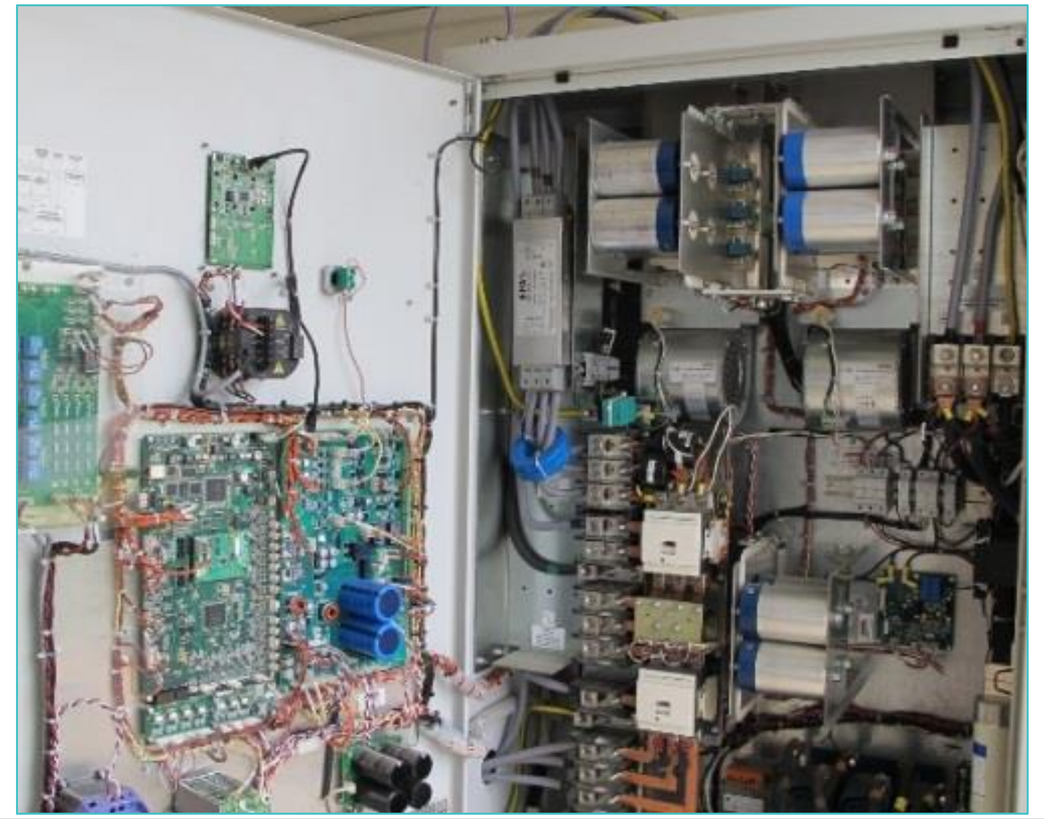


Figure 3: View of the Princeton Power Systems' rectifier/inverter unit

The monitoring principally consisted of retrieving logged data from the installed LV Gridkey monitoring of the substation, and the connection to the energy storage system, plus limited retrieval of data from the data logged on the energy storage system control systems.

An overview of the as-installed scheme for a single site is shown in Figure 4.

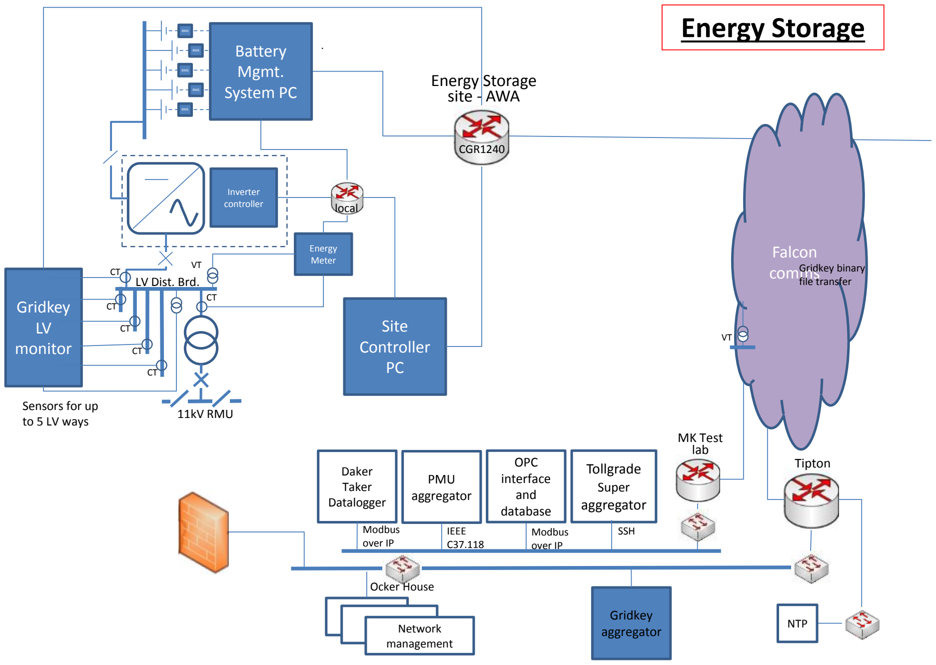


Figure 4: Schematic overview of a single energy storage site

These units charge the batteries at designated times or triggers (e.g. when load is less than threshold value whilst in peak shaving operation, when frequency is above a threshold value in frequency response operation), and discharge energy from the batteries either:

- As specified manually;
- At specified times regardless of network conditions;
- When substation load is above a specified trigger point (peak shaving operations); or
- When grid frequency is above/below a specified trigger point.

In addition, the inverters can also import or export reactive power, influencing voltage at the point of connection:

- As specified manually;
- At specified times regardless of network conditions; or
- When substation voltage is above/below a specified trigger point (voltage response operations);

The location of the energy storage sites on the 11kV feeder is shown in Figure 5

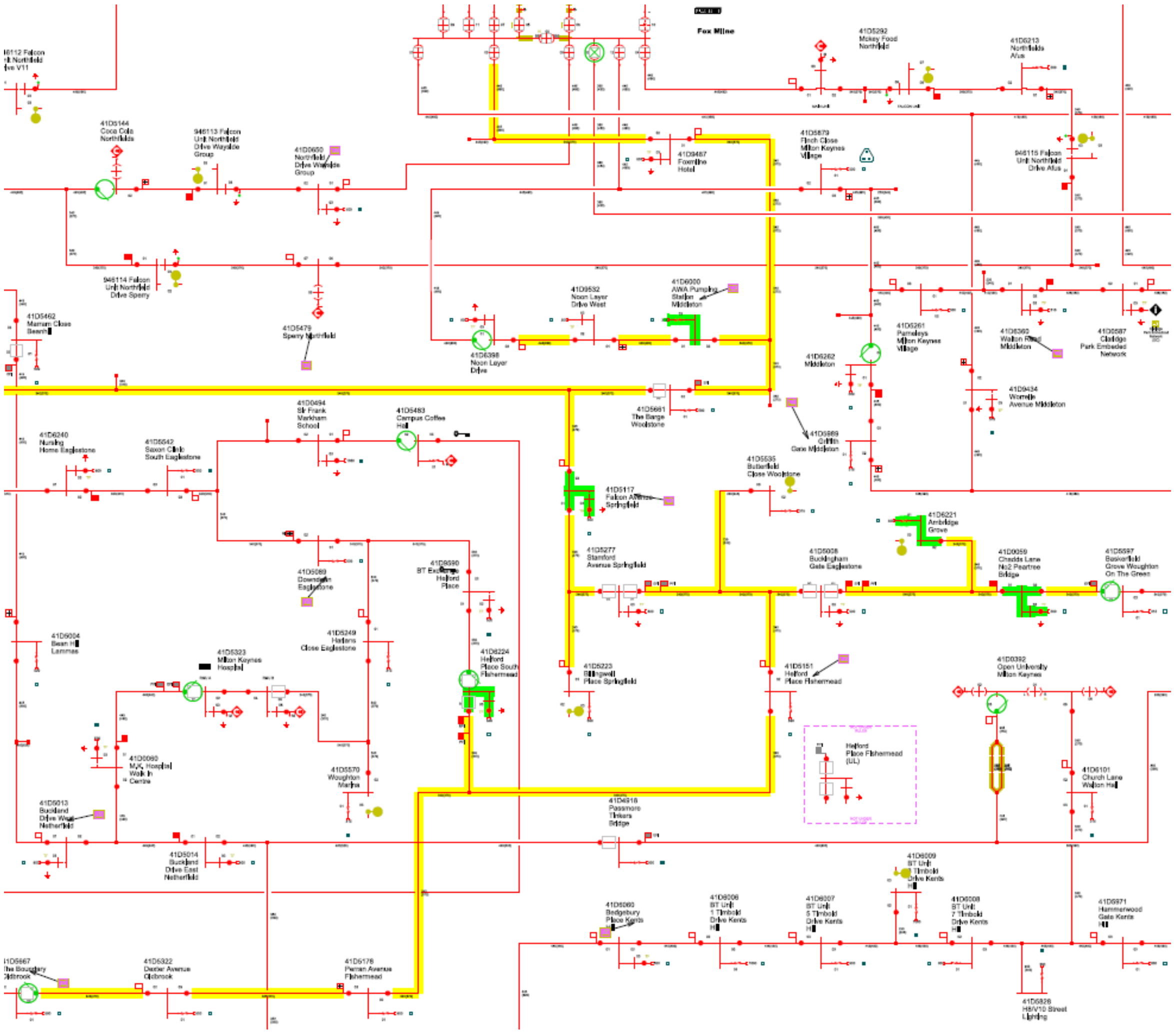


Figure 5 : 11kV feeder from Fox Mile Primary with five connected Energy Storage Sites highlighted in green.

3.2 Key Learning from Implementation

3.2.1 Technique-Specific Learning

LP 1.	Having selected an HV feeder for the trial, it proved difficult to find five suitable sites to locate the energy storage systems.

- Factors included in assessing site suitability included:
  - Available room in the substation confines to accommodate the equipment;
  - Proximity of nearby customers or passing public and the possibility of exposure to noise nuisance;

- Availability of a spare LV way in the substation to connect the input/output of the battery installation. to allow initial battery installation without disturbing adjacent customers

Note: there are 18 substations on the selected HV feeder. Although the trial focused on locating the batteries adjacent to existing substations this wasn't essential and any large LV main at a suitable location where there was room within the bounds of the public highway could have been chosen. There may not have been a dedicated LV supply but then this option wasn't available at trial locations Helford Place or Chadds Lane. It must be remembered that remaining in permitted development rights requires the whole unit to be 35Cu metres or less. Manufacturers should be challenged to produce a fully integrated unit that mirrors a standard GRP substation.

- Initially provided equipment size information from the bid documentation[2] did not give a complete indication of the footprint required for the main equipment, ancillary equipment and interconnection (supply cut-out, inverter supply switch/breaker, auxiliary distribution board - small power and lighting, inverter power isolating transformer, DC switch, battery interface chamber).

- Of the five sites originally selected through desktop studies (Noon Layer Drive West, Stamford Avenue, Ambridge Grove, Perran Avenue, and Falcon Avenue), only two were actually developed, alternatives found due to:
  - Insufficient/unobtainable space (Noon Layer Drive, and Stamford Avenue) for total equipment required
  - Proximity of customer/party wall with substation (Perran Avenue)

- The five developed sites were: Ambridge Grove; AWA Pumping Station; Chadds Lane; Falcon Avenue; and Helford Place South.

- Of these sites, energy storage equipment was installed inside the existing brick substation at Falcon Avenue only; all other sites had existing GRP enclosures. This necessitated bespoke site arrangements of an additional GRP enclosure, with external siting of the battery and battery interface chamber.

- The initial intent to connect via a spare LV way was not achieved at two sites (Chadds Lane and Helford Place South)

LP 2.	Acquiring accurate and unambiguous site requirements early in the planning phase potentially avoids delays in the installation phase.

[2] Basic equipment size information was provided:
- The DC100kWh Durathon Battery Rack at 1530mmW X 1100mmD X 2450mmH
- The 100kW Grid Tied Inverter at 915mmW X 458mmD X 1905mmH

- Four of the five eventually developed sites required land/rights to be procured to accommodate all the necessary equipment. Final clarity over full site requirements did not emerge until equipment was actually delivered to the depot. In part, this led to delays to complete all sites compared to original programme. Any legal/land ownership requirements can take months to resolve. Therefore it is essential to know accurate footprint info as early as possible so the process can be started as soon as possible.
- This desire to achieve accurate and unambiguous information for all suppliers on a large and complex project is clearly the aim of every design team, this learning point is a useful example of what can happen when this intent is (perhaps inevitably) not perfectly achieved in all cases.

LP 3.	Ensure that there is clarity and appropriate alignment in procurement arrangements between: • responsibility for: ○ individual site layout; ○ foundation design; ○ enclosure selection; and • provision of necessary information to undertake this. This must include lifting and handling arrangements, both at site and for goods receipt/warehousing.

- Each site layout was effectively developed by WPD with:
  - a site-dictated bespoke layout arrangements for the main equipment;
  - bespoke layout of internal arrangement of equipment within the installed GRP, principally dictated by arrangement of the battery and interface chamber to the GRP enclosure – this was undertaken during the construction phase rather than the design phase; and
  - extensive work to remove an external wall and lower ground level at the Falcon Avenue site was required to allow the battery unit to be placed in position, and maintain it in a vertical attitude throughout the positioning operation. There are no top lifting points on the battery unit, and no by-design provision for rollers.

Whilst WPD understood site constraints, they were not in full possession of all the detailed technical information until GE installation staff were actually on site – necessitating a riskier "make it fit once on-site" approach.

LP 4.	At the size of unit being installed under Project FALCON, a packaged solution

	would have had many advantages over the trial units.

- Very significant effort was put into establishing the necessarily site-bespoke arrangement of the principle equipment (inverter and battery unit/interface chamber), plus installation/mounting and interconnection of all the remaining essential equipment (supply cut-out, inverter supply switch/breaker, auxiliary distribution board, small power and lighting, inverter power isolating transformer, DC switch) – this amounted to over ten man-days of installation work per site.
- The advantages of pre-assembled packaged solution would include:
  - Greater clarity of the site requirements – whilst this may have made site selection more demanding initially, clarity would have reduced unexpected delay at later stages.
  - Significantly reduced installation time/effort that occurs in field conditions rather than factory conditions with all its attendant delays associated with tools, techniques and consumables when carrying out a task for the first time (e.g. working some specifications that were in American Wire Gauge required unfamiliar conversion to metric sizes prior to selecting cable appropriate for interconnection of the equipment).
  - Reduced testing/commissioning –The isolation transformers (over 300kg) had to be removed and replacement units installed due to damage in manufacture. In addition, protracted field commissioning was undertaken with resource from the USA that could have been substantially avoided with comprehensive FAT of the complete package unit.
  - Highly practicable option to redeploy – the current site-bespoke approach would be costly to redeploy.

3.2.2 Generalised and Cross-Technique Learning

The following points of learning have been found across more than one technique. They are presented with examples specific to the energy storage technique.

LP 5.	Design and specification work stopped at a high level, leaving a significant and initially unrecognised volume of work and problem solving for the commissioning/early operation phase. This applied to all the engineering techniques.

- The design of the lifting/handling arrangements of battery units needs to change to take account of the facilities usually available for offloading in both UK depot and rural locations.
- Difficulties were also experienced with the receipt of the Battery Packs and Interface chambers. These were delivered in a container and the intention was that they would be unloaded by a suitable fork lift truck able to enter into the container from a loading bay level. The WPD depot at Milton Keynes was not however equipped with these

facilities. Furthermore neither of the received units was equipped with lifting eyes so it was very difficult to crane them onto site.

- Necessary G59 protection was installed as a stand-alone relay associated with the supply circuit breaker for the inverter, rather than utilising the protection functionality built-in to the inverter. This additional installation was undertaken as a pragmatic answer to the need to injection test to prove appropriate G59 protection.

LP 6.	FALCON established that traditional approaches to FAT may not be adequate for innovation projects. The use of conventional FAT approaches may necessitate rework at the install / commissioning stages.

- Shortly after power up at the first site the isolation transformer supplied by Princeton Power Systems failed. On investigation it was found that all the isolation transformers delivered to WPD had been damaged during manufacture and they had to be replaced. This resulted in a two week delay during the installation/commissioning phase.
- Commissioning was a protracted activity involving GE and Princeton Power Systems personnel for a number of weeks in total. This could have been significantly reduced with a comprehensive FAT approach.

LP 7.	FALCON demonstrated the importance of establishing measurement and data strategies as part of the programme design phase to help (dis)prove the technique hypothesis being trialled.

- Limited data was available through the battery management system (BMS) and long term logging of this data would have been useful to understand more fully changes in battery operational efficiencies and degradation. Clarity over access to this data from project conception would have helped.

LP 8.	Control room interaction with the technique was light. The data on battery availability and real time capacity was not available to be sent onto a central control.

LP 9.	Limited training of operational staff was undertaken to allow the trial to take place. This resulted in the need for a high level of support from the manufacturer which is not sustainable in the long term. Additional more widespread training would be required if energy storage were adopted as a BAU technique.

SECTION 4

Overview of Trial Operations

The trials consisted of a number of investigations to look at

- Baseline operation of the LV substations and HV feeder without operation of the energy storage units;
- Peak lopping and trough filling using demand forecasts;
- Voltage response;
- Frequency response;
- Impact on power quality;
- Specific operational circumstances, for example, response to circuit fault/disturbance.
- Reliability and degradation

This was done through scheduling different operational modes on each of the five sites. During these periods data was collected and later analysed to assess the impact and benefits.

Testing configurations were dependent on battery and communication availability.

SECTION 5

Trial Results and Discussion

5.1 Trial data

Data supporting the trial analysis and assessment comprised of:

- Two data sources for battery operation analysis. One is the measurements from the GRIDKEY device (AC side measurement), and the other one is the measurement from the BMS (DC side measurement).

The information that can be taken from the raw data is shown in Figure 6.

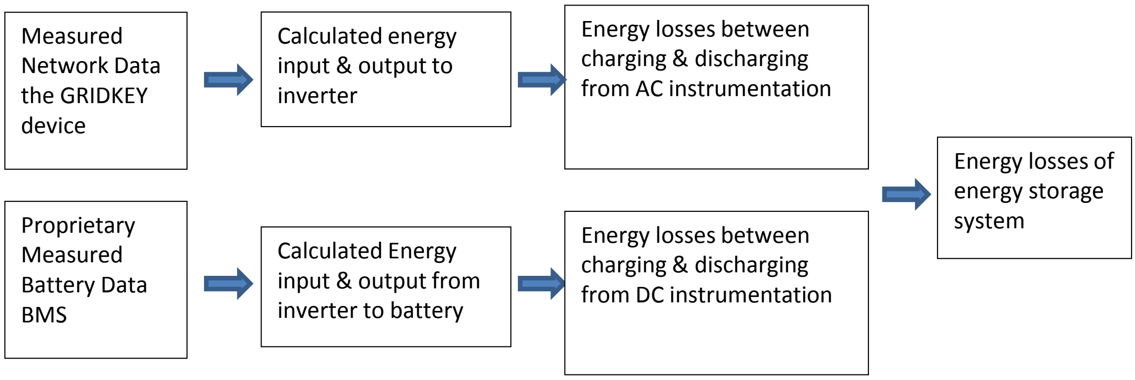


Figure 6: Utilisation of the measured AC and DC data

5.2 Trial Modelling

Some energy storage modelling was undertaken prior to the trials commencing. The approach to the analysis was as follows:

- A model of the battery trial network was established in TNEI's modelling package IPSA using the 11kV schematic diagram to derive connectivity from EMU data – the trial's area network model;
- Demand at each substation node was estimated as a proportion of total feeder load. This pattern has held constant at all times of the day, and for all days in the year. A refinement to this, the use of dynamic distribution, is recommended;
- Feeder loads for 1 year were used with estimated percentage of feeder load at each substation to produce a load at each substation for each half hour period of the year;
- Power flow, voltage, losses and fault level studies were carried out to investigate the impact of various aspects of battery operation on the trial's area network;

- In the absence of actual power factor data, initials checks were made using load estimates and setting power factor to 0.9 (lagging), 0.95 (lagging) and unity. No significant sensitivity to power factor was found, and an estimate of 0.95 lagging was used throughout the analysis;

The key findings from the study were that:

- Modelling of the proposed size of batteries for the trial network and estimated magnitude and shape of circuit loads suggests that a very limited reduction in peak feeder currents occurs.
- Appropriately tuning battery operating/triggering strategies to the output/capacity characteristics of the installed batteries and the shape of load appear to be critical to deriving benefit.
- The battery life is dependent on the number of cycles the battery goes through and how much the battery is discharged in each cycle. Minimising these two variables maximises the battery life and the life cycle financial investment. Operating the battery by trigger rather than on a daily basis, leads to a modelled gain in battery life.
- Studies into the impact of modelled energy storage as lumped capacity or distributed capacity show that for the trial radial circuit networks there is little change to the impact on peak current or voltage support; therefore proposed battery arrangements for the trials are appropriate in this respect. Where the % battery penetration is more significant, modelling will be needed to fully assess location impact.
- Studies show no expected problems due to fault level.

5.3 Key Learning from Trial Operations

The total system losses include the energy conversion losses, the energy used for keeping the battery temperature within limits, the energy to cool the system, other auxiliary sources of energy and battery charging/discharging efficiency as shown in Figure 7. Battery management system (BMS) date was not widely available but would have been useful for ongoing understanding.

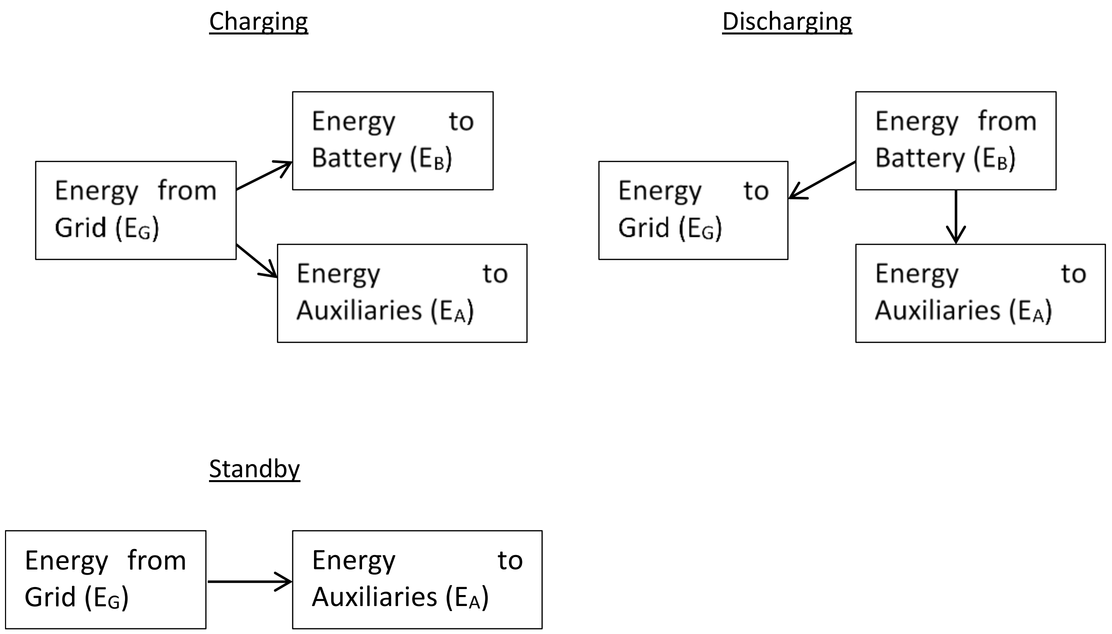


Figure 7: Energy Flow under different operational modes

LP 10.	Basic charge and discharge operations reveal significant differences between discharge and charge rates that have implications on functionality of the system.

- Discharge – in line with rating of capacity of the battery.
- Charge characteristic – shows exponential shape, Initial charge rate being much higher than charging with the battery approaching full capacity.
- Because "rated" charge declines as full capacity approaches, the full charge time is much longer than the fastest full discharge time.
- Figure 8 provides an example of the difference between rated discharge time and corresponding maximum achievable charge time. Discharge occurred with 2.5 hour, whereas recharging took over six hours to broadly complete. Further analysis of this operational performance will occur when logs of state-of-charge become more readily available (work with the supplier on this point is ongoing).
- Further detail of charging suggests that each battery has its own controller, and this manages the rate of charge and state of charge of an individual battery. The consequence of this is that each battery string (there are 5 that make up the Falcon individual installations) reaches its top-of-charge point at different times. During discharge this can be seen as different discharge currents. This can be seen in Figure 9 where the 100kWh capacity of the battery is being discharged. The batteries at each site although nominally identical are discharging at different levels and are finishing their discharge at different times (up to 30minutes difference). The staggering at the

end of the discharge cycle is indicative of sets of battery strings being turned off by the battery management system as they reach limits. Limited details were available from the supplier, due to expressed sensitivities about the release of technical and protection strategy details that are regarded by the supplier as "proprietary knowledge".

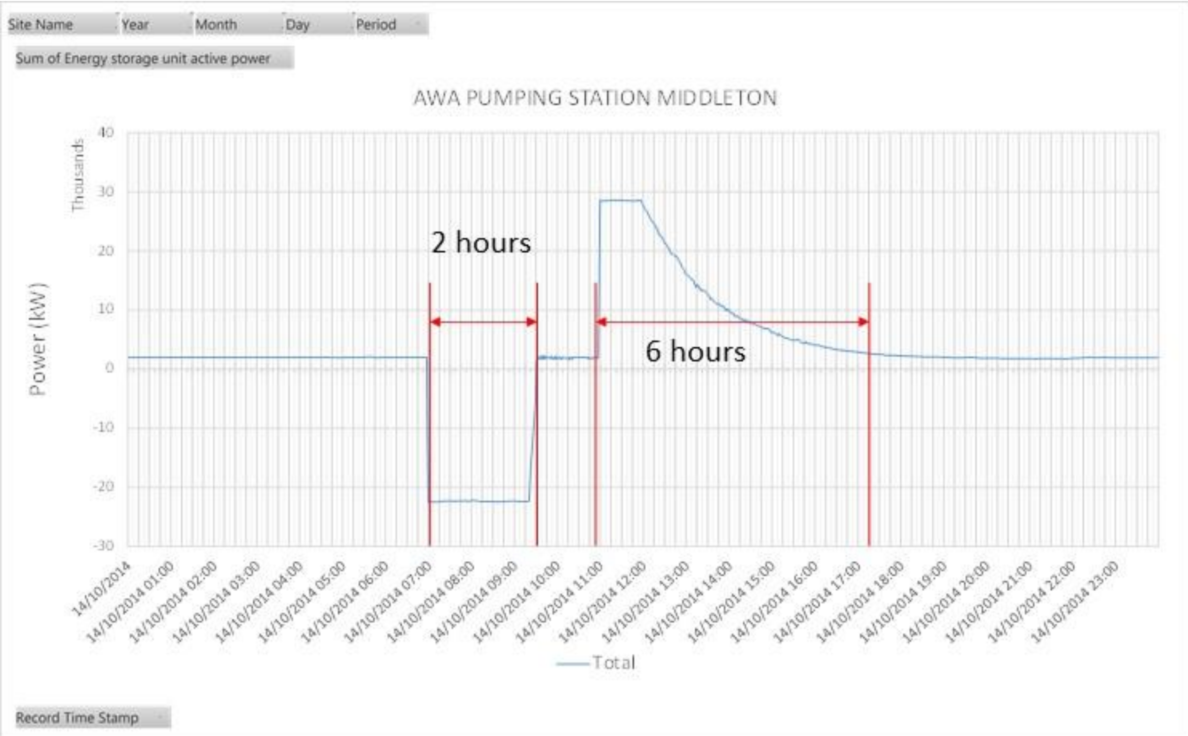


Figure 8: Illustration of charge and discharge periods for available battery capacity

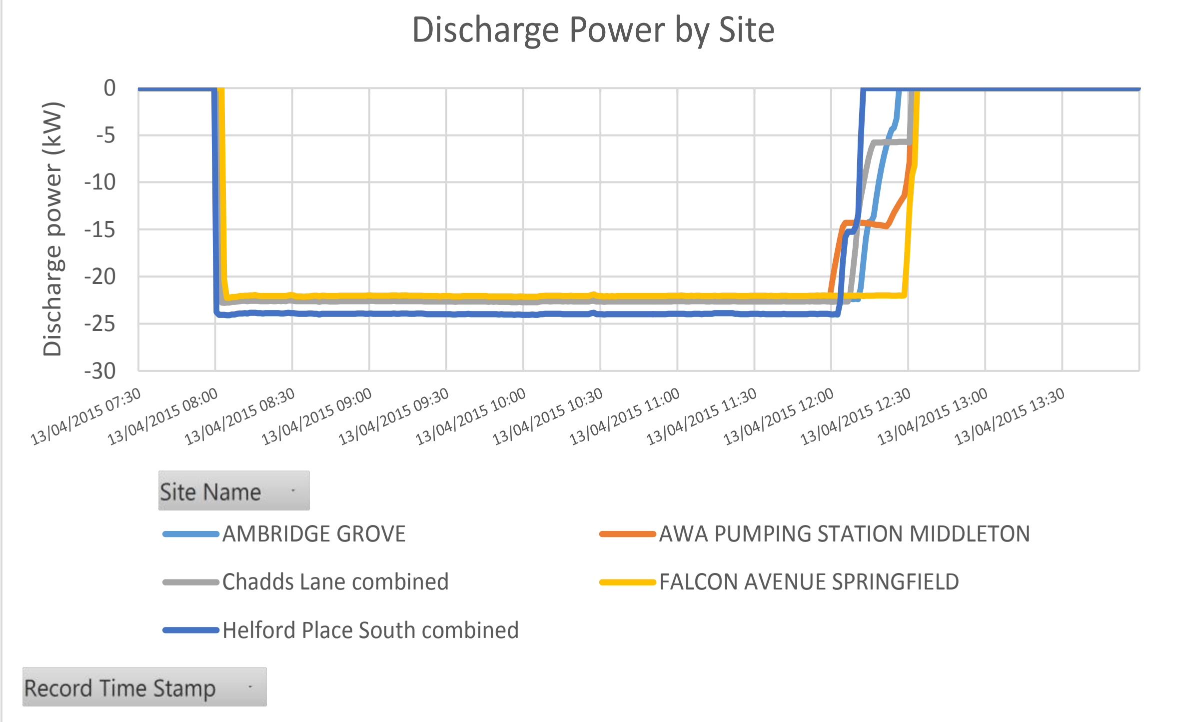


Figure 9: Illustration of discharge cycles showing variation between both batteries and strings over different discharge cycles on different days

LP 11.	Battery charging and discharging efficiency is estimated from BMS data at 98% - in line with manufacturer's data.

The battery efficiency is the chemical efficiency of charging and discharging the batteries. However this figure does not include the power to operate the heater (up to 600W) or the other auxiliary power requirements.

LP 12.	Power required for the auxiliaries has been assessed to be between 2kW and 3kW from GRIDKEY reported data.

This is the power that is required when the battery is on standby and represents around 50kWh loss per battery per day if the battery is sitting idle.

LP 13.	Auxiliary power requirements are higher for this type of battery due to the need for additional heating. The temperature range of battery operation should be considered as part of the design specification as heating will

	impact ongoing operational costs.

LP 14.	Audible noise from the initially installed inverters is a concern.

- Initial trials indicate that the inverter emits a noise at a frequency of approximately 7 kHz with harmonics at approx. 14 kHz and 21 kHz.
- The level of the noise at these characteristic frequencies varies dependant on the charge / discharge power but has not been observed to be greater than the level of isolation transformer noise or background noise.
- The pitch of the noise may have an impact on some people due to the frequency – further research is necessary. Levels of noise were within applicable limits;
- The level of noise can be judged to be site specific – for example an industrial site or park would negate any noise, whereas adjacent to a dwelling may have a greater impact;
- Trials proceeded with caution with only a few enquiries about the noise from customers adjacent to the Chadds Lane (inverter noise) and Ambridge Grove sites (mechanical noise from cooling fans).
- Actions were taken following customer enquiries:
  - Thermostats on the battery/interface unit were adjusted such that they only ran when necessary (initially they were running continuously).
  - The inductors used in the static filters were changed which are reported by the supplier to be the source of the audible noise. This significantly reduced noise at 7/14 and 21kHz.

LP 15.	Battery maintenance is a significant activity with consequential availability issues.

- Extensive time can be required for a battery maintenance cycle, see Figure 10;
- A maintenance cycle on the five battery sites is recommended by the manufacturer to be run every week/168 hours within FALCON. This maintenance cycle is started at a fixed time each week however, the control system decides how the cycle will proceed. This results in two key unknowns;
- Although the cycle may be set to a fixed time slot – the actions/number of actions taken by the control system are not pre-determined.
- The maintenance cycle activity, if it occurs, is not a fixed time period as shown in Figure 11 but can vary from less than an hour to many hours/days.
- The apparent non-deterministic nature of the maintenance algorithm is compounded by the supplier regarding the BMS as proprietary, making the process more uncertain to the end-user. From an availability perspective – this means the battery cannot be

routinely relied upon for service over the twelve hour period from the control system start of a maintenance cycle.

- Battery maintenance apparently plays a role in the calibration of the state-of-charge of the batteries. If this calculated indicator drifts from the actual condition of the battery, then operating characteristics start to alter from expected characteristics, and control systems can start to (falsely) sense fault conditions, leading to protection disconnection of individual strings. This is clearly an evolving area for the supplier, as software updates to the individual battery controllers and the combined (5-string) battery management system have been undertaken. Data to indicate the successful completion of battery maintenance cycle is not easily acquired.

LP 16.	The Output power set point refers to the dc output power from the batteries and not the output power from the system at the point of common coupling. The latter is harder to control but potentially more useful for the operator.

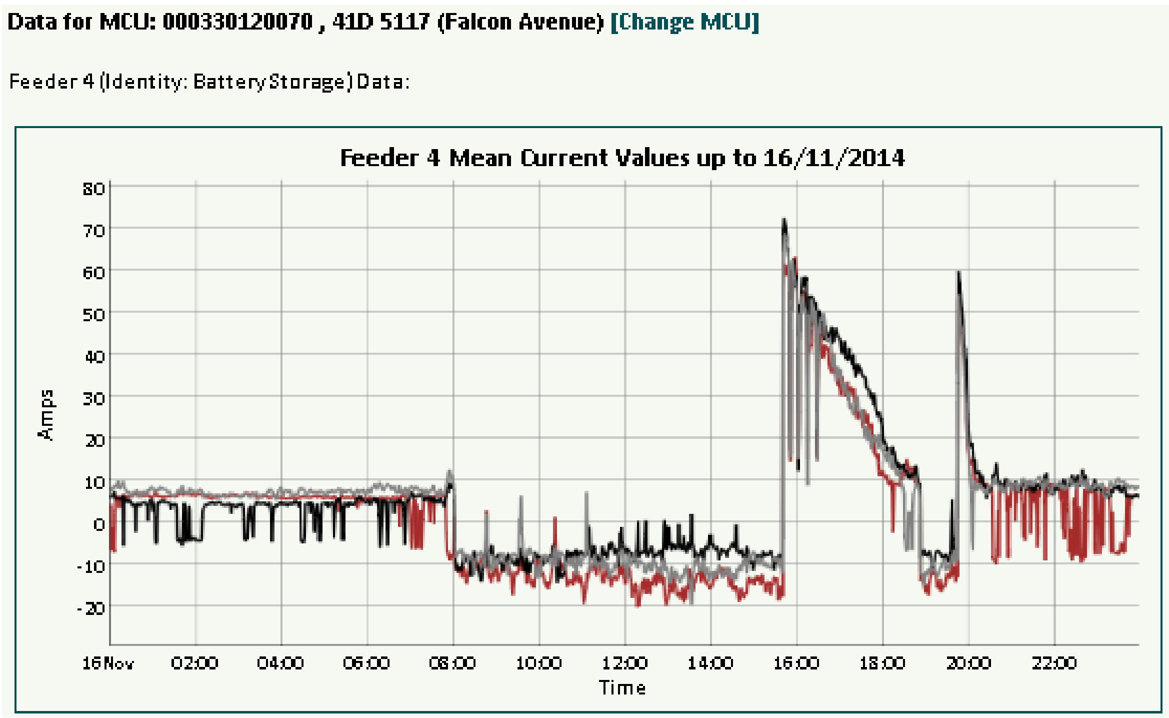
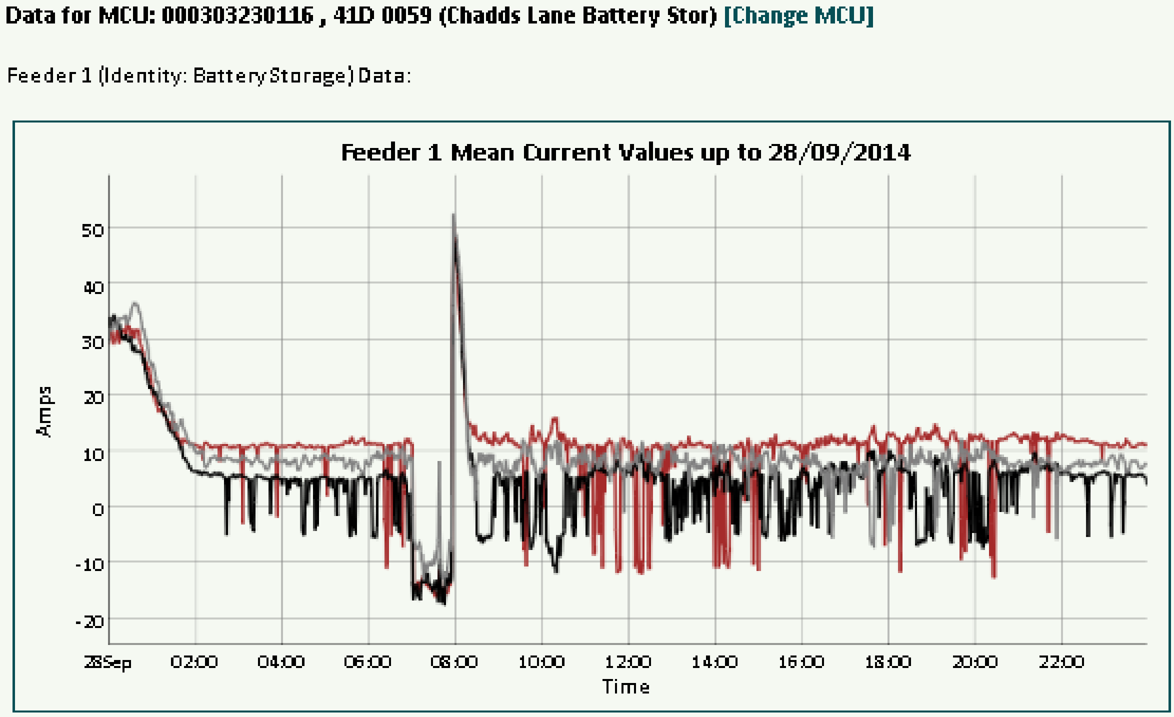


Figure 10: Illustration of a 12 hour battery maintenance cycle



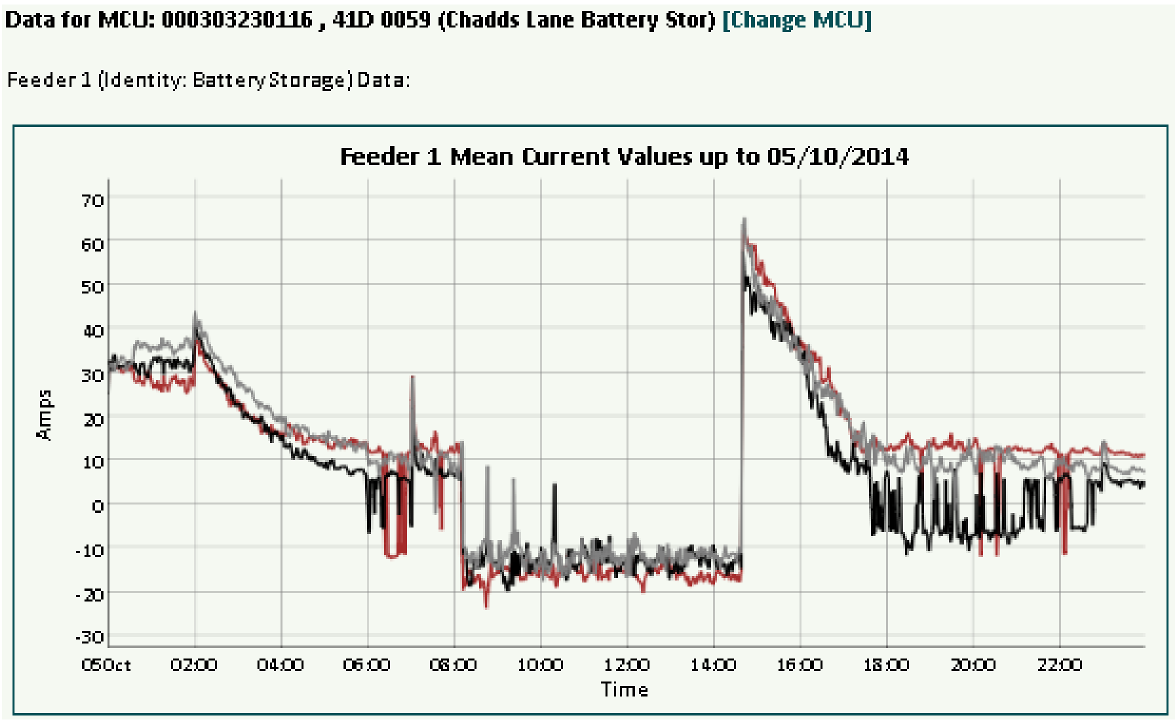


Figure 11: Illustration of a short battery maintenance cycles, showing variation in time to complete maintenance cycles

LP 17.	Whilst the battery management clearly alters signalled available power and capacity for the overall battery module, this is not fully fed into wider (Site Controller) control system.

Unavailability of individual battery strings in a battery module prompts battery management reductions in the (battery) rated output power and rated capacity; however, these do not feed through consistently to wider control systems. For example, changes to capacity are not currently alarmed, and did not change peak shaving thresholds; the consequence being that the battery may well not be about to peak lop the entire peak (see illustration in Figure 13)

LP 18.	Issues with reliability and availability have been encountered.

Some issues of reliability have been encountered, with some hardware and software issues reported. For example, a replacement battery string was required at AWA Middleton, replacement of inverter measurement board and earth fault detection board at Helford Place; replacement of a battery management system at AWA Middleton due to heater IGBT failure. As previously mentioned, there have been revisions to software managing SoC indicators.

- Availability has been affected by reliability issues (with some extensive down periods as fixes have been developed/service teams become available), but perhaps most systemically by the amount of battery maintenance time required.
- Availability is also naturally limited by the charging time required.

LP 19.	Peak shaving functionality (using pre-determined load threshold) has been demonstrated to effectively limit substation load.

In Figure 12, as the substation load (shown in grey) rises to 55kW, inverter operation (shown in orange) occurs, and the net load on the substation (shown in blue) is limited to the control setting level of 55kW

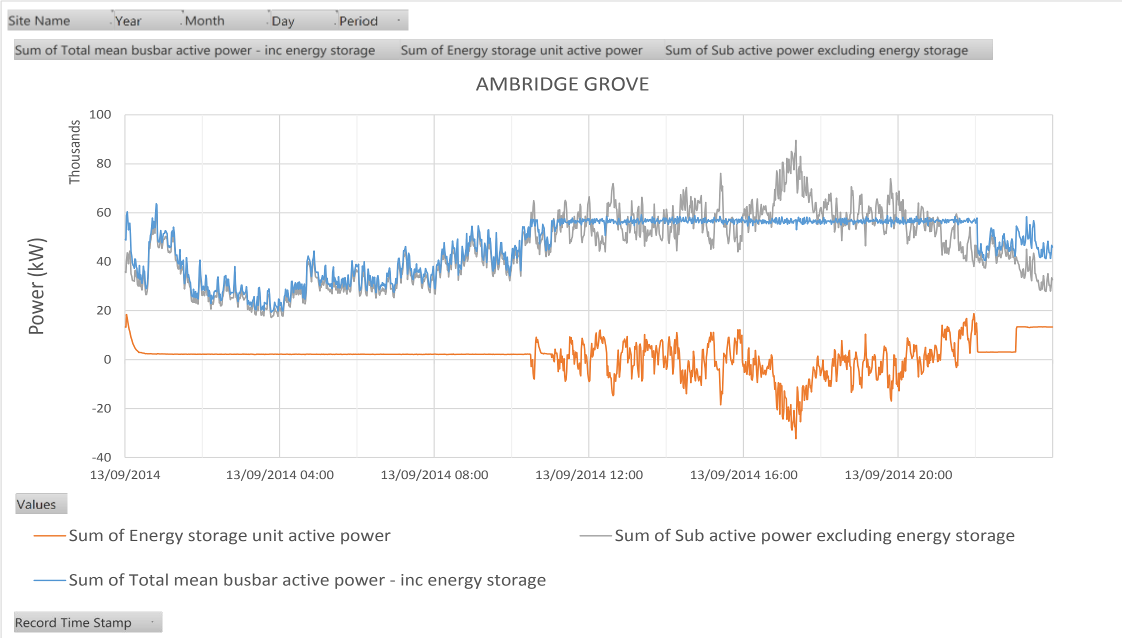


Figure 12: Peak Shaving operation at energy storage sites

LP 20.	The peak shaving function is clearly repeatable.

Figure 13 shows reliable repetition of the peak shaving function over the course of 1 week.

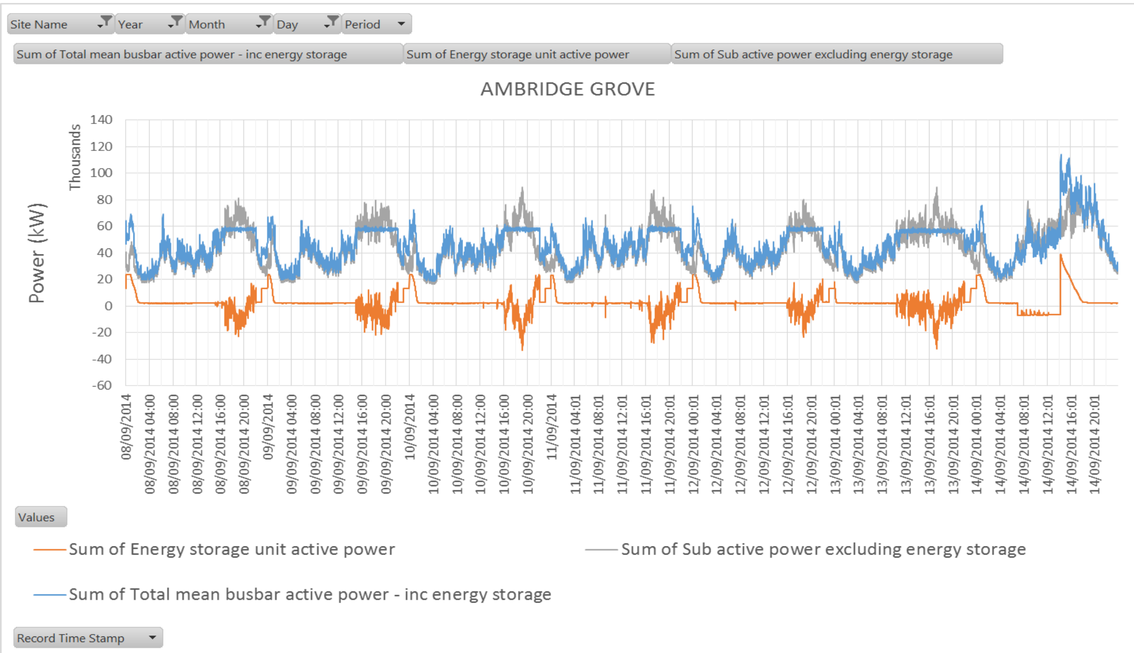


Figure 13: Peak Shaving operation over a sample week

LP 21.	As load changes throughout the year, the peak-shaving thresholds need to be actively monitored.

Figure 14 shows one week of operation at the Ambridge Grove site, where it can be seen that the battery becomes fully discharged during peak shaving operation on 29th October. This is seen as a sudden increase in the net substation load (blue trace) at around 20:00hrs.

The chart also shows a period of battery maintenance (on Sunday 02nd Nov) – battery discharges at a slow rate to allow a number of open circuit voltage checks at a variety of States of Charge of the battery, followed by recharge of the battery and any necessary re-calibration of state of charge indicators.

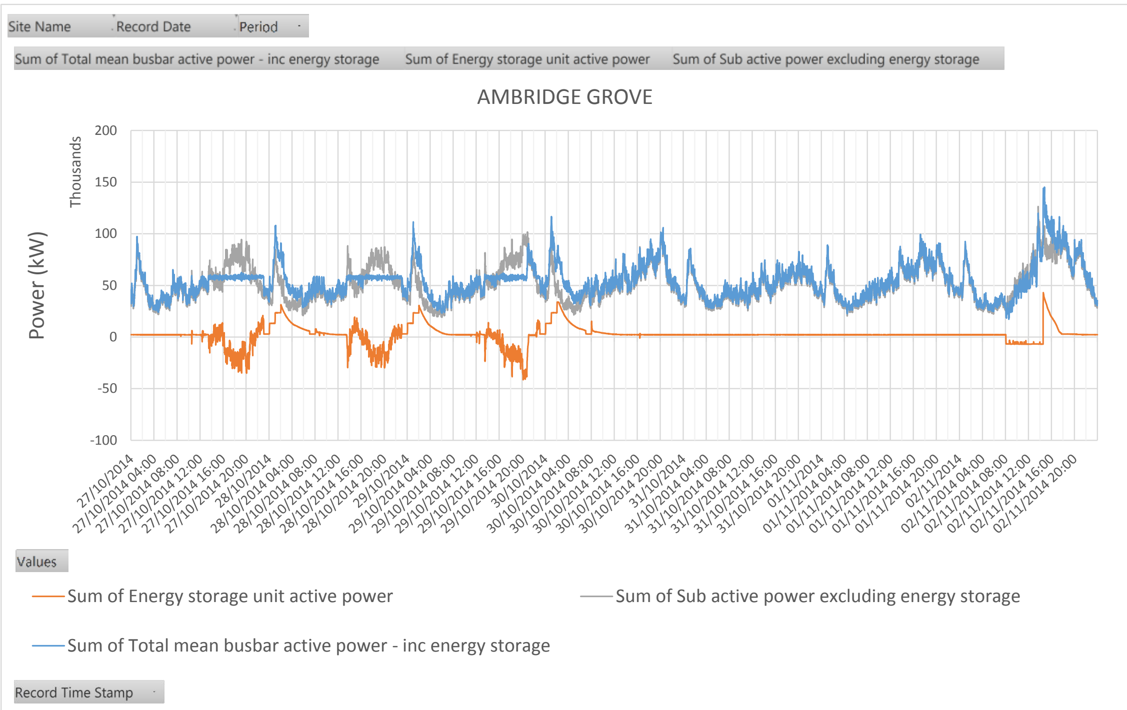
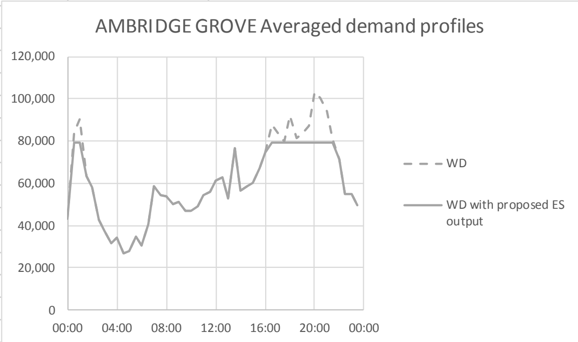


Figure 14: Peak Shaving operation with threshold set too low (battery becomes fully discharged prior to the peak demand passing)

LP 22.	Tools to effectively establish appropriate peak shaving thresholds are required and have been developed.

- These are based upon having substation load monitoring in place within the control system.

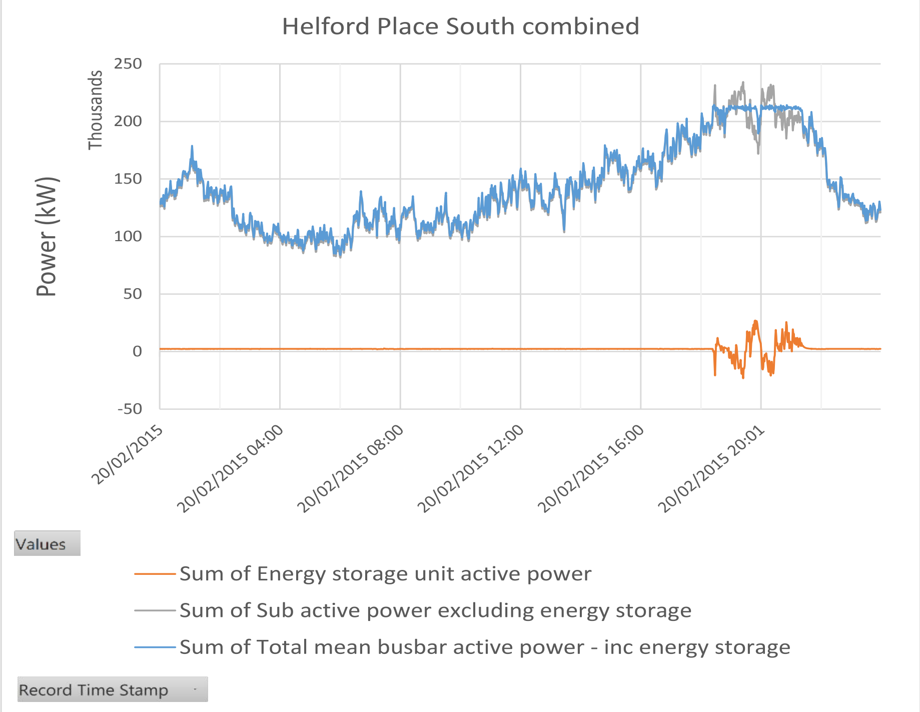
- However, it is still a manual process of revising the threshold setting, and scheduling this on a regular basis if required.
- Analysis shown in Figure 15 indicates that a peak shaving threshold around 80kW would have been more appropriate than the actual setting of the day (see Figure 14)



WD		
Include Std Dev in analysis	y	
Number of Std Dev	2	
WD Peak shaving level	79.1	kW
Season used for profiling	(All)	
Peak power in profile	103	kW
Max power above	24	kW
Energy above peak shaving level	60	kWh

Figure 15: Tools for analysing substation load data and establishing appropriate peak shaving levels

An issue of peak load lopping at a fixed level is that as the seasons progress – less energy is required to meet a fixed peak load lopping target and the battery may become obsolete for this purpose throughout the summer months as shown in Figure 16.



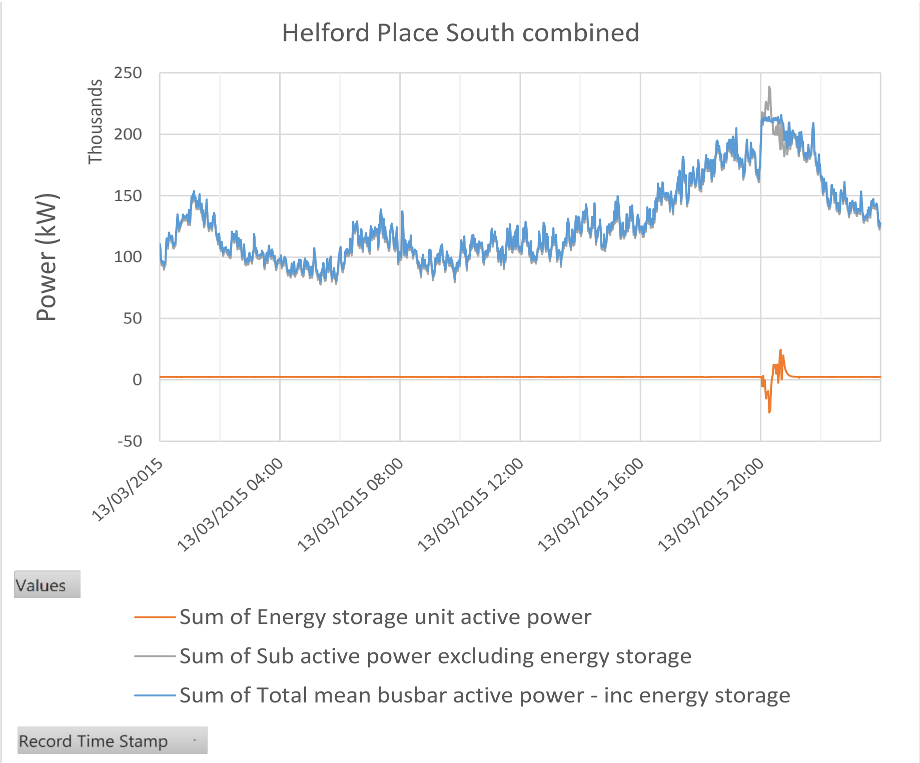


Figure 16: Peak load shaving same day - but three weeks later showing reduction in required energy.

LP 23.	Coordinated peak load lopping to reduce primary substation loading has been demonstrated.

It is not just a case of influencing substation load. In many cases, the most heavily loaded branch on an 11kV feeder is the first branch out from the primary substation, and it is reducing the flow of power along the feeder line that could be the main aim. Where it is not possible to connect a large single energy storage system downstream of an affected feeder, it becomes necessary to use distributed storage. Co-ordinating the five different energy storage sites to peak load lop a feeder is the challenge. Prior to running a test, the batteries were sent through a maintenance cycle in preparation to ensure they registered full charge. Four of the five sites successfully completed the cycle. The maintenance cycles, plus scheduled recharge overnight Sunday to Monday left the ESSs notionally fully charged for operations on Monday, shown in Figure 17.

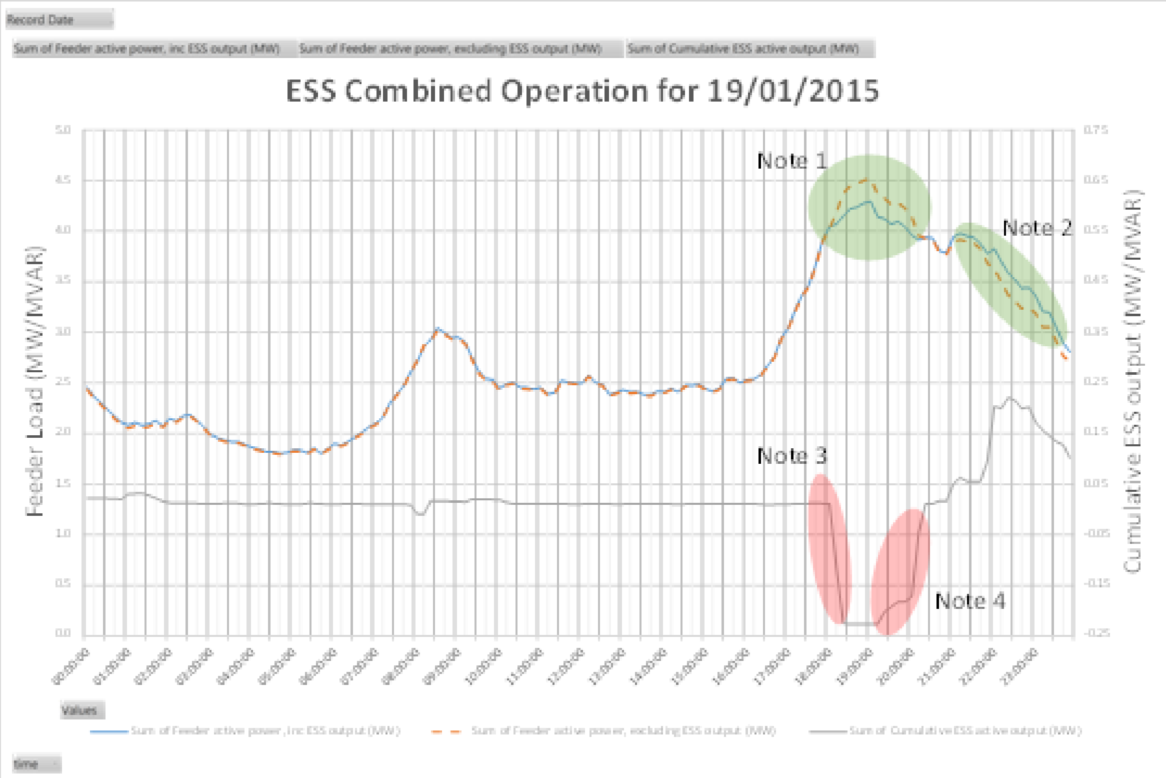


Figure 17: Combined Operation trial 19th January 2015

The Amber dashed line shows the (calculated) demand from load connected to the feeder. The Blue solid line shows the (measured) supplied power to the feeder and the Grey solid line shows the (measured and summed) output from the five ESSs. Four key points are noted on Figure 9:

- Note 1: shows that the combined action of the energy storage system sites (ESSs) reduced the electricity supplied from the Primary. As ESS output increases a difference develops between the power delivered from the primary and the total demand of load on the feeder. Effectively, the operation of ESSs reduces the energy supplied by the primary over the peak demand period. Reduction is in the order of 225kW.

- Note 2: shows a period where the energy supplied by the Primary substation is above the load of the feeder, as the ESSs start to recharge their batteries.
- Note 3: Basic expectation of the shape of the combined output from the ESSs is square. The chart suggests that the combined output builds over a short period of time, even though each site was scheduled to start out at the same time. Further investigation showed that the local time of the individual controllers was not synchronised. Combined output from the five ESSs is around 225kW at its peak. This is less than the nominal combined output of the ESSs of 250kW.
- Note 4: The Combined output from the five ESS falls away over the 2 hours scheduled discharge period similar to that in Figure 9.

LP 24.	The Coordinated peak load lopping to reduce primary substation loading is clearly repeatable.

Figure 18 shows operation over consecutive days including the 19th January 2015 which was the winter peak demand day.

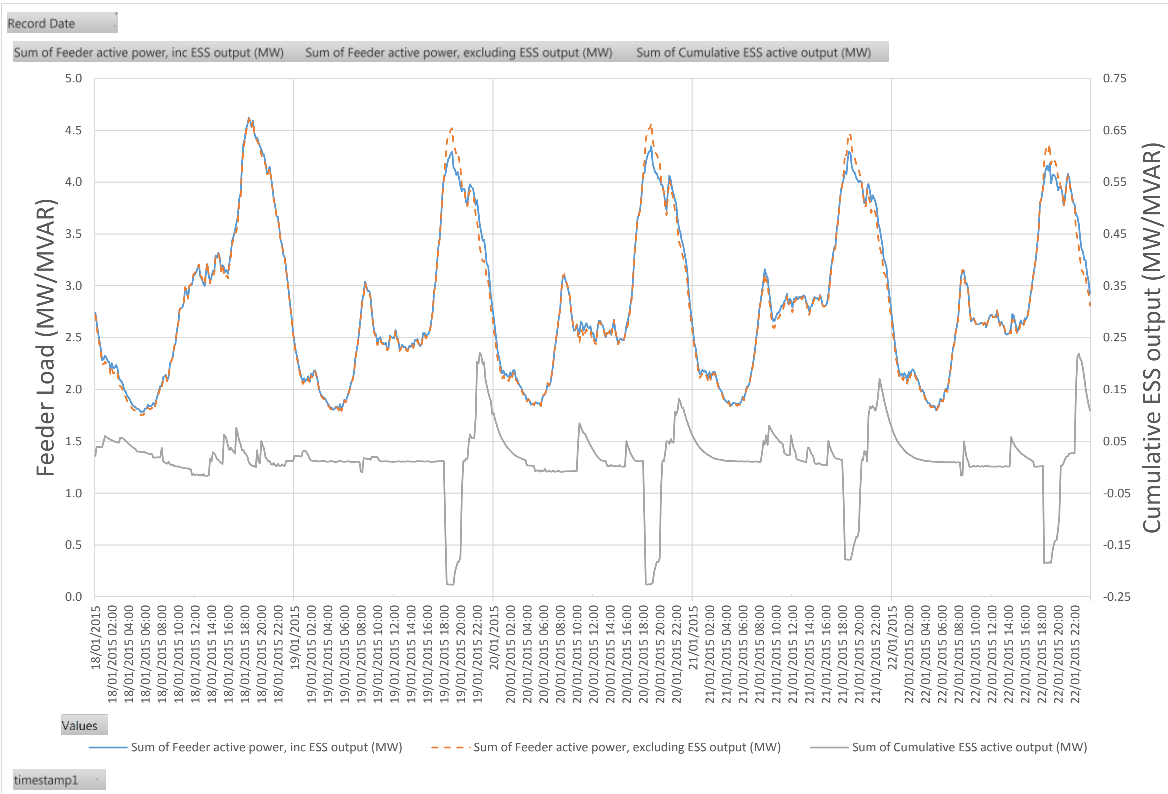


Figure 18 :Repeatable Combined Operation trial 19th - 22st January 2015

LP 25.	Controlling the load at a feeder to a fixed value similar to controlling the load at a single site would require a complex control and energy management system. Therefore co-ordinated functionality is easiest implemented by a fixed reduction in load at fixed times (a different operational strategy).

LP 26.	Frequency response functionality (using droop characteristic) effectively drives battery/inverter output in response to grid system frequency.

LP 27.	The exponential battery charging characteristic impacts the expected droop characteristic – so it's not clear what the combined output response is. This may impact frequency control if implemented on a large scale.

LP 28.	Although technical functionality has been shown, the conversion to commercial functionality is more complex. This includes issues with control, logistics, regulation, current standards and metering. For example, integration of multiple small energy storage sites, results in complications of compliance testing and metering of many sites.

LP 29.	To undertake high and low frequency response it is necessary to start with a battery state of charge that is not 100%. It is not clear what this level should be set to. In addition, running the system real time has resulted in periods where the state of charge after operation is higher than the start and periods where it is lower.

- In Figure 19 the chart shows operational experience of frequency response capability of the inverter/battery unit.
- The operation of the inverter (orange trace), moves to positive charging mode as the grid frequency moves above 50.04Hz (shown as upper broken green line). As the frequency moves below 49.96Hz, the inverter commences discharge operation, with output proportional to difference between measured frequency and dead band boundary.
- These limits are set tighter than those used by National Grid to allow functionality to be more rigorously tested.

- Towards the end of the chart, frequency regulation is disabled, and a period of charging of the battery can be seen, characterised by the declining charging power as the state of charge of the battery rises.

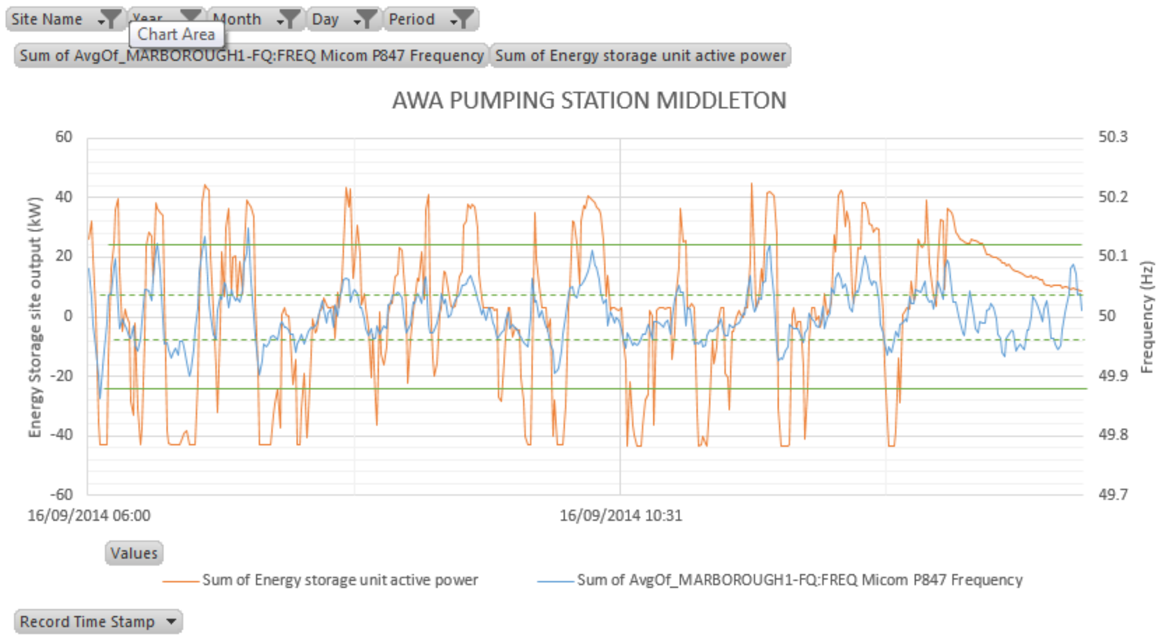


Figure 19: Results of frequency response operations

LP 30.	Voltage response functionality (using configurable droop characteristic) has been demonstrated to change the reactive power output of the energy storage unit.

Figure 20 shows sample results from investigations into the energy storage system's supplied voltage response functionality.

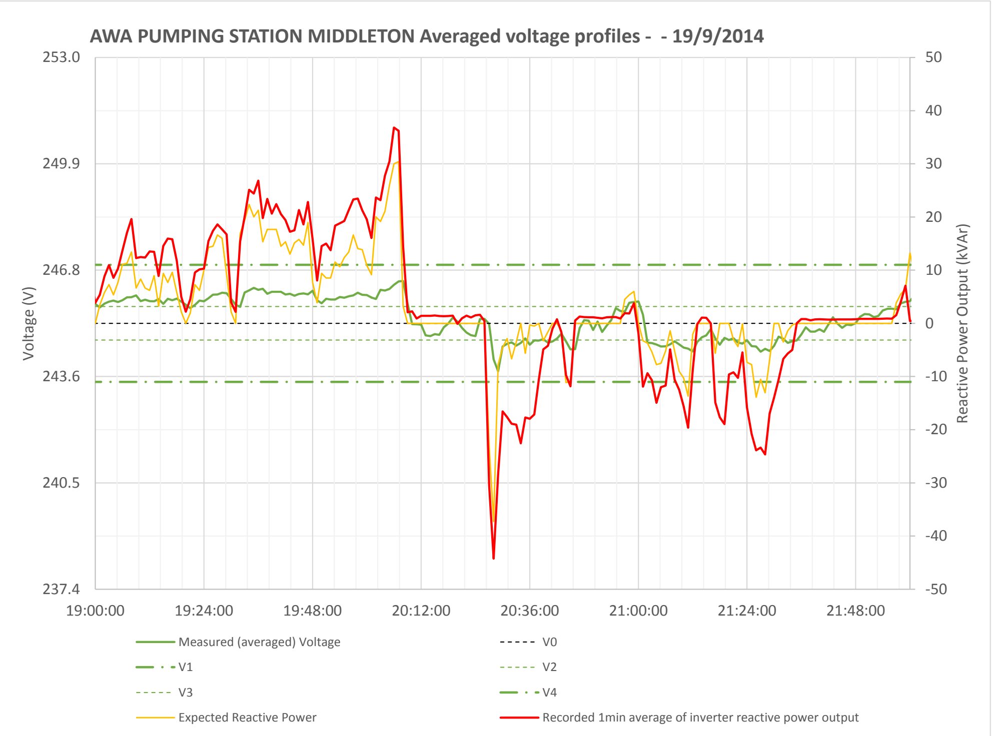


Figure 20: Results of voltage response operations

As the voltage goes above the threshold value reactive power is provided to the circuit in line with a droop characteristic. Figure 21 provides an illustration of the droop type characteristic associated with the reactive power control.

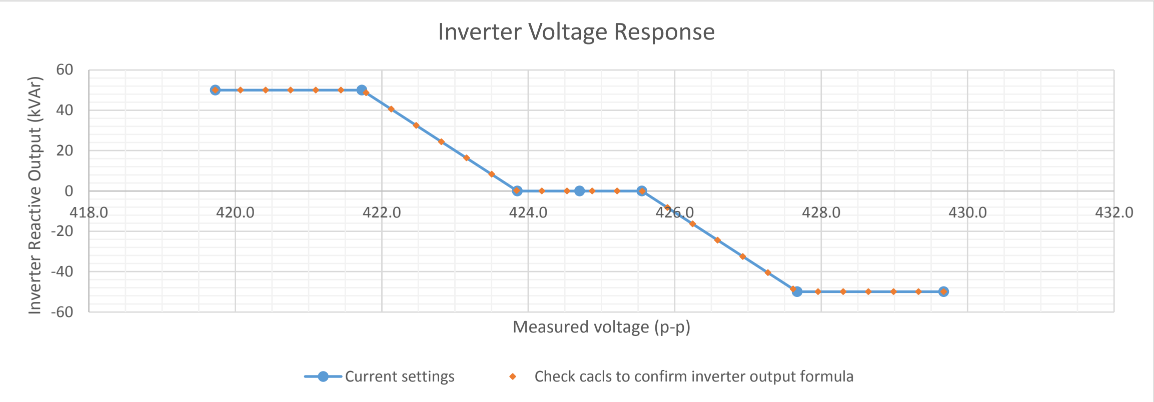


Figure 21: Illustration of droop characteristic control reactive power output.

LP 31.	Although the system output reports a change in voltage/frequency it is difficult to quantify and measure this effect on the Network in practice due to the small size of the battery system in relation to the Network.

It is impossible to show the impact on the grid frequency from such a small energy system. However a new technique to look at the impact of voltage on the Network was developed.

The absolute connected LV busbar voltage is affected by following varying factors[3]:

- the HV system voltage at the primary substation;
- the load on the feeder (both upstream and downstream of the substation); and
- the load on the individual secondary substation.

These factors cannot be controlled and held constant on the public electricity network for the purposes of these trials.

The influence of the HV system voltage at the primary substation and the upstream load/feeder impedance can be removed from the analysis by comparing the ESS reactive output to the difference in LV busbar voltage between the ESS-connection substation, and the adjacent upstream secondary substation. The schematic location of the two adjacent substations at Helford and Helford Place is shown in Figure 5. This can be simplified for the purposes of impact estimation to the per phase per unit (pu) equivalent circuit in Figure 22, where V_{HPS} and V_{HP} are the voltage at Helford Place south and Helford Place respectively. Z is the impedance of the Network between them, I is the current and Load refers to both the real and reactive load at Helford place and the downstream load (P_L and Q_L). The simplified model does not account for load variation which would impact the voltage, but merely serves as an example.

[3] Voltage is also affected by the feeder impedance and the secondary substation transformer ratio – though these factors remain constant over the time of the analysis.

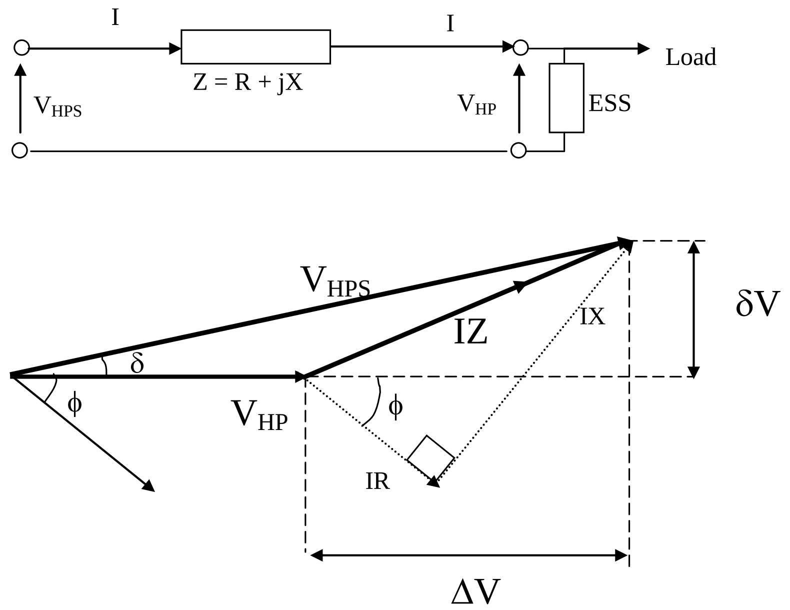


Figure 22: Simplified network schematic to look at influence of energy storage on voltage

Using the vector diagram, the following equation relating to voltage difference between Helford Place south and Helford Place can be derived:

$$\Delta V = V_{HPS} - V_{HP} = \frac{PR}{V_{HP}} + \frac{QX}{V_{HP}}$$

Where P is the total Power at Helford place (=P_L +P_{ESS}) and Q refers to the total Vars (=Q_L +Q_{ESS}). If it is assumed that only Battery VARs change with Q_{ESS} varying between a maximum export (-Q_{ESS})and maximum import (Q_{ESS})with everything else remaining constant, it is possible to estimate the difference that would be expected in ΔV for these two values of Q_{ESS} by manipulating the equation above to get ;

$$(V_{HPS} - V_{HP})_{import} - (V_{HPS} - V_{HP})_{export} = \frac{2Q_{ESS}X}{V_{HP}}$$

X = 0.024 pu (100MVA_b, 11kV_b) and Q_{ESS} = 50kVar, then with respect to the low voltage side of the transformer, the change in voltage between the substations as the energy storage Vars change can be estimated at +/-2V single phase. As this is lower than the absolute variation of voltage over the course of a day, it indicates that the energy storage at this level is not sufficient to deal control the absolute voltage.

The impact of changes in ESS reactive output in the trial has been plotted against absolute (connected) LV busbar voltage, and shows no immediate correlation to changes in ESS reactive power output (see Figure 25).

Figure 26 shows clear correlation between a trough in reactive power (-50kVAr) and a time-localised peak in difference between busbar voltage at the two adjacent sites. The converse is also true, a peak in reactive power output (+50kVAr) correlates to a time-localised trough in difference between busbar voltages at the two adjacent sites.

The time-localised peaks and troughs in busbar voltage vary; however, this variation does not appear to correlate to changes in the absolute busbar voltage. In addition, there are six occasions in Figure 24 where the difference in voltage is less than zero – i.e. that the busbar voltage of the downstream substation is apparently higher. It is not immediately clear what the cause of this might be.

From Figure 26, the range of change in difference between busbar voltages is around 2 volts, broadly suggesting that a change of 50kVA correlates to a change of 1 volt on the secondary Busbar. The negative difference in voltage appears to align with the provision of reactive power from the Energy Storage system. This value is slightly lower than the simplified model but backs the key finding. Given that the range of change in busbar voltage is around 5 volts over the course of one day (Figure 25), a conclusion is that the ESS will not be able to control voltage to a specified figure with a ±50kVAr output.

LP 32.	At 50kVAr levels, the energy storage device cannot be guaranteed to control voltage on the 11kV Network.

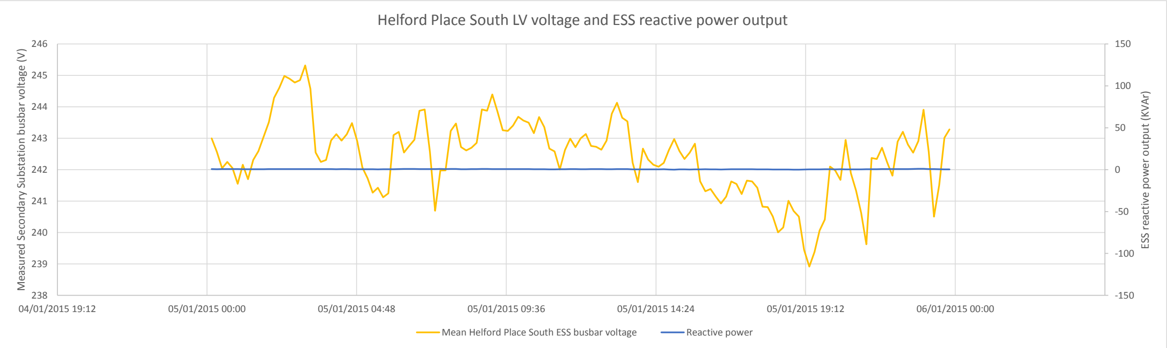


Figure 23 : Helford Place South LV busbar voltage on sample day with zero reactive power output from the ESS

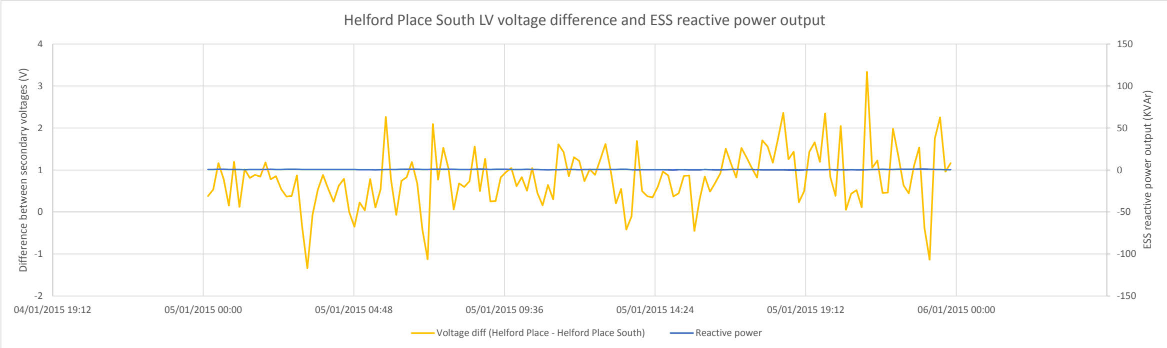


Figure 24 : Difference in LV busbar voltage between Helford Place and Helford Place South (inc ESS) on sample day with zero reactive power output from the ESS.

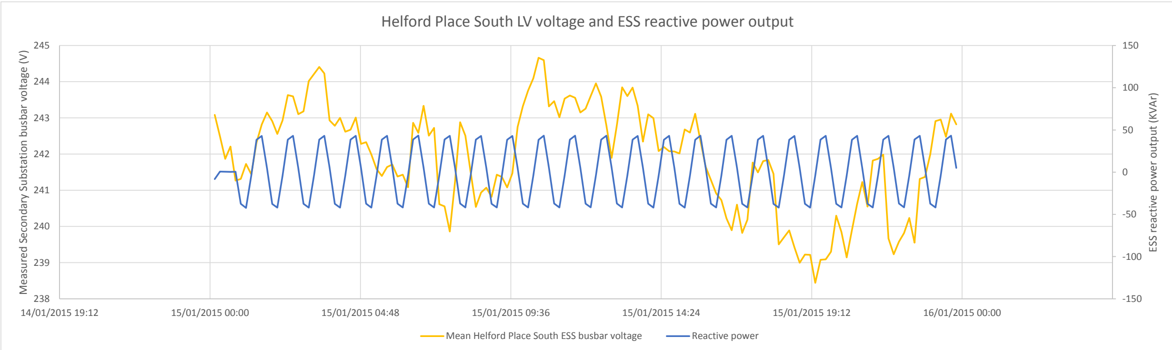


Figure 25 : Helford Place South LV busbar voltage on sample day with varying reactive power output from the ESS.

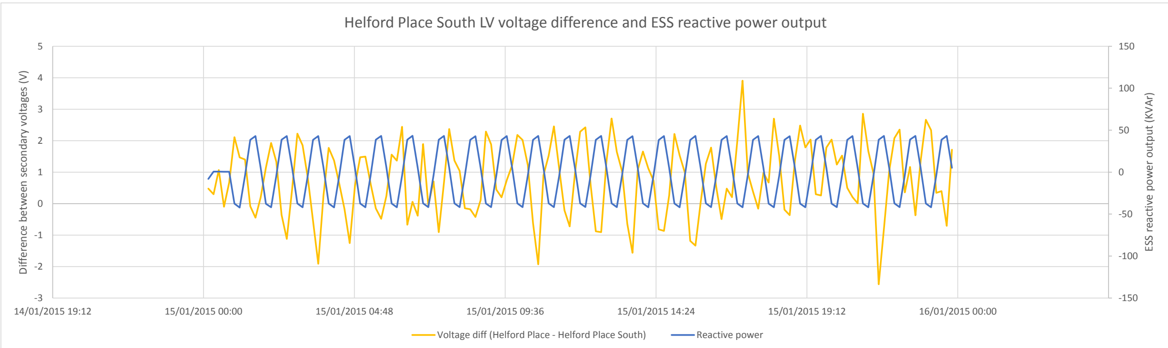


Figure 26 : Difference in LV busbar voltage between Helford Place and Helford Place South (inc ESS) on sample day with varying reactive power output from the ESS.

LP 33.	No impact, on voltage is measureable through the addition of 50kW power on the Network

There is concern that significant penetration of PV panels on residential networks (or other distributed generation) will impact voltage control capability. The ESS was used to simulate a cyclic demand to assess impact on voltage in the same way that reactive power impact on voltage was assessed as shown in Figure 27 to Figure 29. Although no obvious trial correlation can be found – the theory derived from Figure 23 suggests that where R is greater than X (as is the case in this circuit) then a greater impact on voltage will be seen.

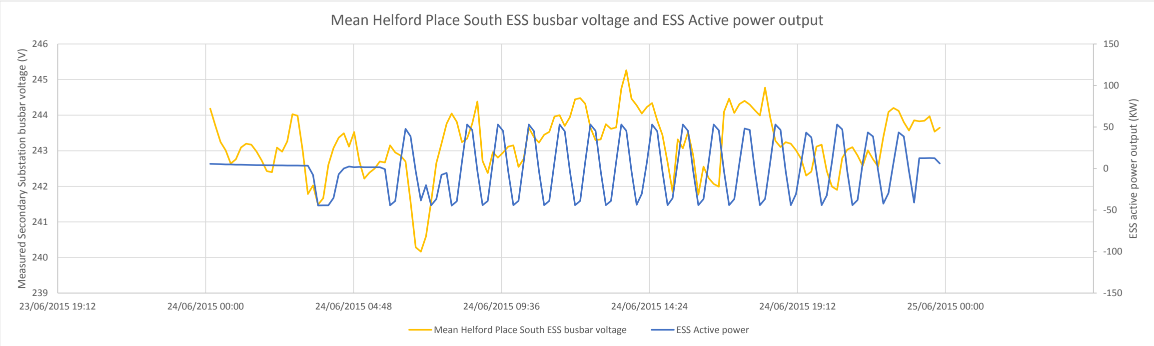


Figure 27: Mean Helford Place South ESS busbar voltage and Active power output

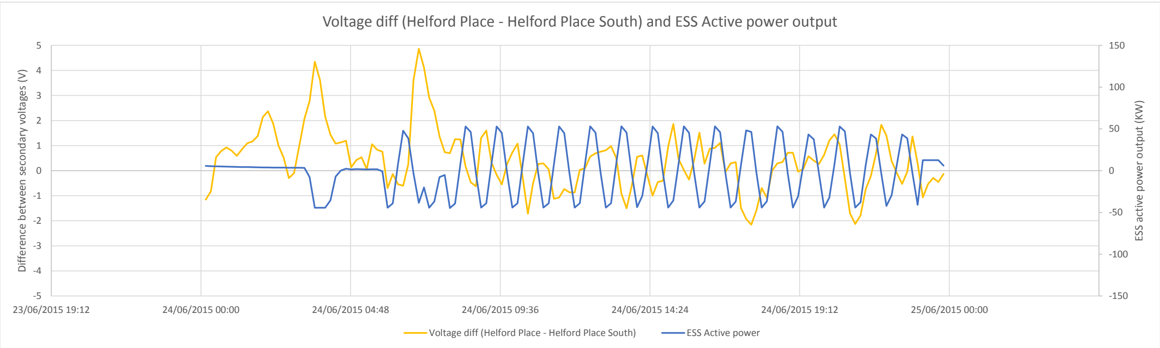


Figure 28: Voltage diff (Helford Place - Helford Place South) and Active power output

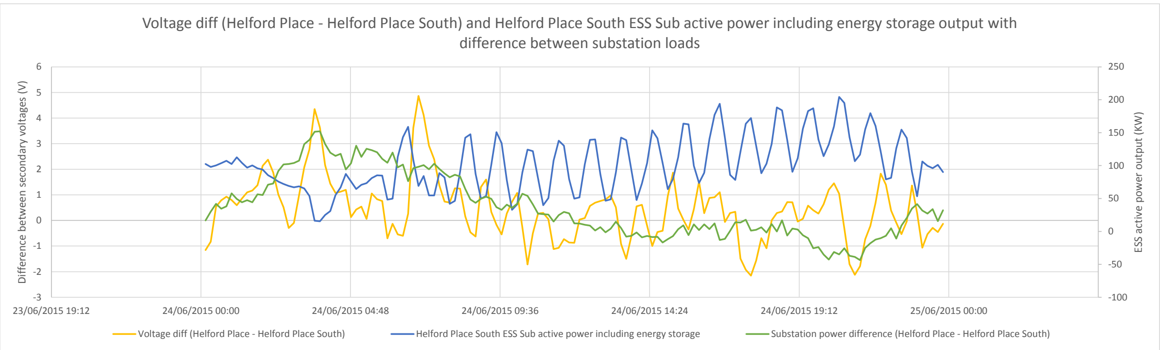


Figure 29: Voltage diff (Helford Place - Helford Place South) and Helford Place South ESS Sub active power including energy storage output with difference between substation loads

LP 34.	No impact, either positive or negative, has occurred on CML during operational phase to date, and this includes instances when the installed G59 protection has actively disconnected the energy storage systems from the network.

- The system has not had any impact on CMLs during its operational phase, either positive or negative. G59 protection is installed which causes the energy storage system to disconnect from the system during periods of voltage and/or frequency disturbance. The energy storage system then reconnects after a pre-set period once normal conditions have been re-established. The consequence of this arrangement is that the energy storage systems are not designed to supply power to their connected LV substation under grid outage circumstances.
- The G59 relay was set using vector shift as opposed to ROCOF for loss of mains protection. However, this proved to be sensitive to weather related activity and the ROCOF approach may have been less sensitive.
- The ESS disconnection arrangements are designed such that internal faults would cause protective devices to disconnect the energy storage equipment before protective devices that would affect customers operate.

LP 35.	There is some evidence that load cycling the battery may lead to reduction in available energy through disconnection of strings. However no other impacts on co-located equipment were encountered in the trial.

Only one of the sites has the inverter and battery equipment located within the substation building. Arrangements for further natural ventilation the substation building were put in place.

Battery temperatures are high under cycling and protective disconnect of the battery string appears to occur at 350^{o}C. The trace in Figure 30 suggests that temperatures have risen and limited both the charging and discharging that has been going on from about 19:00hrs.

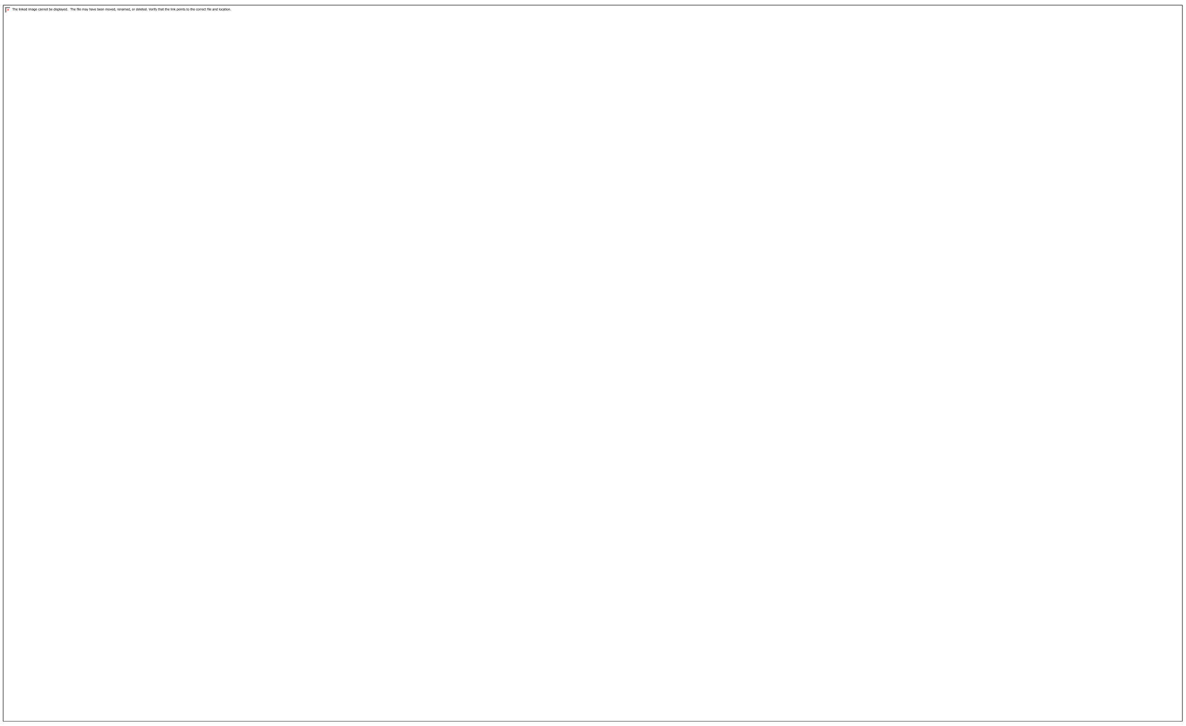


Figure 30: Reported battery output on a constant cycle showing areas of reduced output thought to correspond to temperature protection.

LP 36.	Installation of the energy storage equipment and initial operation has taken place within the existing Distribution Safety Rules, and associated WPD policies.

- The sites have been implemented such that they are compliant with the Distribution Safety Rules, and initial policies to support project operation are approved and in place (also including fires safety).
- The provision of further policy documents to support sustained operation will need to be developed if BAU is adopted for this technique.

LP 37.	At one site, the energy storage system has been seen to beneficially influence power quality, though this is thought to circumstantial rather than systematic.

- The influence of the energy storage systems on power quality at the connection points of the substations have been considered;
- one of the sites (AWA) has a significant disturbing load, this has been the focus of investigations to date;
- Investigations have shown that at this site an improvement in power quality is achieved, though it seems that this occurs somewhat serendipitously;

- A combination of connection impedance and static filter impedance (within the inverter), potentially excited by the disturbing load, appears to create harmonic currents that broadly match the harmonic nature of the disturbing load;
- This effect is reported as an improvement in harmonic component of the power quality as shown Figure 31 and Figure 32 with reported currents both with and without the energy storage unit connected to the grid shown respectively. This reported improvement from the power quality measurement system occurs when the inverter is connected but not necessarily producing power or reactive power (in standby operation);
- Marginal improvement at 11kV power quality is expected in light of this but has not been measured;
- This impact at the AWA site is thought to be co-incidental and improvement in power quality has not been observed at the one other investigated site.

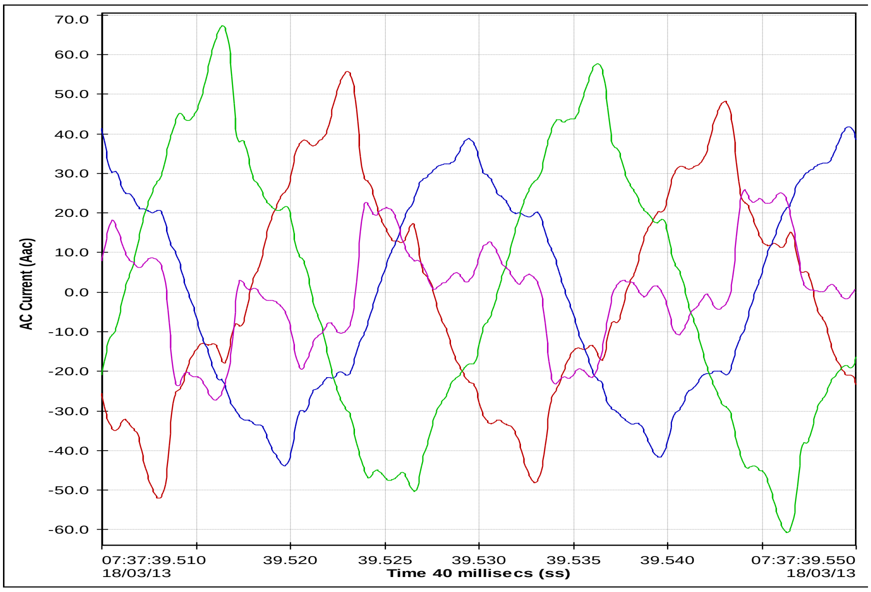


Figure 31: Current waveform capture with no ESS showing prominent 5th and 7th harmonics

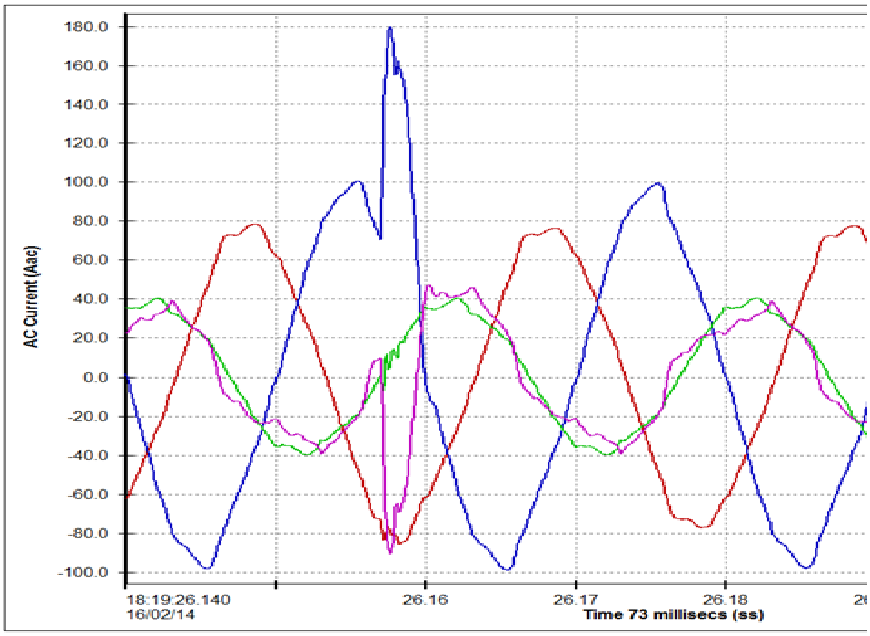


Figure 32: Current waveform capture with ESS showing harmonic improvement when the ESS is in standby

LP 38.	Correcting phase imbalance through energy storage is still very much a research area and this functionality is not commonly available in a product design.

As supplied, the system was not capable of phase imbalance correction, and consequently did not improve phase imbalance, or provide active filter for power quality improvement.

LP 39.	No conclusive evidence around battery capacity degradation was observed through the duration of the trial.

Without access to the battery management system data it is difficult to explicitly assess battery degradation. However;

- One battery suffered a string failure
- Indication of failed battery cells within strings based on limited BMS data indication
- GE have issued a recent press statement on Durathon batteries [1] in which the article states “The company is focused on improving Durathon's longevity, including managing its chemical degradation.”

However, GRIDKEY reported data isn't yet showing symptoms of battery degradation (for example a reduction in battery capacity long term would have shown up as a reduction in available energy from a fully charged to a fully discharged state).

SECTION 6

Feedback to SIM

6.1 Trial data

This trial technique was deployed at five locations, all positioned on the same feeder within the wider FALCON trials network. This pre-positioning of sites, the fact the trial are not occurring on a feeder with an existing constraint, and that the size of the system is already determined, significantly limits feedback directly from the actual field trials to the SIM.

For technique trials we are therefore left with validating some of the input parameters for battery sizing plus any residual items within the technique which may in whole or in part be validated by the trials (items such as loss of battery life, capacity fade etc.).

6.1.1 SIM Algorithm Validation

The SIM functionality is based on

- Sizing of batteries to deal with:
  - Current extent of network violation;
  - Expected load growth in coming years;
  - If a meshed network is potentially in operation;
  - Potential capacity fade;
  - number of year you want the patch to last for (i.e. battery life);
  - efficiency of battery/inverter.
- Locating the battery.
- Determining operating strategy.
- Calculates operational implications (e.g. losses, loss of life and capacity fade) for set location and determined operating strategy.

6.1.2 Preferred SIM Algorithm

The originally intended algorithm remains the recommended approach following the completion of the trials.

Battery Sizing: The trials were only able to comment on battery sizing parameters to a limited extent.

Location of batteries:

LP 40.	Proposed algorithm for selecting locations needs review in the light of the practical difficulties that arose during the trial installation phase. This review may arrive at the conclusion that an approach which incorporates notional placement along the feeder may be appropriate. The feasibility of having and applying sufficiently detailed ANM information to try and assure exact network placement seems unlikely.

Operating Strategy:

LP 41.	It is recommended that if the network has a constraint, the battery to be operated in peak-shaving mode within the SIM.

This recommendation is based in the success achieved with this operating approach, and the benefits over timed schedules, and the improved battery operating life achieved through the battery not discharging unless load dictates.

Calculation of operational implications: This will use the same parameter set as for battery sizing.

SECTION 7

Cross-technique Comparison[4]

[4] This section is common to all the engineering technique Final Reports.

Table 1 provides a high level summary of which techniques impact what network metric, with the remainder of the section providing comparison of the DAR Cable technique with other trials, on a network-metric basis.

	DAR - OHL	DAR-Tx	DAR-Cables	ALT	Mesh	Energy Storage
Thermal limits /capacity headroom	✓	✓	✓	✓	~	✓
Voltage limits	No impact	No impact	No impact	✓	~	✓
Fault levels	No impact	No impact	No impact	No impact	×	×
PQ	No impact	No impact	No impact	~	~	✓
Enablement of DG	✓	✓	✓	✓	✓	✓
Losses	×	×	×	✓	✓	×
CI/CMLs	No impact	No impact	No impact	~	~	No impact
Grid/ network services	No impact	No impact	No impact	No impact	No impact	✓
Key: ✓Positive impact; ×negative impact; ~ network dependant, may have positive or negative impact						

Table 1: Cross-technique comparison of impact.

Network capacity:

- All techniques altered capacity on the network;
- DAR evaluates capacity more accurately than static ratings which may suggest additional or in some cases less capacity. OHLs are predominately affected by wind speed/direction meaning significant variations occur both across seasons and within short time scales (minutes). When this variability of rating is combined with the low thermal capacities of OHLs (i.e. the OHL temperatures respond rapidly to the environmental changes), taking advantage of this technique is limited to particular circumstances. The dynamic ratings of both cables and transformers are dependent on ambient temperatures, meaning diurnal (for transformers only) and seasonal variations are clearly present, and the larger associated thermal capacities means short-time duration changes in ambient conditions cause less short term variability in asset ampacity;
- ALT and mesh shift load from one part of a network to another, thereby potentially relieving constraints. ALT offers a far more intuitive mechanism, whilst mesh is continually dynamic by its very nature. The extent to which benefits exist is highly dependent on the connectivity of any candidate network, and loads/generation connected to the network, and the extent to which the loads vary relative to each other; and
- Energy storage shifts load in time, reducing load at a capacity constrained key point in time, only to increase the load at a less critical point in time. The specified power and storage energy capacity clearly need to be appropriately matched to the network load; and adaptive triggering is required to deal with individually daily variations in load, to optimise the impact that the installed system can have on the network.

Energy Storage may complement DAR by providing a mechanism to alter load patterns such that constrained assets might make the best use of available ampacity.

Voltage:

- Three of the techniques offer some potential for benefits (ALT, Mesh, ES);
- ALT demonstrated the largest benefit (4%), on some of the rural circuits that were trialled, but no significant benefit was found on urban circuits;
- Mesh considered a small urban network and for this example there was no significant impact on voltage;
- In general the voltage benefit of the ALT and mesh techniques networks will depend on the voltage difference across pre-existing NOPs, and does not directly address voltage issues at the end of branches
- The installed energy storage systems achieved little impact. In general, the reactive power capacity in relation to the magnitude and power factor of the adjacent load is modest, and can be expected to be expensive to deliver for this benefit alone.

Fault level:

- As is clearly already recognised, introducing generation (including ES) to a network will ordinarily increase fault level, in this instance the ES were small compared to pre-existing fault levels, and so had negligible impact. Meshed networks will also increase fault level due to the reduced circuit impedance. For the mesh technique trial, this was within the ratings of all circuit equipment.

Power Quality (PQ):

- Mesh trials showed no discernible impact on power quality. Super-position theory and the feeding of harmonic loads via different sources means that harmonics presently fed from one source could be fed from two sources (depending on Network impedances), however, it is unlikely that larger scale trials will show any marked appreciable benefits as the majority of loads are within limits defined by standards and as such it will be difficult to differentiate small changes;
- The installed energy storage equipment did not specifically have functionality aimed at improving PQ. At one site, improvement was noted, however this was a beneficial coincidence arising from the nature of a local (within standards) PQ disturbance and the inductance/capacitance smoothing network in the Energy storage system;
- More targeted studies of a network that has a known PQ issue could be identified to further examine the potential of mesh/ALT techniques to beneficially impact this issue.

Enablement of DG:

- This was not specifically studied as part of the engineering trials (e.g. interaction between the engineering techniques and DG was not designed into the trials);
- Whilst not a direct focus of the FALCON trials, it is clear that DAR systems may offer potential benefit to distributed generation, but is highly dependent on circumstances.

For example, OHL DAR can increase export from OH connected wind farms on a windy day; but solar farm output peaks occur on clear summer days when DAR OHL is less likely to provide additional benefit;

- ALT may facilitate the connection of more distributed generation. However, this needs to be looked at on a case-by-case basis as the location of the generation along the feeder, in relation to the ratings and load, can have an impact. Where the generation is close to the source (such as in the FALCON ALT OHL trial), there is scope to add a significant amount of generation so that the feeder is able to export at the Primary and also meet the load requirements along this feeder. The nominal location for the open point may well be different between when the generation is running or is off and this may impact other metrics such as losses and voltage regulation if generation operating condition is not considered.
- Meshing may facilitate the connection of more distributed generation by providing a second export route in certain scenarios, thus saving on line and cable upgrades. Modelling also indicates that there may be cost savings from reductions in feeder losses when meshing a network with DG connected to one feeder. However, the benefits of reduced losses would have to be compared on a case-by-case basis with the costs of more complex protection required for meshing (potentially necessitating replacement of existing protection relays as well as new relays).
- ES systems offer potential benefit to distributed generation. Examples of this include: peak generation lopping - storage of peak energy production (say above connection agreement levels) for later injection to the grid; and storage of energy to allow market arbitrage.

Losses

- As discussed in the preceding technique-trial specific section, ALT and Mesh offer some potential, though the magnitude is network specific.
- The trialled ES systems increased losses, and DAR will tend to increase losses if higher circuit loads are facilitated.

CIs and CMLs

- ALT changes NOP positions and consequently affects numbers of connected customers per feeder. The trial algorithms:
  - Increased one feeder numbers by 15% (whilst optimising capacity headroom) on a rural/OHL network; and
  - Increased one feeder numbers by 50% (whilst optimising losses/voltage) on an urban/cable network.
- Meshing networks does not improve customer security as such; the improvement only occurs if additional automatic sectioning/unitising occurs beyond that offered by the pre-existing NOP. Due to communication system limitations, the implemented trials did not increase the number of sections, essentially maintaining the pre-existing customer security.

Grid/network Services:
Whilst these trials have demonstrated that frequency response is possible with the ES technique, a marketable service is not fully delivered by the installed equipment. In addition, further work would be required to put DNO owned energy storage on an appropriate commercial basis. Refer to the WPD Solar Store NIA project.

SECTION 8

Conclusions and Recommendations

In summary:

- The trial has highlighted that battery chemistry and manufacturer design philosophy impacts greatly on performance characteristics (e.g. differing charge/discharge rates, auxiliary power loads and consequential efficiency, battery calibration/maintenance requirements). This results in a trade-off between purchase cost/operating cost/battery life span/specific technical requirements (such as ramp rates). It is recommended therefore that future functional requirements for battery systems remain open ended at this time (until battery chemistry becomes more established) to ensure battery purchase is not too restrictive. In addition, it is recommended that particular use of reference sites is made, so that operating experience can be judged.
- Good availability of technical performance parameters (including battery state of charge) and data logging from the battery management system are key on demonstration and research projects and a clear and detailed discussion with the manufacturer on proprietary data (both for access and dissemination) is recommended prior to purchase.
- At 11kV, and for fixed systems, a single site energy storage system (if a suitable site can be found) would simplify the challenges of installing/commissioning multiple times, and the complexity of control equipment coordinating across multiple sites. However a dispersed site could offer the same functionality while potentially improving on availability and make it easier for customer owned energy storage assets to be integrated into Network management.
- Peak shaving:
  - The technique trial effectively demonstrated the capability of energy storage systems to shift load in time, reducing load at a capacity constrained key point in time, and increasing the load at a less critical point in time
  - Whilst trials have demonstrated the capability of energy storage to effectively peak-lop, the trials also show that the trigger thresholds used are only effective (i.e. only call the ES into service) for a relatively small number of weeks in a year. Outside of this period the equipment is not required (for capacity), and could be used for other purposes such as frequency response.
  - Peak-shaving at individual substations is dependent on: assessment and forecasts of future load; decisions about the available state-of-charge; and magnitude versus duration of the targeted peak reduction. For a fully operational device, this functionality should be specified as an adaptive peak-shaving controller.
  - Peak-shaving of an 11kV feeder that involves coordination of multiple ES systems is broadly similar to the requirements for peak-shaving at an individual site, but requires additional control logic that allocates the operation out to the individual sites (factors to consider in the allocation to individual sites include: initial state of charge; life management of individual batteries; and site outages).
  - The trial showed that it is difficult to measure and demonstrate the impact of reactive power output on LV network voltage (given the installed capacity), and

consequentially a method of assessing voltage-differentials across adjacent sites was developed.

- Frequency response:
  - The trial demonstrated a capability to deliver frequency response, as one example of potential ancillary service provision.
  - Considerably more work, beyond the scope of FALCON, would be required to detail service capability in this area. Details would include: linearity of response to high/low frequency (and how this varies with state-of-charge); number of events per day, duration/energy content of events, optimum state-of-charge that frequency response would start from (to allow high and low frequency response) and impact on lifetime;
  - Where multiple battery units are envisioned, it seems likely that multiple registrations and multiple metering arrangements would also be required. Dispersed installation might also challenge prevailing commercial arrangements, with aggregated operation not being recognised commercially.
- Audible noise was also a concern with the equipment and its locations. Work with the manufacturer led to modified inductors being fitted to the converters which reduced audible noise. The construction and electrical size of such components is clearly important to achieving satisfactory performance.
- There have been issues with availability and energy level uncertainty caused by;
  - Battery system commissioning and early trial issues;
  - State of charge (SOC) control and reporting;
  - Onerous re-calibration procedures;
  - Differences between strings and batteries manifesting as different discharge/charge timings;
  - Different discharge/charge curve shapes.

Understanding the available energy in the control room is key to effectively managing the batteries on the Network. This creates a challenge and further research and work is necessary on these systems in order for them to be considered as a reliable source of energy on the UK grid system.

Whilst energy storage has been shown to improve network capacity headroom over peaks, the experienced costs within the trial are high. In view of the reductions that have already occurred in energy storage prices, and that further reductions are anticipated, it is recommended that technology tracking in this area is carried out, to monitor for key changes in: capability/cost; practice of connected customers downstream of the meter; and development in market practice (including second-life batteries). A follow on project investigating the interfacing, metering, control and energy management of multiple customer battery units operating to provide capacity headroom at a feeder in conjunction with frequency support (to provide an income stream outside of this) would assist with accelerating remaining operational issues of energy storage within the grid. However, in view of the changes in technology, it is recommended that this is undertaken in conjunction with a mixed set of battery technologies, so that impacts of different battery chemistries can be investigated in regards to energy management and aging in multiple operating modes.

Appendices

A References

[1] Reuters, July 26th 2015.

http://uk.reuters.com/article/2015/07/26/us-general-electric-energy-storage-idUKKCN0Q00FS20150726

B Initial learning objectives

	A	B	C
1	Charge/discharge period	Relationship between capacity and power output	Ramp rates required
2	Reliability	Availability	Revenue for ancillary services
3	Peak lopping	CML impact	Extra switchgear required
4	Thermal limitations of substation	Cost of implementation	Advantages of multiple sets working in co-operation
5	Control/NMS requirements	DSR/Safety requirements	Protection of networks
6	Effect of faults on operation	Power quality resolution on different voltage levels	Phase imbalance resolution on different voltage levels
7	Effect on transformer	Effect on RMU GCB breaking capacity	Communications required
8	Local versus remote control	NMS/BMS requirements	Training for operational staff
9	Measurements and instrumentation required	Commissioning process	BMS maintenance routine
10	Ability to redeploy the assets	Effects on later conventional reinforcement	How close to the NOP is the asset deployed for voltage reasons?
11	How close to the feeder is the asset deployed for current reasons?		

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