

Demonstrating the benefits of short-term discharge energy storage on an 11kV distribution network

UK Power Networks

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Foreword

Both the last and the current coalition governments have set binding targets in law for the UK to reduce its contribution to carbon emissions, and UK Power Networks knows that it will play a leading role in enabling this low carbon transition. The renewable and low carbon technologies needed to meet these targets will pose significant challenges on distribution networks and the wider electricity system.

The two main challenges are expected to be: more pronounced peak demand caused by distributed low carbon technologies, such as domestic heat pumps and electric vehicles; and intermittent or non-dispatchable low carbon generation that will reduce the flexibility of the system, creating challenges for real-time balancing of the system.

UK Power Networks is a strong believer that energy storage is a key source of flexibility that can help address some of the challenges associated with the transition to a low-carbon electricity sector. Although it is our view that the storage technology itself is getting mature, there still many questions outstanding for the DNO community – application, reliability, cost, financial model, market entrance, etc.

In response, we have started two storage demonstration trials. Initially, we commissioned a smaller scale installation at Hemsby (200kW/200kWh) to start answering questions regarding application, reliability and efficiency. Based on the early learning from this trial, we launched a larger scale installation at Leighton Buzzard (6MW/10MWh), the Smarter Network Storage project. This trial will investigate the economics and business models involved in operating a storage device.

This report details the methods, outcomes and learning from this first energy storage trial, the LCNF Tier 1 project 'Demonstrating the benefits of short-term discharge energy storage on an 11kV distribution network'.

I trust the following report will be of use to DNO community and will progress the UK knowledge base on energy storage.



Martin Wilcox

Head of Future Networks

Note: Over the course of the project, EDF Energy sold their distribution networks to CKI, creating UK Power Networks. Furthermore, the main academic contributor moved positions from Durham University to Newcastle University, which became the new project partner. Both changes are reflected in this report.

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1. Executive Summary

1.1 Introduction

UK Power Networks installed a 200kWh Li-Ion Energy Storage System (ESS) at an electricity substation site at Hemsby, near Great Yarmouth, to understand the impact and potential benefits of small-scale electricity storage on a distribution network. The battery was procured in 2007 as part of the AuraNMS (Autonomous Regional Active Network Management System) research project, which received support from the Engineering and Physical Sciences Research Council (EPSRC) and the Innovation Funding Incentive (IFI).

Having commissioned the device in April 2011, UK Power Networks registered the first Low Carbon Network Fund (LCNF) Tier 1 project to gain real, practical experience with the device and its capabilities, and to disseminate the findings to the other DNOs.

In the process, UK Power Networks also demonstrated a smart grid architecture comprising ABB's devices and which were demonstrated to support software written by a third party (neither UK Power Networks nor the vendor) and reacting to signals from multiple remote sites. To separate software from hardware is considered an important move towards open standards for future smart grid applications. The application in this trial is believed to be an industry first by UK Power Networks.

Table 1 Project details

LCNF Tier 1 project details		
Funding for trial period	Project budget:	£340,000
	LCN Funding budget:	£250,000
	Partner (ABB) Contribution:	£90,000
Cost of trial	Total project cost:	£388,433
	LCN cost incurred	£228,786
	Partner (ABB) Contribution:	£90,000
	Additional funding from UK Power Networks:	£69,647
Duration	June 2010 to January 2014*	
Reference	UKPNT1001	
Title	Demonstrating the benefits of short-term discharge energy storage on an 11kV distribution network	

* The original project close date was October 2012. The project was formally extended after delays in commissioning of the ESS, and an incident with the CO₂ fire suppression system which caused the site to be inoperable for several months. Both extensions are discussed in Chapter 6.

1.2 Aim of the project

The aim of the trial was to explore how electricity could be stored to overcome the challenge of intermittent power production from renewable sources. The battery technology was tested to see how much electricity could be stored from local wind turbines when power generation exceeds demand. In particular, the trial explored the potential to reduce voltage fluctuations and manage demand on the distribution network.

The benefit of being able to automatically manage demand and reduce voltage fluctuations is the potential to accommodate additional demand or generation on the existing feeders, within the thermal limits of the plant and circuit, without breaching voltage limits or needing to curtail generation.

The installation used for this trial is now considered small in terms of the amount of energy that can be charged / discharged. A facility of this size fitted the aim of the project very well as the project focussed on demonstrating the proof of concept without making a significant impact on normal network operations.

1.3 Project objectives

The project included multiple objectives to maximise the learning potential:

- Test the storage device's capabilities on a real electricity network
- Demonstrate load-shifting capability of the device
- Study how a battery could manage larger amounts of demand or generation
- Consider and rank the value of other proposed uses for batteries, both to electricity network operators and intermittent generators
- Understand the potential lifetime of the battery
- Embed the findings into a design tool for network planners and share the tool with other DNOs

1.4 Stakeholder benefits

The project included three main benefits for its stakeholders:

- Demonstrate that storage could enable more renewable generation or additional load to be connected to the network without the need for conventional reinforcement
- Understand the performance of a storage device on the network
- Identify any practical difficulties and explore solutions

1.5 Trial description

The battery used in this trial was procured as part of the AuraNMS project. The AuraNMS research and development project commissioned the first UK-based electrical energy storage device on a distribution system, along with an open architecture for substation control based on ABB's COM600 substation computer. This LCNF Tier 1 trial built on that project by using the facility already in place and was designed to take the readiness of the solution to the next level by

demonstrating the benefits of storage connected to an 11kV network. To achieve this outcome the trial focussed on voltage control, power flow management and validation of the manufacturer's data sheet.

To understand the network impact (voltage control and power flow) and behaviour (data sheet validation) of energy storage, a series of control algorithms were developed in collaboration with Newcastle University as part of a testing regime.

To provide network visibility, the trial included the installation of remote monitoring across the network to enable the control algorithms to respond not only to local (at ESS) network events, but also to wider network issues such as under-voltage at remote feeder locations, generators or reverse power flows.

Trial system overview

- Energy capacity: 200 kWh
- Real power: 600 kW (peak) for short durations
- Reactive power: 600 kVAr
- Four-quadrant operation
- Li-ion battery
- Can be connected to two feeders
- 7 Remote monitoring points



Figure 1 the energy storage installation as built

The three trial Methods

1. Voltage control
2. Power flow management
3. Manufacturer's data sheet validation

Each Method comprises several sub-methods explained in chapter 3.

1.6 Project outcomes

The trial met its objectives by demonstrating real network benefits of 11kV connected and DNO owned energy storage. To achieve this outcome, the project built a smart network integrating the energy storage system, remote monitoring of distributed generators and the wider network, and a series of advanced algorithms for the ESS controller written by a third party, neither UK Power Networks nor ABB. This enabled the energy storage device to operate autonomously, without centralised control room intervention. This is major technology achievement as decentralised intelligence and open architecture are the key principles of a smart grid.

This achievement comprised the following key project outcomes:

- **Autonomous voltage control** via both reactive and real power control was carried out and a reduction in voltage fluctuations achieved.
- **Peak shaving and feeder demand management** was successfully demonstrated by carrying out short term imports or exports of real power. A reduction in peak feeder demand was achieved.
- **Autonomous charge and discharge operations** of the ESS were achieved without the direct intervention of the control room.
- **Autonomous interaction between the energy storage and local renewable generation** was demonstrated.
- **The efficiency of the device was measured and the relationship with auxiliary power consumption was better understood.** The efficiency of the batteries alone varied between 90 – 95%. Auxiliary power consumption had a significant impact on the round trip efficiency and could be as low as 78%, depending on the amount of power exchanged, as the auxiliary power demand remained constant over time. This is discussed in section 4.6.
- **The accuracy of the manufacturer’s datasheet was tested and validated.** Deviations were identified between the controller set-points and the system’s behaviour. These were analysed and used to calibrate the controller.
- **The lifetime of the energy storage system was assessed.** The lifetime of the primary equipment and the valves was estimated at 25+ years, 15 years for the control system and 20 years for the batteries, depending on the mode of operation. Operating the energy storage on a daily cycle that accesses 75% of the battery capacity will reduce the available capacity at a rate of 1.5% per annum. This equates to a 20 year lifetime if end-of-life is taken to be 70% of the installed capacity.
- **Use Cases for energy storage were developed, tested and assessed.** The use cases that deliver most benefits to both DNOs and distributed generators are the power-flow management ‘Peak-shaving’ and ‘Reactive Power Following’ use cases. The use cases which required manual intervention or had local control only were considered to have diminishing returns.
- **The impact of energy storage on the Ormesby and Martham networks was monitored.** The methods of planning prior to the trial did not consider the time dimension (considering static situations instead of dynamic situations), which is required to simulate charge/discharge behaviour. The knowledge used was captured in the energy storage planning tool developed as part of this project.
- **The operational experience gained was shared with DNOs through publications, conferences and the Energy Storage Operators’ Forum.** These experiences contributed to de-risking recent storage projects such as the Smarter Network Storage second tier project.

1.7 Key learning

This trial was an early demonstration of the impact and benefits of energy storage on distribution networks. Through its challenges and its successes, this trial generated necessary knowledge to advance the readiness of this technology as a smart solution. This will enable future larger scale

storage projects to be set up more effectively and more cost efficiently, which ultimately benefits customers.

Key learning includes:

- **Readiness:** Energy storage is a technically viable smart solution that can operate autonomously.
- **Load management:** If the demand profile behaviour is sufficiently well understood and thus predictable, the feeder peak power can be reduced by utilising the storage system power limit defined in the “controlling” algorithm.
- **Network location:** Locating the energy storage between two feeders can increase flexibility and utilisation assuming they have complimentary characteristics.
- **Voltage management:** Although both real and reactive power have an impact on the voltage, reactive power has been confirmed as the most effective way to manage voltage. The behaviour of the wider voltage control scheme (i.e. on-load tap-changer automatic voltage control relay) also needs to be accounted for.
- **Capacity management:** To manage capacity issues due to thermal constraints, real power exchange is needed. Storage can deliver this capacity but its effectiveness is dependent on the demand profile.
- **Open architectures:** The project has shown that if vendors make software libraries available, third parties can write effective software code which controls the network.
- **Increasing generation output:** Using the Normal Open Point to charge and discharge the ESS allowed up to 50% of energy that would otherwise be curtailed to be exported. An isolated ESS would require a substantial capacity to have much effect in this situation. Substantial energy storage capacity is required to increase the energy output of a constrained embedded generator without spilling energy if no further control actions such as curtailment or network switching are available.
- **Round trip efficiency:** The auxiliary power consumption and the operating regime of the energy storage have a significant impact on total round trip efficiency; whole life costing is needed to assess the financial relationship between round trip efficiency and benefits achieved. Optimisation of auxiliary support systems could reduce power consumption in future installations.
- **Remote network measurements:** Operating a GPRS/ADSL Ethernet based measurement and control system has shown good general availability, but suffers some data dropouts that would need to be accounted for in an enduring solution.
- **Accuracy:** Deviations between expected and actual ESS behaviour were detected. Calibration could mitigate the inaccuracy, however as the set-points are dependent on the network impedance, the calibration might no longer be accurate if network conditions change.
- **System reliability and protection:** Stability of both ESS and communication network proved a major challenge. Over the course of one year, the site experienced one mis-fire from the fire suppression system, three hardware failures and six trips due to the installation of a G59 relay which was installed as an additional protection whilst experience

was gained with the ESS's software protection solution. Now that confidence with the ESS has increased, consideration should be given to a more appropriate protection scheme or more suitable protection settings.

- **Battery operation:** Although the capacity of the ESS was 200 kWh, it was recommended to use only 75% of the battery capacity to preserve battery life. Hemsby was therefore mainly operated with a discharge lower threshold of 25%.

1.8 Recommended areas for future work

The Hemsby ESS trial demonstrated that energy storage is a key source of flexibility that can help address some of the challenges associated with the transition to a low-carbon electricity sector. The UK energy sector echoes this sentiment and the Smart Grid Forum has identified it as one of the key smart interventions likely to be required in the future smart grid. However, challenges remain in utilising the full potential of storage on distribution networks. The challenges include:

Table 2 Key recommended areas for future work

Area	Detail
Quantification & allocation of the benefits and costs	The cost of procuring a storage device is still deemed high, although this is expected to reduce with large scale uptake, or commercialisation of lower-cost technologies. The costs of operating storage can also be significant due to energy conversion losses and powering the auxiliaries. Quantifying the benefits of storage needs to be further investigated to build the business case. Multiple use cases will benefit the wider system but the benefits can typically accrue to parties other than the DNO.
Expand services of DNO owned storage	Depending on the network conditions, a storage device could be idle for some time, during which time it could offer services to the market. Without doing so the asset is likely to be under-utilised and inefficient. This is part of the scope of the Smarter Network Storage project.
Reduction of cost of installation and operation	Reducing the cost of installing and operating energy storage will have a positive impact on the economic viability of storage connected on distribution networks.
Improvement system stability and reliability	For this technology to become part of business as usual operations and be a suitable smart alternative to traditional network interventions, the reliability of the full ESS facility will have to improve significantly. Areas such as interoperability will have to be addressed.

Development of Regulatory Framework	There is currently uncertainty regarding the compatibility of the current regulatory framework with large scale, DNO-owned storage and how this storage may be operated. This is being explored by both the Smart Grid Forum and the Smarter Network Storage project.
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In response to the challenges around the economics of DNO owned storage, UK Power Networks was awarded funding for the Smarter Network Storage (SNS) project under LCNF Tier 2 scheme. This project is carrying out a range of technical and commercial innovation to tackle these challenges and facilitate more efficient and economic adoption of storage.

<http://innovation.ukpowernetworks.co.uk>

2. PROJECT OVERVIEW

The following table outlines the project objectives as laid out in the updated registration proforma (dated 12 August 2013).

Table 3 Extract from updated registration proforma

Section	Description
Project Title	Demonstrating the benefits of short-term discharge energy storage on an 11kV distribution network
Project Background	<p>Electrical storage offers one means to manage intermittent demand and intermittent generation on a distribution network within existing network constraints, principally thermal capacity.</p> <p>UK Power Networks has previously explored with Newcastle University and ABB the benefits that storage can offer in managing intermittent generation. As a result, UK Power Networks purchased a Li-Ion storage device which was commissioned in April 2011.</p> <p>This project will take the existing results from network simulations and validate them by running progressive experiments on the storage device itself, throughout a number of seasonal, load and generation output variations on the network.</p>
Scope and objectives	<p>Martham primary substation is an example of a primary substation on UK Power Networks' 11kV networks which has distributed generation (DG) attached. This comprises a wind farm with 10 turbines, each of 200kW generating capacity. Whilst the network is robust to all current combinations of load and generation, future load growth or additional generation would eventually push thermal capacities to the point of requiring reinforcement.</p> <p>The objectives of this project are to:</p> <ul style="list-style-type: none"> • Perform validation of the storage device's capabilities with respect to data sheet performance, when installed on a real network. Specifically, the efficiency of the device will be measured • Demonstrate load-shifting within the limits of the device capability (200kWh, 1 hour discharge duration) • Understand the extent to which these interventions could be scaled up to manage larger quantities of demand or generation • Validate a number of existing use-cases which have been proposed and simulated, rank their usefulness and understand their relative value to the DNO and to an intermittent generator • Understand the potential lifetime of the device • Embed the learning into a design tool for network planners, and into dissemination material for the UK DNO community

	<ul style="list-style-type: none"> Propose next steps <p>Newcastle University will suggest a number of modes of operation based on their previous simulations, which have shown potential benefits in relieving thermally stressed components, reducing technical losses, reducing reverse power flow, and preserving headroom for further DG to join the network. Each mode will be verified by ABB and UK Power Networks' Control before being trialled.</p> <p>Equipment and commissioning costs have already been provisioned and are out-of-scope of this project.</p>
Success criteria	<p>The project will have succeeded if the partners are able to:</p> <ul style="list-style-type: none"> Validate, and if necessary update and re-run existing network simulations of a number of use-cases Report practical, measured performance of storage with respect to data sheet performance Report on any practical difficulties encountered and new operating practices required to manage a storage device on the 11kV network Categorise use-cases for storage on the 11kV network into those of most value and those which only offer diminishing returns Indicate the conditions under which storage may present a compelling option (such as network characteristics, and the level of fund-sharing with other actors)

3. DETAILS OF THE WORK CARRIED OUT

Key messages

- This trial is building on the findings of the AuraNMS project and operated the ESS already installed
- The site has the ability to switch between two feeders from two primary substations to increase flexibility and utilisation
- A communications network for remote monitoring was established across the distribution network
- The trials were designed to start with basic manual control and gradually move to autonomous 'network supportive' mode

3.1 Introduction

The ESS was originally installed as part of the Autonomous Regional Active – Network Management System (AuraNMS), a previous innovation project run by a partnership pursuing the concept of active power distribution networks. ABB were contracted to deliver the device as a turn-key, energy storage product, which was based on Saft's Lithium-ion Intensium Flex battery technology. Other battery technologies were considered at the time, but lithium-ion (Li-ion) was chosen due to the low operating temperature and wider industry interest for this technology. One of the key objectives of AuraNMS was to prove the technical viability of energy storage as a smart solution.

This LCNF trial was designed to take the readiness of this promising technology to the next level by demonstrating the benefits of storage for an 11kV network. To achieve this outcome, the trial focussed on voltage control, power flow management and validating of the manufacturer's data sheet.

This chapter sets out how the trial was designed and which trial methods were used to demonstrate these benefits in a real-life situation.

3.2 Trial design

3.2.1 Energy Storage System overview

The ESS had a 200kWh Li-ion battery, capable of exchanging real power up to 600kW for short durations (<15mins) and reactive power up to ± 600 kVAr for unlimited periods of time. In most scenarios, the real power was limited to under 100 kW to maximise the duration of energy exchange, and the reactive power was limited to ± 200 kVAr to prevent excessive reactive power flows which could impact normal operation of either the Martham or Ormesby feeder. Both the real and reactive power limits were typical values used during real ESS operations and by limiting these, the components' life spans were prolonged.

The Storage device consisted of:

- Saft's Lithium-ion Intensium Flex batteries
- ABB's SVC Light power conversion system
- A step-up transformer and AC filter components
- A thermal management system
- A prefabricated building and an integrated control and protection system

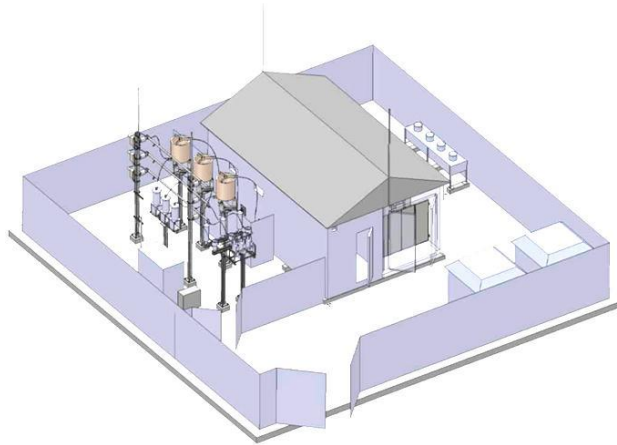


Figure 2 Drawing the of the commissioned site

The last three components were all designed and specified by ABB in Sweden. The development activity for these included making the system suitable for installation on a distribution network, as previous designs only had been used at transmission levels.

A full description of each component with photos is available in Appendix C.

3.2.2 Network overview

As part of the AuraNMS project, a network location was selected such that the maximum range of benefits with the ESS could be considered from a single installation. It was decided to install the ESS near a 2.25MW wind farm in North Norfolk in the Eastern Power Networks (EPN) licence area, between two 11kV feeders and establishing a Normal Open Point (NOP), as shown on Figure 3. This gave the trial the added flexibility of changing network conditions. The two feeders were Winterton, fed from the Martham primary substation, and the Hemsby feeder, fed from Ormesby primary substation.

A mixture of residential areas, rural areas and seasonally occupied accommodation were supplied by the feeders in this region. The average load on the feeders was 1.15 MW and 1.30 MW with peaks of 2.3 MW and 4.3 MW respectively. The wind farm with 2.25 MW installed capacity was connected midway along the first of these feeders. This installation had ten fixed speed induction generators, so there was significant reactive power demand while generating (approximate 0.5MVar was required for every MW generated).

Accordingly the ESS was rated such that it could provide roughly half of the reactive power required and could smooth between 10% and 25% of the wind farms' output for varying lengths of time.

Network simulations were conducted on the two 11kV feeders connected to the ESS to understand the existing levels of load and generation, and to identify possible current or future issues that energy storage could help with. Several locations across these 11kV feeders were chosen to have additional monitoring equipment installed to provide real-time information at key points on the network. These data sources were used by the ESS to respond to remote changes in network behaviour.

Daily load profiles show that the two feeders had quite different characteristics. On the first, the most significant demand occurred during the night during winter, due to a high number of homes heated by night storage heaters. The second feeder had much less storage heating, and in this

case summer loading was higher due to increased holiday demand. These dissimilar characteristics meant that events requiring ESS support (e.g. reverse power flows, voltage deviations, etc.) were likely to occur at different times, increasing the utilisation of the ESS.

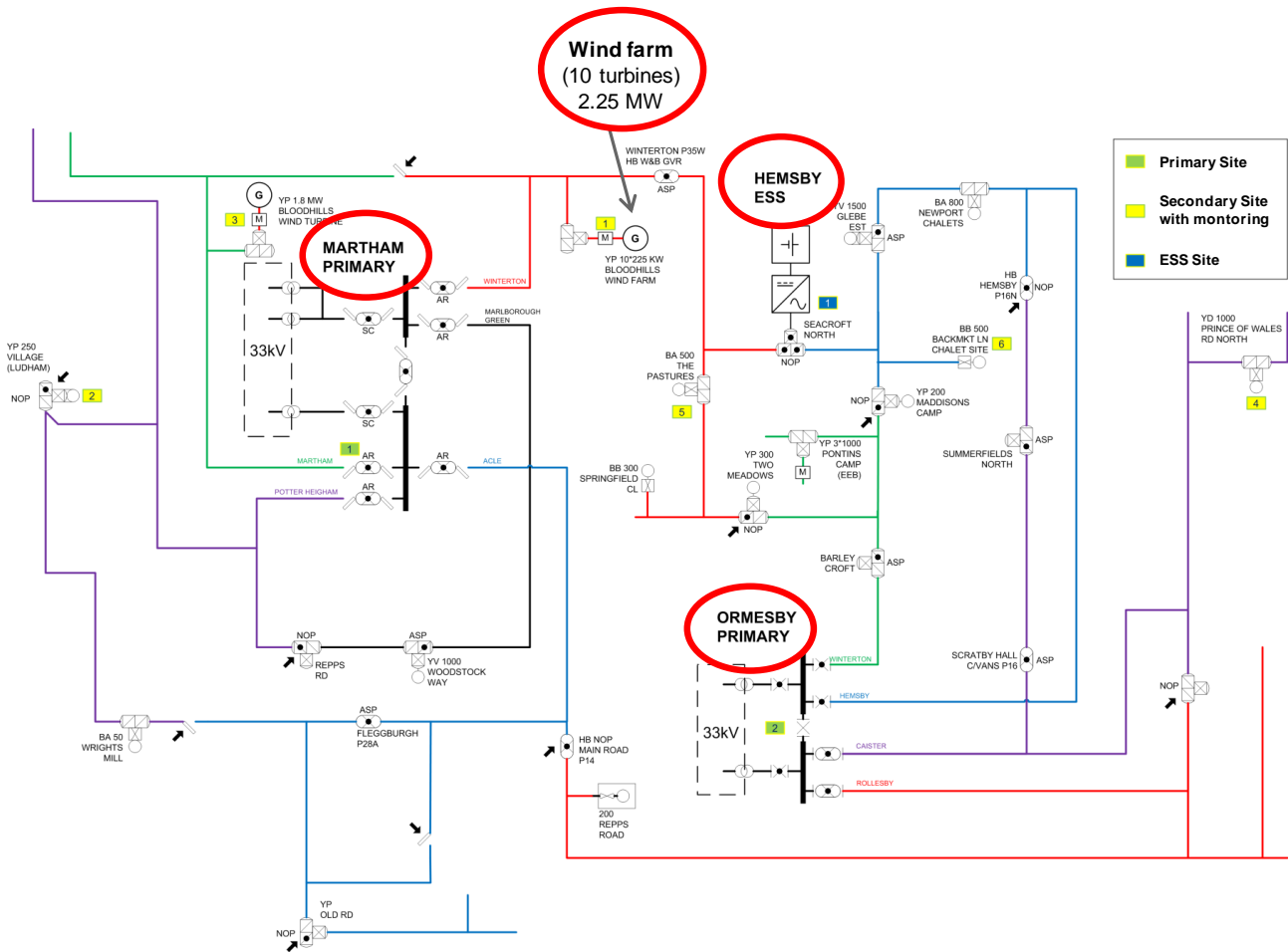


Figure 3 Overview of network configuration and remote monitoring network

3.2.3 Remote monitoring and communications architecture

The scope of the AuraNMS project was limited to ESS operation based on local monitoring only. To advance the readiness of energy storage as a smart solution with this trial, UK Power Networks installed remote monitoring across the network to enable the control algorithms to respond not only to local (at ESS) network events, but also to wider network issues such as under-voltage at remote feeder locations, generators or reverse power flows.

This network comprised new real-time monitoring and communication installations at both Martham and Ormesby primary substations as well as installations at secondary locations across both 11kV feeders to provide measurements at remote locations across the feeders, as shown on the diagram above.

3.3 Design implementation

3.3.1 Network modelling

To test a number of assumptions, simulation models were developed to understand the expected impact of control algorithms before implementation, and to test scenarios that could not be

carried out in practice (e.g. changing location, power or energy ratings). The simulation software comprised three main parts; a network model, an ESS model and a control system.

- **Network model:** A load flow model was constructed in IPSA+ power system analysis software, which reports the power flows and voltages in the network. The model was built with detail of transformers and conductors from the 33kV connection point to the level of distribution transformers on the feeders to which the ESS can be connected. On the other substation feeders, the demand was represented by a lumped load for each feeder. IPSA+ provides an interface to the Python programming language, which enables automated control of the network model and load flow engine. This functionality was used by the control system, described below, to implement algorithms that use measurements of the current network conditions.
- **ESS model:** The ESS was modelled in the network as a combination of load and generator, both of which can operate with a power factor from zero to unity. In this way, the ESS device could absorb and/or source real and/or reactive power in any combination within the rating of the system. Although reactive power up to the rating of the power electronic converter was always available, the duration of an action using real-power was a function of the power level and limited by the capacity of the battery.
- **Control system:** At the centre of the simulation software was a control algorithm that followed deterministic rules to manage the operation of the ESS. Information processed by the algorithm came from measurements of the network state and internal registers which retain the prior actions of the ESS. The algorithm ensured that the capabilities of the ESS for both power rating and energy capacity were never exceeded. Decisions on what power level to operate at, when to switch the ESS between feeders and battery management were reached by following a set of rules in the algorithm. State-of-charge management could either operate on a scheduled basis or in a responsive mode. In responsive mode, any time the battery was not in the preferred state-of-charge (e.g. when the site was idle), power would be exchanged with the network to adjust the battery charge, unless this process would cause the network to move into an undesirable state.

A wide range of control parameters were available, these included:

- which network measurements to respond to
- what measurement value triggers a response
- how much power to use once triggered
- what to do if battery energy is expended

3.3.2 11kV Site Operation

The ESS was controlled by ABB's Mach2 control system. Initially, the Mach2 only had a local interface on site meaning it required a physical operator to be present to perform the energy exchanges. This was a restriction in the operation of the device.

The interface was upgraded to allow for remote control operation via a VPN connection from the user to the Mach2 system. This enabled for a higher level of control of the device, and also the ability to monitor the impact of the energy exchanges.

For testing the more advanced ESS functionality, the system was set up to accept and execute various algorithmic scripts which enabled to run continual tests by responding to real time

network measurements. These algorithms used the newly established communication network between the primary substations, secondary installations across both feeders, and the ESS itself, as described above.

These various stages of system independence were set up systematically; initially, local control of the active and reactive power set-points by UK Power Networks staff was allowed. Following this, control of the set-points was carried out by UK Power Networks staff remotely. Once confidence in the performance and stability of the system was sufficiently high, control of the system by set-points determined by a computer control algorithm was allowed.

UK Power Networks control room staff were involved during this process, either by notification or by direct coordination depending on the expected network impact.

3.3.3 Safety considerations

As energy storage devices are new to distribution network operators, safety considerations were a vital part of project. This trial used the experience of commissioning and operating the site developed during the AuraNMS project to revise an Engineering Instruction as an operational point of reference. This Instruction was included in the report ‘Early learning from an electrical storage installation on an 11kV distribution network, Oct 2012’ and has been used as a guide to other DNOs wishing to install similar equipment on their distribution networks.

3.4 Trial Methods

To demonstrate the benefits of storage on an 11kV network for a distribution network operator and answer operational questions such as battery lifetime and round-trip efficiency, a trial programme was developed for the Martham and Ormesby networks with increasing levels of complexity.

Network simulations were used to verify a number of assumptions and control algorithms. After initial on-site testing to increase confidence levels, trial methods to control network voltages and power flows could be started.

First, measurements local to the ESS were used. Gradually, the trial increased complexity by setting the algorithms to accept remote measurements from primary and secondary sites. The trial programme concluded with performance tests of the ESS, independently from its interaction with the electricity network, to determine the efficiency of the battery system and the auxiliary power demand of the overall system.

The table below provides an overview and high-level description of the Trial Method. A more detailed and technical description for each Method is provided in Appendix D.

Table 4 Trial method statements and high level description

Method	Category	High-level description
Method 1: Voltage control (STATCOM mode)	a) Scheduled	Depending on the cause of the voltage disturbance, absorbing or injecting reactive power on the network is a suitable way to control the voltage. The ESS Mach2 system controller had a built in voltage control algorithm that responds to a measurement of the 11kV network voltage at the ESS. Reactive power was exported to boost voltage

		when low, and imported to decrease voltage if it was high. The operation of this function was tested by varying the set points of the algorithm and recording the impact.
	b) Algorithm (secondary monitoring points)	Instead of regulating voltage from the local measurement, with this enhanced method, the voltage was regulated from the secondary measuring unit furthest away from the Primary Substation. The control algorithm read the voltage at secondary measurement location and used this to determine the set-point of the energy storage system.
Method 2: Power-flow management	a) Scheduled (no measurement point, based on expected power)	<p>As an initial basic method, the (real) power flow was managed manually. By analysing historical demand data the expected demand profile for particular future days could be determined. This was done for short periods of time so that a manual switching schedule could be specified and implemented by UK Power Networks staff.</p> <p>To gain initial understanding of potential benefits of basic power flow management, information from the energy supply contract was used to calculate the cost of operating the trial and an estimate of the revenue that would be received from the sale of energy.</p>
	b) Algorithm	A set of three more advanced methods of increasing complexity ranging from prescheduled manual switching towards more intelligent and autonomous switching: Peak-shaving, Reactive Power Following and Wind Following.
	i. Peak shaving	<p>The pattern of demand changes from day to day, week to week and season to season. In order to be able to assess the capability of the ESS to perform real-power peak-shaving, an algorithm was developed that estimated the upcoming time and magnitude of the demand peak.</p> <p>This algorithm controlled the point in time and the power threshold at which peak-shaving starts, to make the best use of the limited energy resource available in the ESS.</p>
	ii. Reactive power following	Suitable management of reactive power can be beneficial to real power flows as reactive power does use physical network capacity.

		<p>By supplying the reactive power locally onto a feeder, the network could benefit by reducing the reactive power demanded from the wider network. Voltage control can be simplified in some circumstances by adjusting reactive power flows.</p> <p>This methods trialled this concept on the Martham-Winterton feeder, which had a particularly significant reactive power demand due to the induction machines that generate power at Bloodhills wind-farm.</p>
	<p>iii. Wind following with network switching and automatic voltage control</p>	<p>The Hemsby ESS was deliberately built between two feeders. This method trialled the concept of using both sides of the network during a prolonged network event for which the ESS energy capacity was overwhelmed. In this scenario, the wind generation was considered to be overloading the network and would require curtailment without any intervention. By charging the battery from the wind-farm side, switching to the non-wind-farm network and discharging, the ESS could be reconnected to the wind-farm network to consume further wind generated power; reducing curtailment by up to 50%.</p>
<p>Method 3: Manufacturer's data sheet validation</p>	<p>a) Set point control accuracy & efficiency</p>	<p>The ESS system had 'out-of-the-box' set-points available to control active and reactive power exchange between the 11kV network and ESS. This method determined the accuracy and efficiency of these set-points by confirming the relationship between the set-points and actual measurements of power exchange with the network.</p>
	<p>b) Auxiliary power consumption</p>	<p>The performance of the ESS was tested, independently from its interaction with the electricity network, to determine the efficiency of the battery system and the auxiliary power demand of the overall system.</p>
	<p>c) Determine expected lifetime of batteries</p>	<p>As part of this Method, the accepted lifetime of the batteries was considered, assuming the batteries had been operated for a longer period.</p> <p>The adaptive peak-shaving control algorithm was used to generate representative operation profiles for the ESS. These were given to the battery manufacturer, Saft, who carried out a lifetime assessment of each operating regime.</p>

4. THE OUTCOMES OF THE PROJECT

Key messages

- The trial demonstrated real network benefits of 11kV connected and DNO owned energy storage
- Feeder peak demand was managed and in some instances reduced by the use of short term energy storage
- Autonomous charge and discharge operation of an energy storage device was achieved without the direct intervention of the control room
- Automated reactive power feeder demand, control and reduction were achieved by the coordinated operation of the energy storage STATCOM and the primary substation
- Automated interaction between the energy storage and embedded renewable generation was demonstrated to reduce potential constraint conditions

4.1 Introduction

The following chapter presents the key results of the trial methods described in Chapter 3. More details on the methodology, assumptions and results can be found in Appendix D 'Detailed results'. The chapter concludes with outcomes not directly derived from the trial methods, but from additional studies performed.

4.2 Method 1: Voltage control (reactive power exchanges)

4.2.1 Scheduled manual control

Result:

The local network voltage at the energy storage could be controlled by regulating reactive power using the Automatic Voltage Control of the STATCOM provided by ABB.

Method 1 trialled control of the voltage by absorbing or injecting reactive power on the network. The ESS Mach2 system controller had a built-in voltage control algorithm that responded to the 11kV network voltage measurement at the ESS, also called the Point of Common Coupling (PCC).

The operation of this function was tested by varying the set points of the algorithm and recording the impact. The main set point that was modified was the voltage dead-band. A reduction in the dead-band meant that smaller voltage deviations from the 'voltage reference' caused the controller to begin exchanges of reactive power with the network.

Figure 4 illustrates the impact of changing the dead-band settings (under and over voltages thresholds) from $10.96\text{kV} \pm 0.11\text{kV}$ to $\pm 0.08\text{ kV}$. 'Vpcc--No ESS' shows the voltage when no voltage control is applied and 'Vpcc--With ESS' the voltage after the dead-band settings change. It can be seen that the higher voltages are frequently reduced.

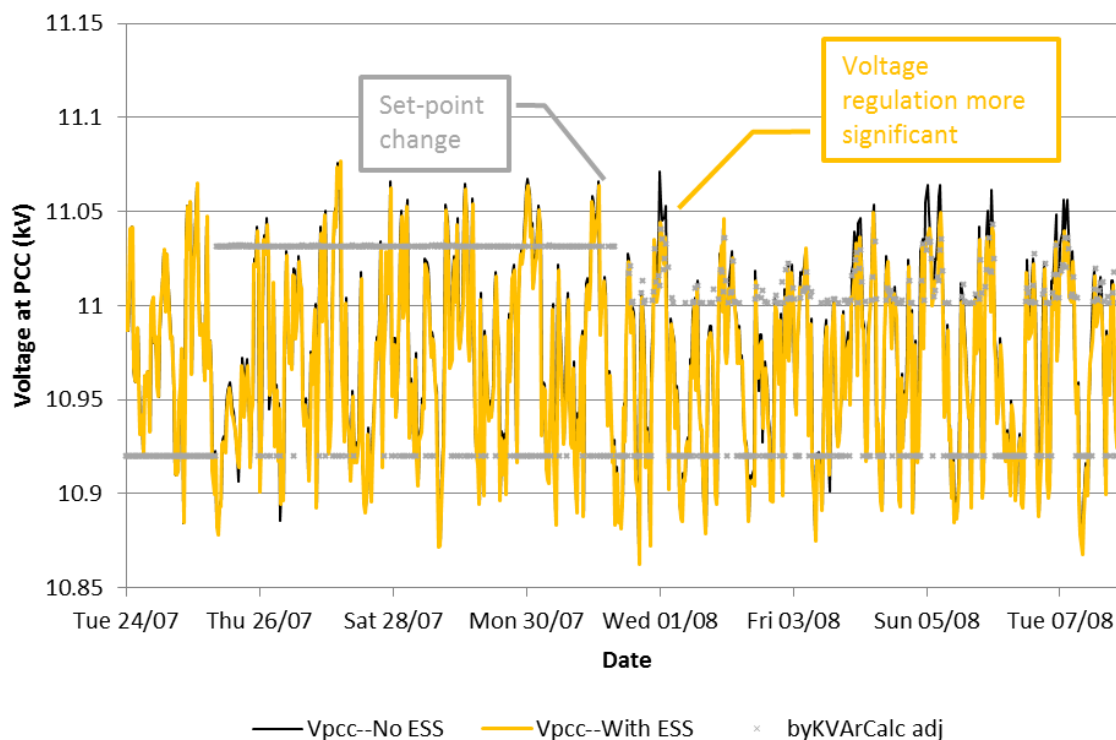


Figure 4 Impact of Automatic Voltage Control on the local voltage at the energy storage device

4.2.2 Algorithmic control using secondary monitoring points

Result:

- Network voltages remote to the ESS could be regulated. The algorithm proved successful in responding to both under- and over-voltage. A combination of real and reactive power was used to regulate the voltage. The specific location of the busbar under control relative to the ESS changed the efficacy of this control mode.
- Increasing the ESS power capability would increase the possible reduction in the network voltage deviation. Trial and model data indicate that in the case of Hemsby / Pastures (one of the remote locations monitored), each 10 kW of imported or exported real power affects the voltage by 0.04%.

For the second part of the Method 1, a control algorithm was developed and used with the aim to control the voltage at one of the remote monitoring sites. The control algorithm read the voltage at secondary measurement locations and used it to determine the set-point of the energy storage system. To trial this method, the point furthest available from the Primary Substation, the Pastures, was used.

The result of this is shown in Figure 5, where the both real and reactive ESS power exchanges, battery state-of-charge and remote voltage measurement are displayed. In addition to the measured quantities, the network model is used to determine what the voltage profile would have been without the storage system operating, as described by the annotations.

It must be noted that the charge and discharge effects were deliberately kept small for this trial, as this project was designed to introduce measurable effects without significantly disturbing normal

network operation. These measurable effects could be extrapolated to assess the potential of larger installations capable of large charge/discharge cycles.

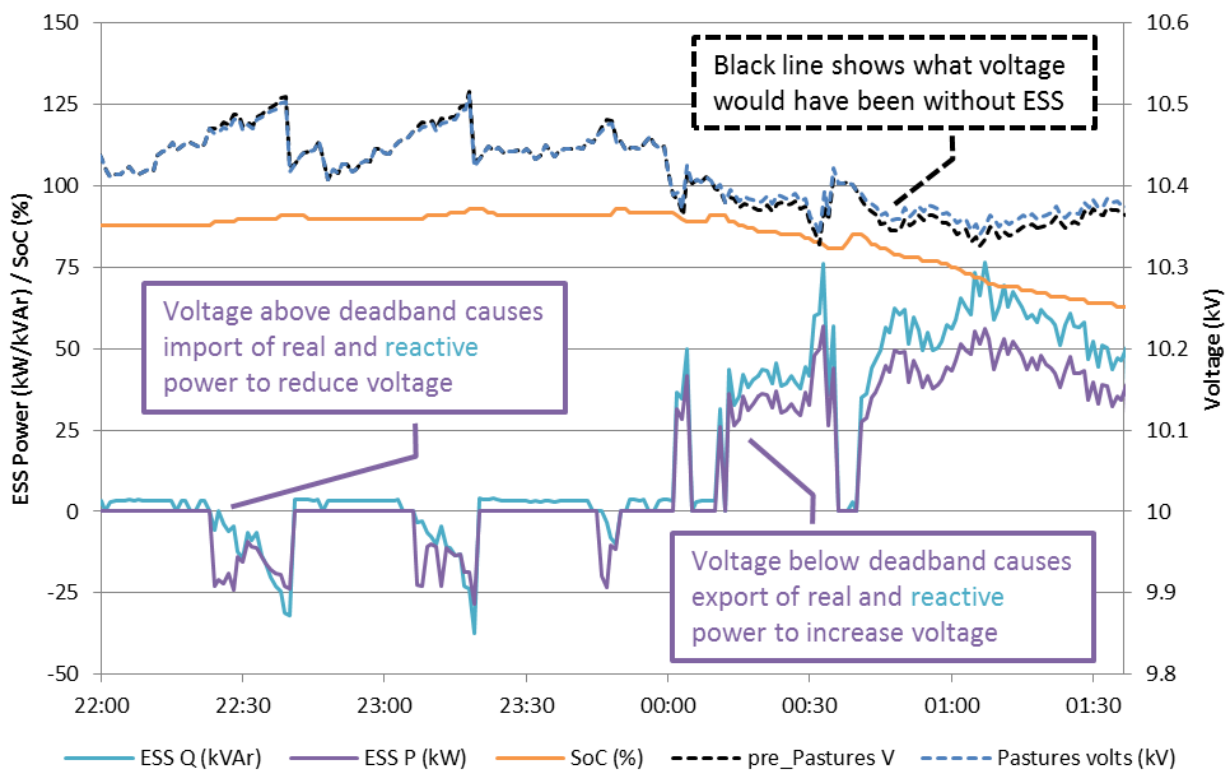


Figure 5 Voltage control in response to voltage measurement at far end of feeder.

4.3 Method 2: Power flow management (Real power exchanges)

4.3.1 Scheduled manual switching

Result:

- With a good understanding of the daily demand profile, the peak real power flow on the feeder could be reduced by scheduled manual interventions.
- The limited available energy resource could be managed to provide the maximum peak power reduction, by operating over the peak demand period without running out of energy, before the peak has passed. Modulation of the power output would have had the potential to produce an absolute power reduction closer to the maximum output level.
- The energy import charges were higher than the revenue that could be generated from exporting a similar amount of energy back onto the network, when considering the specific tariffs being used in this project, resulting in an operating loss per cycle.

Method 2 focused on managing the (real) power flow on the network. As an initial basic method, the power flow was managed manually. By analysing historical demand data the expected demand

profile for particular future days could be determined. This was done for short periods of time so that a manual switching schedule could be defined and implemented by UK Power Networks staff.

The effectiveness of this method is illustrated in Figure 6. It can be seen that the demand profile is significantly flattened by this operation, even with relatively modest power exchanges of -43 kW and 65 kW. In this case the evening peak is reduced by 45 kW. The battery state-of-charge varies from 16% to 83%, as described by the annotations.

Information from the energy supply contract was used to calculate the cost of operating the trial and an estimate of the revenue that would be received from the sale of energy (not known in advance as revenue is a function of the System Buy Price, determined in the Balancing Mechanism). An example is provided in Table 5 below.

Table 5 Pre-determined power exchanges for manual implementation

Week	Month	Day	Date	Time	Energy cost	Estimate revenue	Set-point change	
							Real-power (kW)	
							Import	Export
3	Jan	Mon	21-01-13	13:00	£8.16		-43.3	-
3	Jan	Mon	21-01-13	16:00			0	-
3	Jan	Mon	21-01-13	17:00		£5.76	-	65
3	Jan	Mon	21-01-13	19:00			-	0

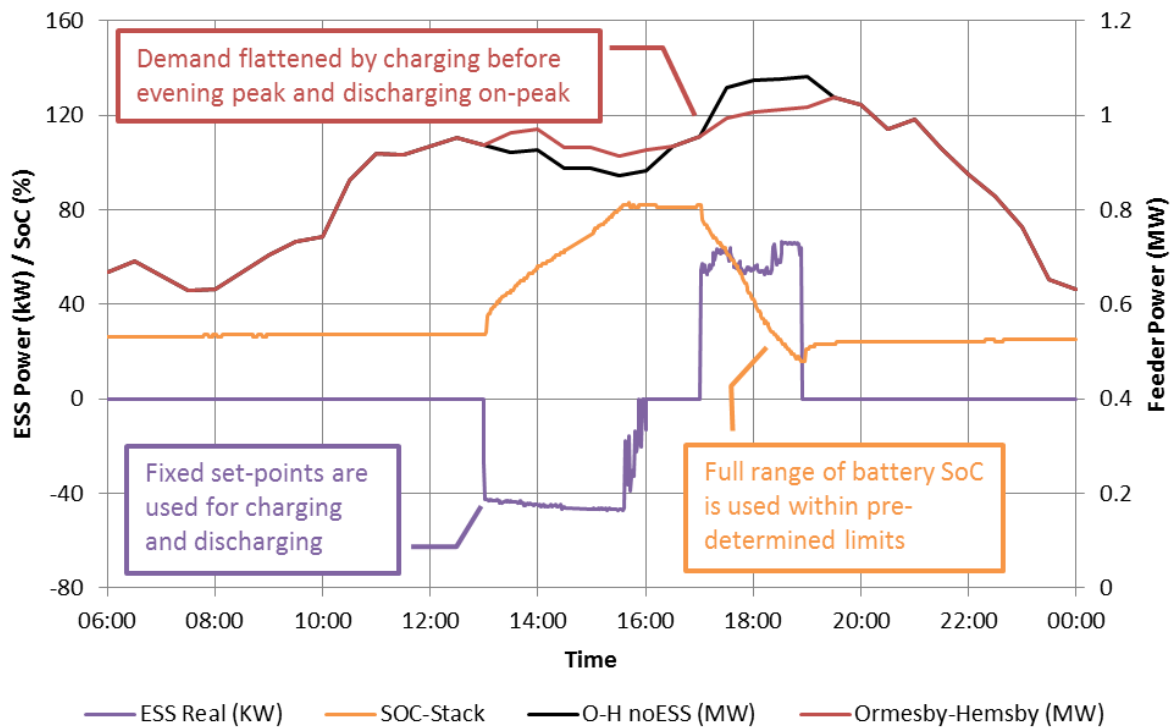


Figure 6 Scheduled real-power operations, timed to charge in afternoon's period of lower activity and discharge during evening peak.

4.3.2 'Adaptive Peak-shaving' algorithm

The second part of the Method took into consideration that the pattern of demand changes from day to day, week to week and season to season. This algorithm controlled the point in time and the power threshold at which peak-shaving starts by estimating the upcoming time and magnitude of the demand peak, in order to make the best use of the limited energy resource available in the ESS.

Figure 7 demonstrates the effectiveness of this adaptive peak-shaving algorithm, where the annotations describe the actions that have taken place. The impact of charging and discharging the ESS using the algorithm had a limited impact on the peak as the algorithms had operation safety margins applied (operate between 20% and 80% SOC) compared to previous manual power exchanges and the charge/discharge power was limited to 75kW.

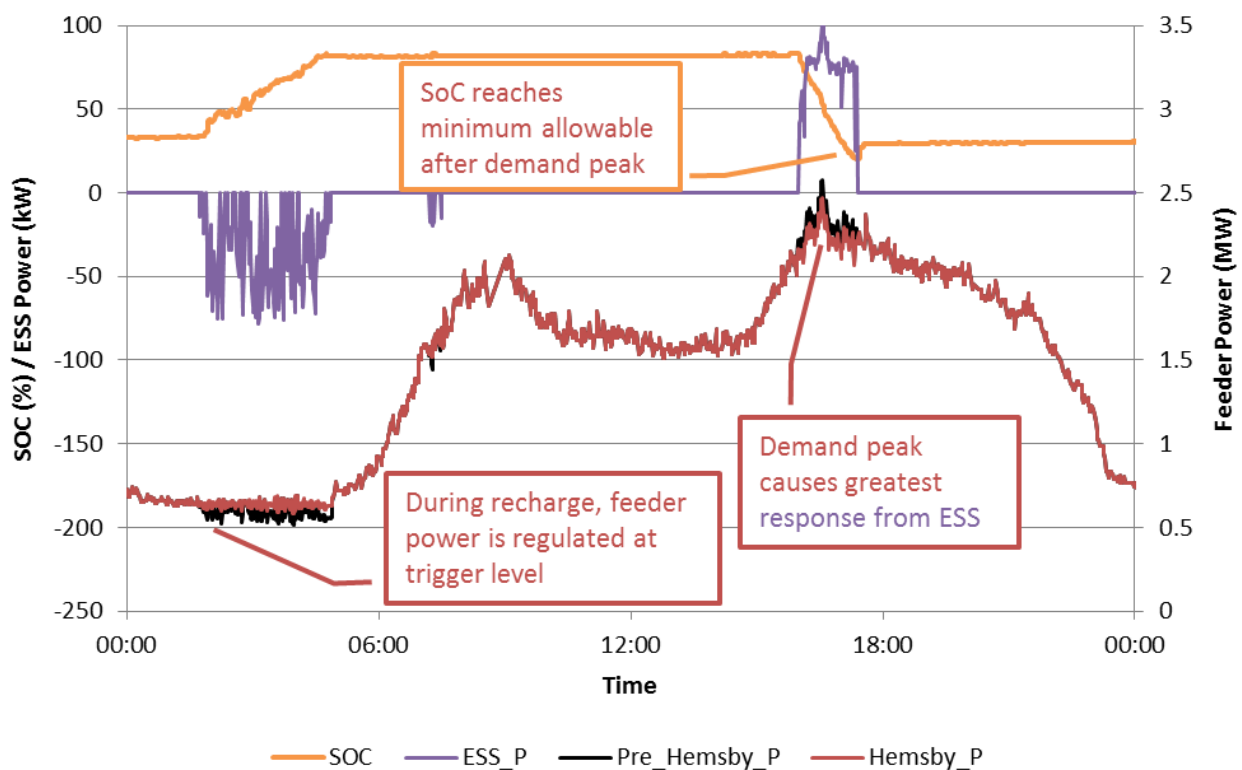


Figure 7 One day of adaptive peak-shaving operating with a 75 kW charge/discharge limit.

The trial was repeated with a 200 kW charge/discharge limit as shown in Figure 8, which demonstrates a larger but shorter impact.

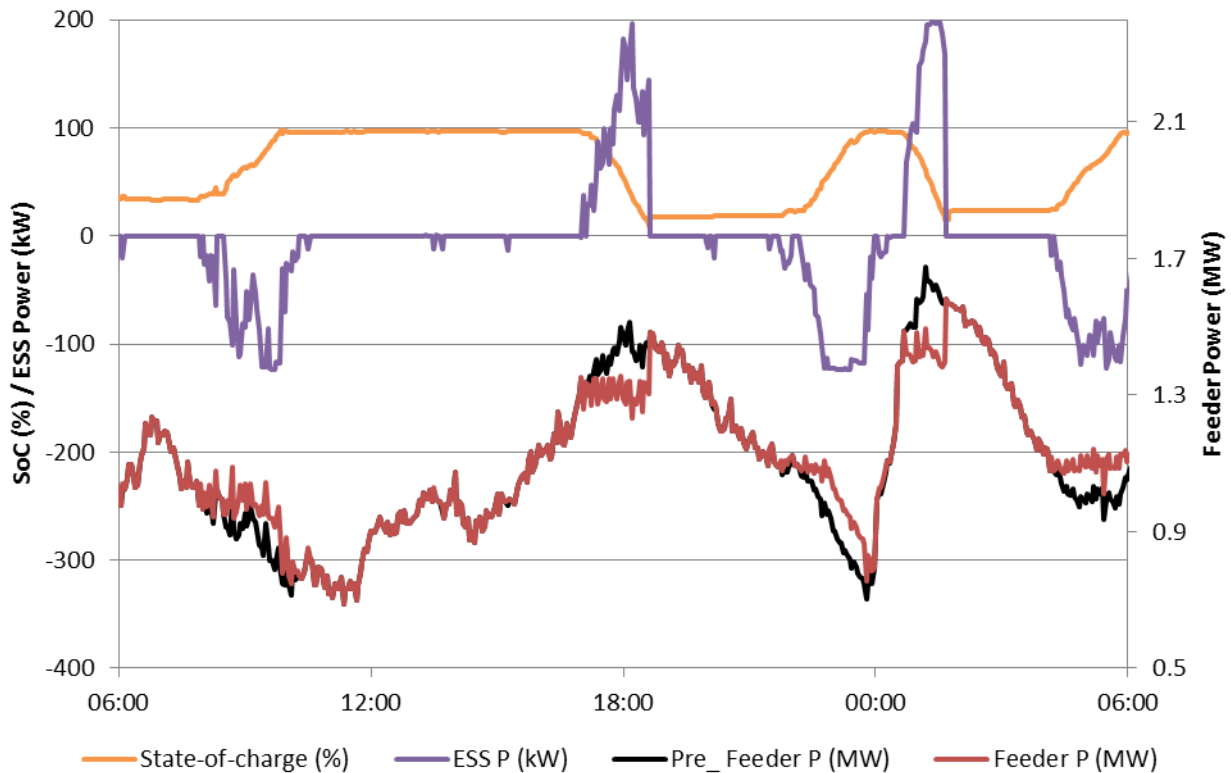


Figure 8 One day of adaptive peak-shaving operating with a 200kW charge/discharge limit.

4.3.3 'Reactive power following' algorithm

Result:

Reactive power can be supplied locally by the STATCOM function of the ESS. The impact of this is to reduce the requirement of the upstream network to supply reactive power and thus reduce the apparent power flow.

Suitable management of reactive power can be beneficial to real power flows as reactive power flows require physical network capacity, reducing the amount of capacity available for real power flows. By supplying the reactive power locally onto a feeder, the network can benefit by reducing the reactive power demanded from the wider network. The third part of Method 2, the reactive power following algorithm, trialled this concept on the Martham-Winterton feeder, which had a particularly significant reactive power demand due to the induction machines that generate power at Bloodhills wind-farm.

Figure 9 shows the ability of the control algorithm to regulate the reactive power delivered onto the feeder at Martham Primary substation over a period of one day. The algorithm is limited to 200 kVar instead of the maximum value of 600 kVar to not disrupt normal network operations during trials. The modulation of the ESS Reactive Power output can be clearly seen in the turquoise trace in the low chart, resulting in a stable reactive power demand of 0.1 MVar (brown trace). If the ESS had not been operating, reactive power would have followed the black trace. Once the wind-farm is generating above 0.5 MW, its reactive power demand exceeded the 0.2 MVar output limit that had been set on the ESS output. This is shown where the ESS output saturates just after 12:00.

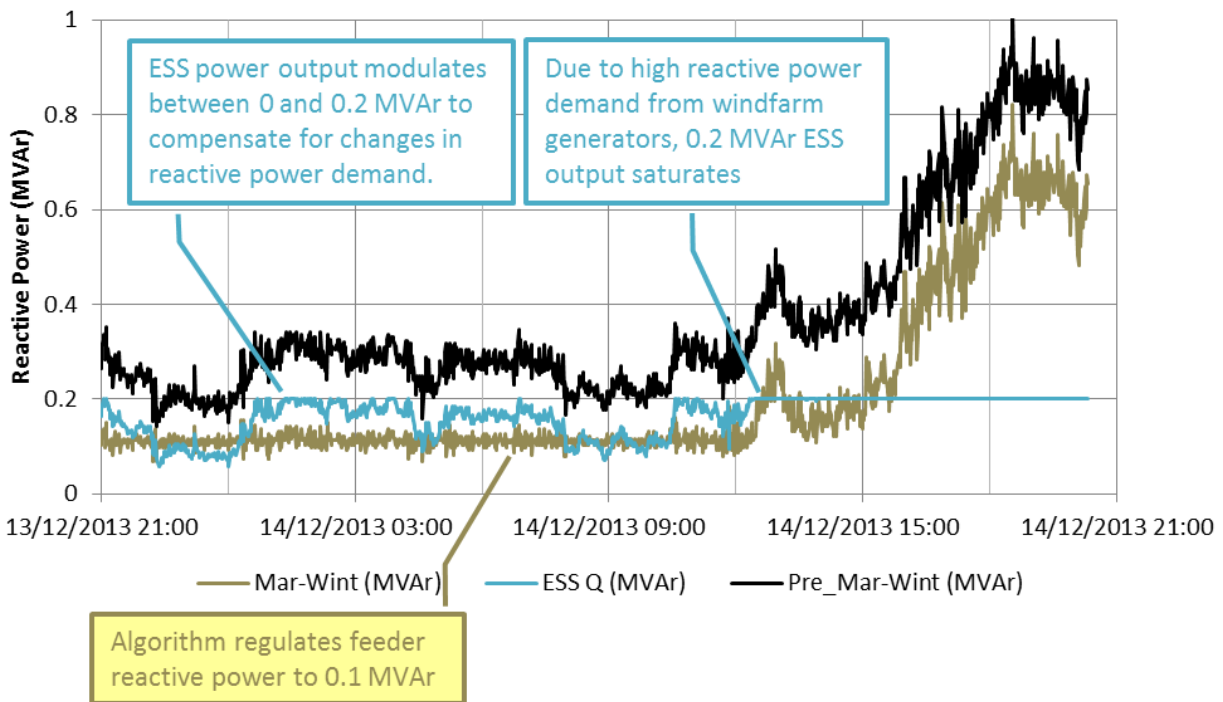
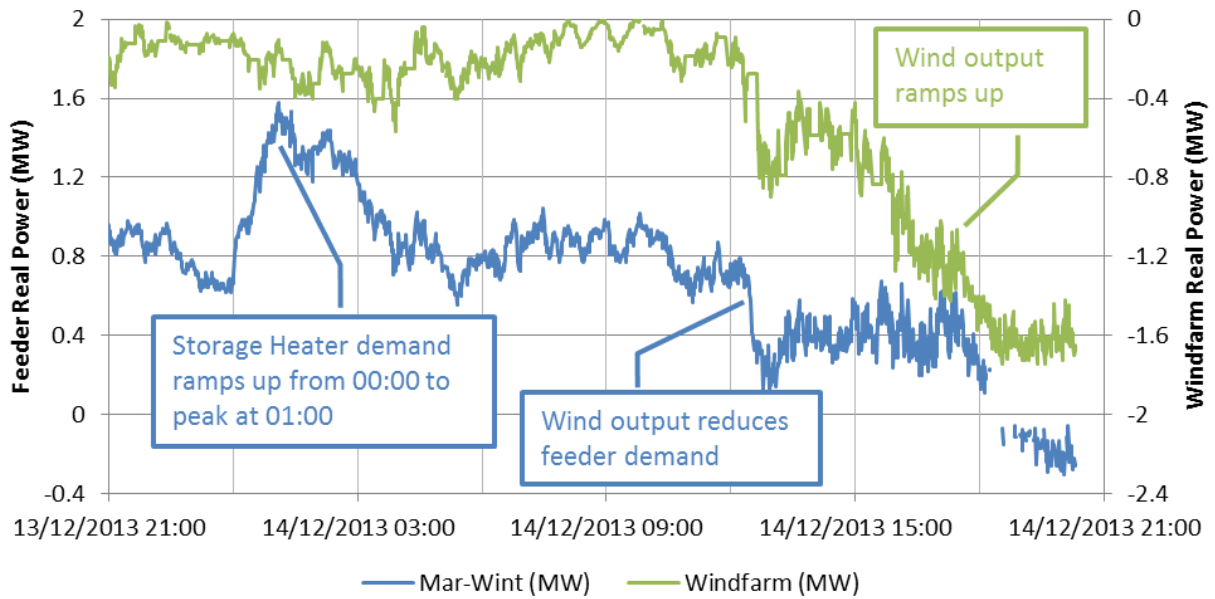


Figure 9 Reactive power compensation at primary substation for one day.

The upper chart shows the cause of the reactive power demand. The increasing wind-farm output is shown by the green line becoming more negative. The corresponding reduction in feeder demand is shown in blue, which is becoming negative (exporting) after 18:00. As noted above, the wind-farm requires a substantial reactive power supply to generate power.

4.3.4 'Wind following with network switching and automatic voltage control' algorithm

Result:

- The ability to expand the limited energy capacity of an ESS through the use of network switching, enabled by its location between two feeders, was demonstrated.
- Wind following to increase generation output in a situation where the alternative would be curtailment was demonstrated. Using the Normal Open Point in this network allowed up to 50% of energy that would normally be curtailed to be exported. An isolated ESS would require a substantial capacity to have much effect in this situation.

As the fourth and final part of Method 2, an algorithm focussing on wind following with network switching and automatic voltage control was trialled. The Hemsby ESS was deliberately built between two feeders and the complimentary characteristics of the Martham and Ormesby networks were confirmed during analysis of historical data.

This provided an opportunity to trial the concept of using both sides of the network during a prolonged network event for which the ESS energy capacity is overwhelmed. In this scenario, the wind generation was considered to be overloading the network and would require curtailment without any intervention. By charging the battery from the wind-farm side, switching to the non-wind-farm network and discharging, the ESS could be reconnected to the wind-farm network to consume further wind generated power.

This process was successfully trialled, with the results shown in Figure 11, where the annotations describe the actions that have taken place. The top graph shows the load reduction due to the ESS operation. This is most noticeable when the ESS turns off just before the blue line. The effect is limited as the maximum output of the storage device is 125kW relative to a 1MW feeder power (~10%).

During this trial the ESS was also operating in automatic voltage control mode so that the voltage variations that took place either due to the real power exchanges or general network conditions were compensated. This action is evident in the last chart in the figure.

In this case the HV network, switching was a manual operation sanctioned by HV Control Engineers. In an enduring application, it is likely that an automated process and associated procedures would be developed. As part of the trial, the potential benefit of network switching was quantified using the network model.

Figure 10 below shows the quantity of wind spill that could be avoided over the course of one year. The graph shows the amount of wind that would not be spilt ('avoided curtailment') for two ESS power ratings with varying threshold levels for curtailment. The energy rating of the device did not need to be considered, as the purpose of using the NOP is to remove the energy capacity limit; the calculation accounts for the time needed to discharge on the other feeder.

Moving along the x-axis corresponds to changing the threshold of wind-farm output at which curtailment is required, this is analogous to a varying constrained connection. If curtailment started earlier (e.g. 1.5 MW in comparison to 2 MW), more wind would be spilt, which provides a greater opportunity to save by deploying energy storage. The graph shows that increasing the power rating increases the benefits, but the incremental improvement is lower with additional power.

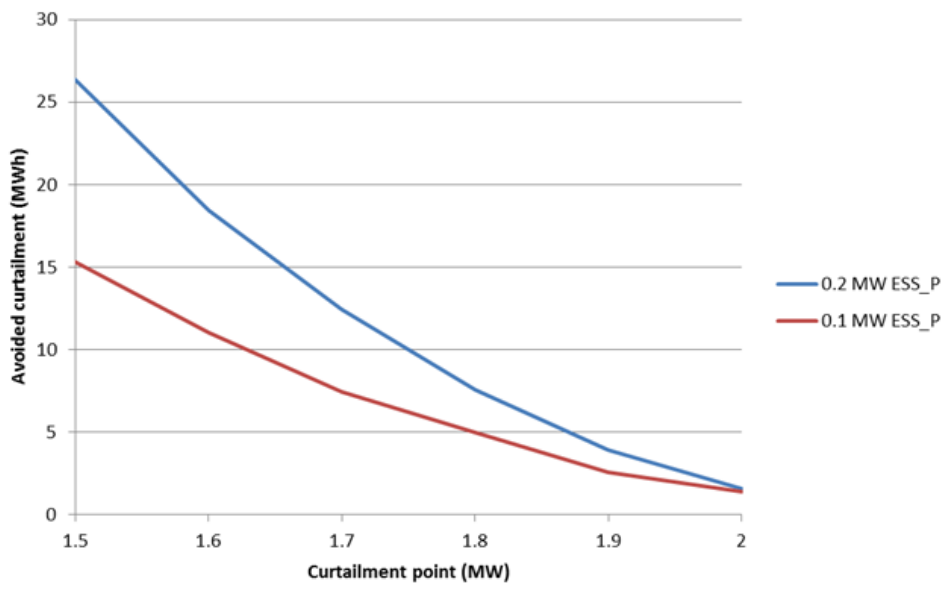


Figure 10 Quantification of the benefit of feeder switching

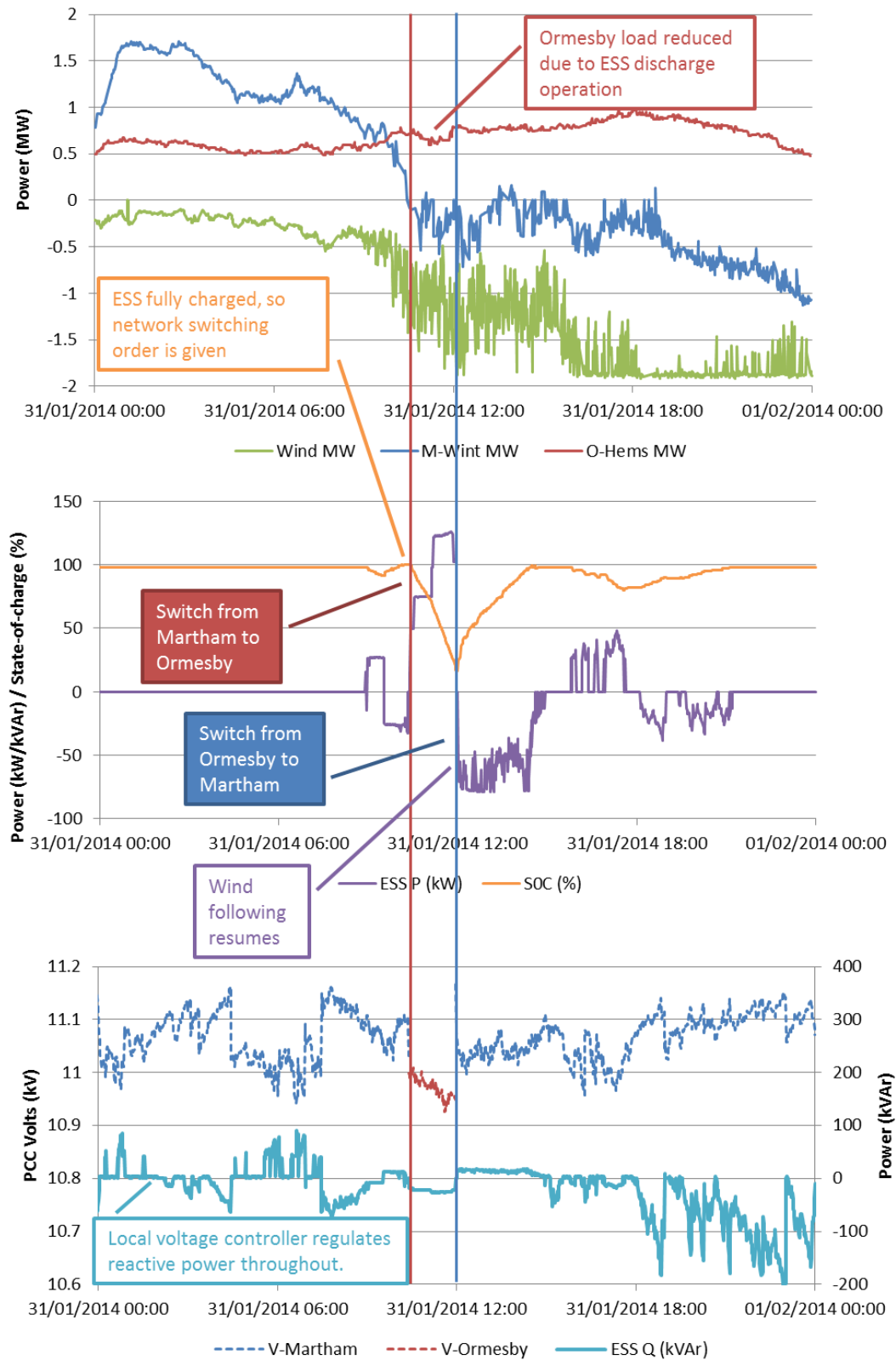


Figure 11 Use of two networks to exchange energy from wind farm to non-stressed network.
Top: power flows on both networks and wind generation.
Middle: ESS power exchanges and state-of-charge.
Bottom: voltage of network connected to ESS point of common coupling (PCC).

4.4 Method 3: Manufacturer's data sheet validation

4.4.1 Accuracy of the system

Result:

- A deviation was identified between expected and actual ESS behaviour using the set-points. The accuracy of the ESS was improved by using this data to calibrate the control algorithm. When commissioning equipment of this nature, testing procedures to validate the operation should be considered.
- If network conditions change, the calibration might no longer be accurate as the set-points were dependent on network impedance.
- Although not a priority in this project, for some applications, the difference between the set-points and delivered power may be critical, such as if a contracted service was arranged where revenue is dependent on exchanging a specific volume of energy at the meter point.

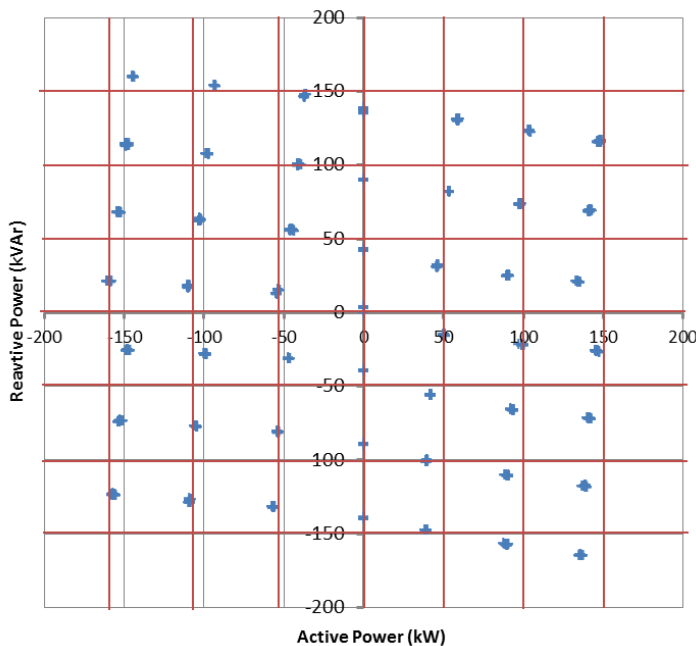


Figure 12 Measured set-point accuracy and stability

The ESS system had 'out-of-the-box' set-points available to control real and reactive power exchange between the 11kV network and ESS. The third method determined the accuracy and efficiency of those set-points by confirming the relationship between the set-points and actual measurements of power exchange with the network.

A series of tests were enacted to achieve this validation by issuing set-points to cover the four-quadrants of power exchange as shown in Figure 12. The real power import (battery charging) set-point is higher than export (discharge) to account for system losses (illustrated by the red lines) and maintain a steady peak state-of-charge throughout the course of the study.

The actual power delivered to the network deviates from the set-points and is plotted in the same figure. The groups of blue crosses would be expected to align with the crossing points of the red grid (the set-points).

The deviation was dependent on amount of real and reactive power the ESS was set to import or export, for instance when expecting the export of 150 kW and 150 kVAr, approximately 149 kW (99%) and only 116 kVAr (77%) were delivered. At another extreme, when set to export 150 kW and import 150 kVAr, approximately 138 kW (92%) and -118 kVAr (79%) were delivered.

Calibration of these set-points could mitigate the inaccuracy, however if network conditions changed the calibration might no longer be accurate as the set-points are dependent on network impedance.

4.4.2 Efficiency of the system

Result:

- Efficiency depends on the amount of power being exchanged and the operating regime. Auxiliary power consumption had a significant impact on overall round-trip efficiency. Design specifications to minimise auxiliary power consumption should be considered for future projects.
- Careful consideration should be given to what is meant by efficiency. Individual components in the system could be considered in isolation, or combined together into a single figure for efficiency. How to account for the standing losses is open to interpretation. Whether these should be smeared across the periods of operation, or considered separately is a choice that has a substantial impact on the final quoted efficiency.

The main components that would impact the efficiency of the system are (as shown in Figure 13):

- The transformer to step up the voltage from 2.2kV to 11kV
- The power conversion system including the harmonics filter (SVC Light)
- The Li-ion batteries
- Auxiliary power demand

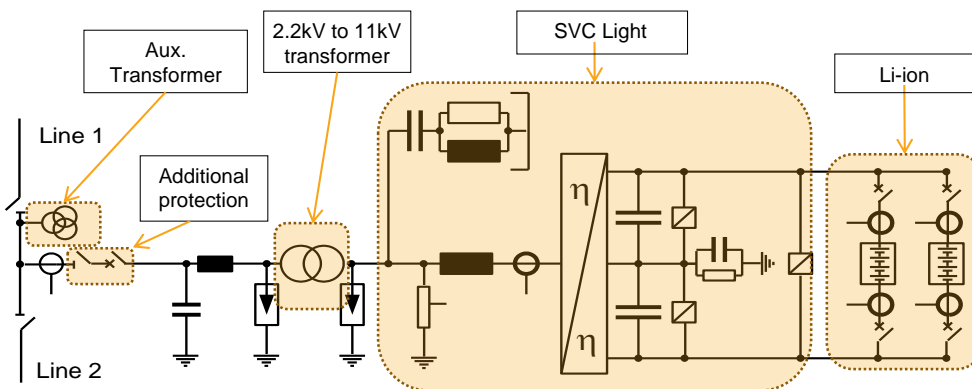


Figure 13 Single Line Diagram showing main components of ESS

The round-trip efficiency of ESS was measured. Fixed quantities of energy were repeatedly transferred in and out of the battery, during which the state-of-charge (SOC) was monitored. The difference between the SOC at the start and end of this process gave a measure of the amount of energy expended during the equal in/out energy transfers.

The results could be expressed in a number of ways. The instantaneous efficiency of the battery system, the instantaneous efficiency of the battery system and PCS, the instantaneous efficiency including accounting for auxiliary power and lastly as an efficiency measure over a period of time

in which the ESS was only operating for part of the time. This last measure accounted for standing losses in addition to the operational losses. These results are presented in Table 6.

From the table, it is demonstrated that battery efficiency (comparison of instruction vs output of the batteries) decreases when the power exchange increases. This was as expected and has contributed to the increase in internal losses at higher power exchange rates.

It could also be concluded that the round trip efficiency (comparison of instruction vs what is delivered to the network) is impacted by both the amount of power exchange and the operating regime of the energy storage. Both were due to the auxiliary power consumption which is more or less a fixed value as was concluded above. If less power was exchanged per cycle or fewer cycles are performed per day, the full round-trip efficiency dropped significantly, even to 0% in some instances.

Table 6. System efficiency by three different measures

Power Exchange (kW)	Battery efficiency (%)	Round trip efficiency (no aux power)	Round trip efficiency (with aux power)	Round trip efficiency (4-hrs of ops per day)
50	95%	94%	78%	0%*
100	94%	93%	85%	43%
150	90%	89%	83%	53%

*more energy was consumed by auxiliary systems and losses than the battery throughput

4.4.3 Auxiliary power consumption

Result:

- For the Hemsby ESS, no correlation was found between auxiliary power consumption and utilisation of the installation.
- The auxiliary power demand of this equipment added up to a significant amount of energy. Careful assessment of the auxiliary energy demands should be made and where possible be reduced in similar equipment.

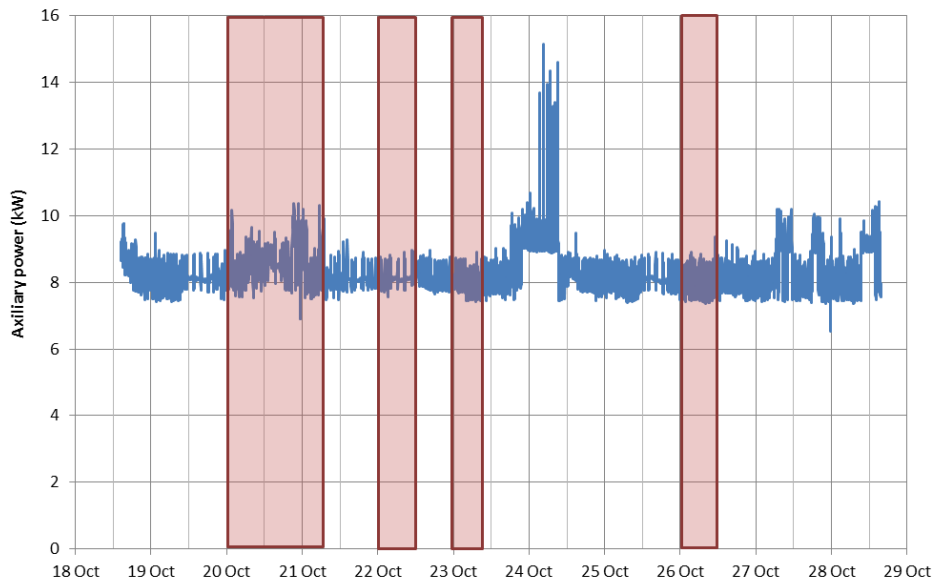


Figure 14 Auxiliary power draw; highlighted blocks showing when the ESS was under active control.

The ESS had two Low Voltage (LV) auxiliary feeds that supply the power required for heating or cooling the battery room, the thermal management system for the power conversion system, supporting IT equipment, and general site loading such as lighting. All auxiliary loads were measured and not classed as ‘losses’, but as an operational expenditure, and were accounted for separately when determining the overall system cost of operation.

The main contributors to the power consumption are:

- Two cooling pumps of 3 kW each (only one is active at any time)
- Four air conditioning units of 4 kW max each
- Three heaters of 3 kW each

Power consumption on site ranged from 7 to 15 kW and was typically around 8 kW, as demonstrated in Figure 14. The red shading shows when the ESS was actively exchanging power with the network. No pattern can be seen to indicate that exchanging power with the 11kV circuit increases the auxiliary power draw.

Power consumption of the individual auxiliary support systems was not measured over time and a desktop assessment was performed. At a minimum, one of the two 3 kW cooling pumps was always active and the air cooling drew several kW of power to keep the rooms at a set temperature. These two contributed to the standing auxiliary power draw of 7 – 8 kW. In some instances, the full capacity of the air cooling was necessary, driving up the auxiliary power draw to 15 kW (as is shown in the Figure above).

4.4.4 Lifetime assessment of the battery

Result:

The battery lifetime for representative operating regime needs to be understood when calculating the lifecycle cost of using an ESS. To evaluate the battery lifetime for a given battery technology, cooperation with the battery manufacturer is advisable in order to access their battery models, which vary for each kind of battery technology.

Two sets of representative duty profiles were sent to the battery manufacturer, Saft, who carried out a lifetime assessment of each operating regime.

The adaptive peak-shaving control algorithm was used to generate representative operation profiles for the ESS. The depth-of-discharge had a significant impact on the battery lifetime. In this simulation, three conditions were tested, where the allowed energy use was 100, 125 and 150 kWh, corresponding to a 50%, 62.5% and 75% depth-of-discharge. The power exchange was limited to 100 kW.

The impact on battery lifetime found by running this data through Saft's battery ageing algorithms gives the reduction in battery capacity for each scenario as:

- 100 kWh – 1.1% per annum
- 125 kWh – 1.2% per annum
- 150 kWh – 1.5% per annum

This meant that running the ESS in this peak-shaving mode allowing use of 50%, 62.5% and 75% of the total energy capacity reduced that capacity by 1.1%, 1.2% or 1.5% per annum respectively. For 1.5% this equates to a 20 year lifetime if end-of-life is taken to be 70% of installed capacity.

In the second case, the battery was operating in voltage control mode which results in a considerably more stochastic duty profile than the regular diurnal pattern seen in the peak shaving profile. The import and export power was allowed to reach up to 200 kW. The state-of-charge was typically in the 50-100% range, but a significant drop to around 10% was experienced within the profile. The battery capacity degradation from this profile is 1.21% per annum, comparable to the middle peak-shaving case above.

The battery ageing characteristics are clearly an important factor to be considered when evaluating the overall cost/benefit case for energy storage on distribution networks. The specific operating regime in combination with the specific battery technology will determine the actual lifetime of the system components. For the voltage control and power-flow management applications tested here, the lifetime expectations are comparable.

Note that this research is equally applicable to larger installations using the same battery technology. Storage manufacturers work carefully to distribute charge and discharge duties across the cells, so the aging is expected to be applied evenly across many more batteries.

4.5 Experience from operating the Energy Storage System

Result:

UK Power Networks planners, field staff and IT department gained experience operating the Energy Storage System.

All experiences are captured in Chapter 8 'Lessons learned' and were disseminated across the business and project partners.

4.6 Planning tool

Result:

The planning tool allowed for greater visibility of how energy storage could influence demand and generation at various points across the network.

In the early stages of the Hemsby energy storage project, it was identified that there was a need to simulate the ESS operating in the particular distribution network it was being connected to. This was to allow the impact of different ESS operations to be tested and explored before carrying out live network trials. The solution developed was a tool based on an IPSA model of the 11kV network to perform load-flow analysis. The model was populated with time-series data comprised of historical demand and generation. Node voltages and branch power flows were monitored to determine the state of the network for making decisions on how to use the ESS to positively impact network conditions.

To facilitate usage by a DNO planning department, variables can be set via a user interface – the Storage Planning Tool. This gave the planners access to the simulation configuration parameters and allowed a range of ESS operating strategies to be explored, without having to understand the detail of the code structure.

The main configuration parameters were:

- Network model to be used
- Historical demand and generation dataset
- Duration of simulation
- ESS parameters (power, energy)
- Network events and the corresponding ESS response

Once the configuration parameters were specified, a user carried out the simulation. An analysis page (Figure 15) provided key information extracted from the results. The complete results were available to the user in a comma separated values file to enable the user to perform any additional analysis using another tool such as Excel.

More detail information and an example of use is presented in Appendix E.

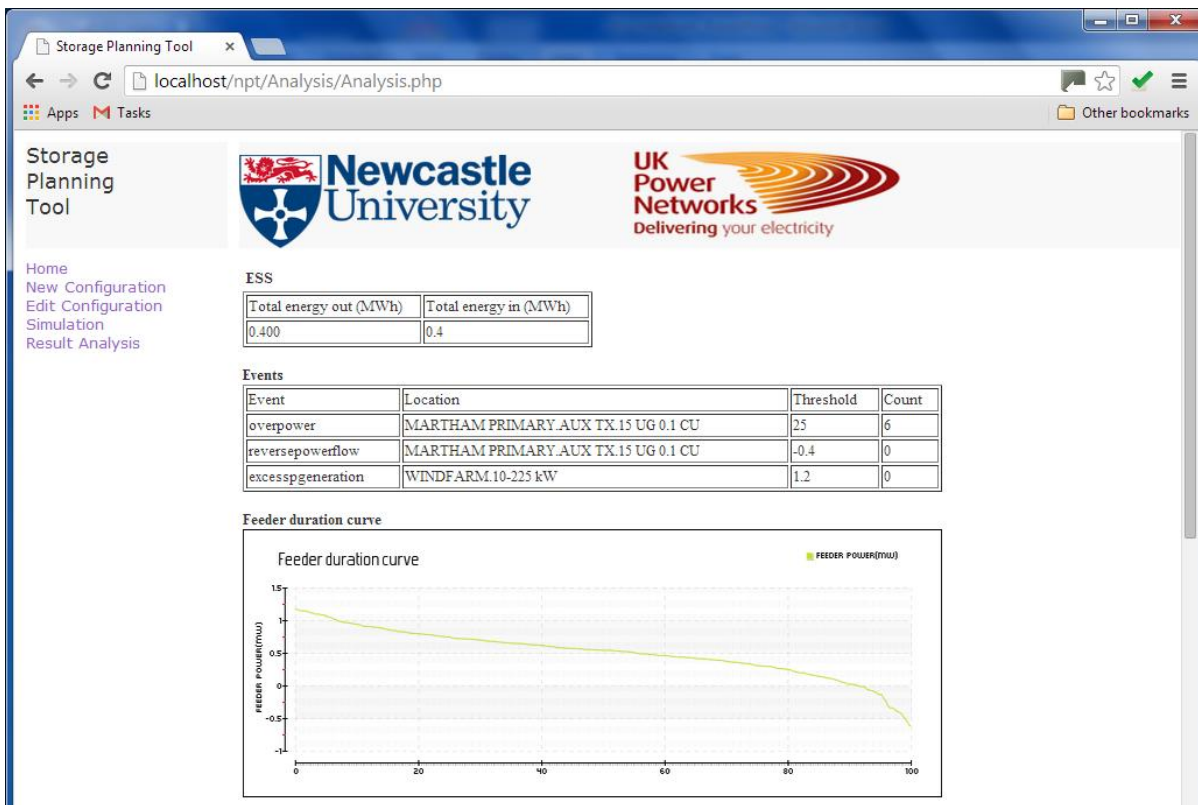


Figure 15 Analysis page example of the planning tool

4.7 Other trial outcomes

4.7.1 Relationship between installation footprint and capacity

Result: The installation footprint does not necessarily increase significantly for installations with a higher rating and/or energy capacity.

The footprint of the site for the Hemsby ESS was 625m² (25m x 25m) for a capacity of 200kWh. It is important to note that for larger Li-ion battery installations, and for energy storage devices with power ratings of similar magnitudes (i.e. <10 MW), the physical size of installations will only marginally increase.

This is illustrated in Figure 16 on page 38 where the footprint of Li-ion battery options considered as part of UK Power Networks' Smarter Network Storage (SNS) project were compared to Hemsby, as well as examples of the physical footprint of other battery technology installations. It should be noted that Li-ion is a broad family of technologies with different chemistries, energy densities and operating requirements which may impact the footprint.

It should also be noted that the footprint of the physical installation could be further reduced by using a more advanced power conversion system, and by removing the need for harmonic filters. This option would increase, however, the overall cost of the installation.

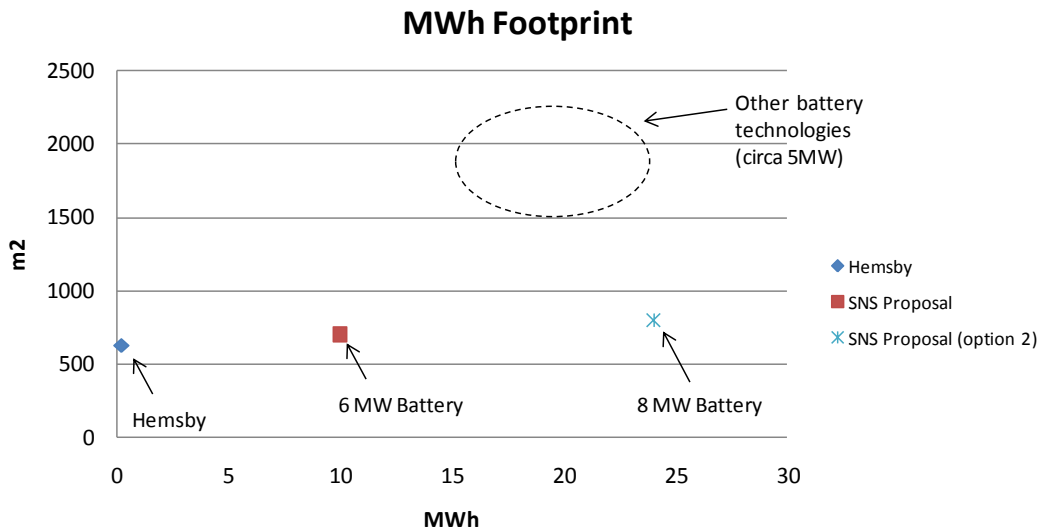


Figure 16 Comparison of footprint vs. installed capacity

4.7.2 On-going costs to be considered when operating an energy storage device

Result: Whilst the costs for future installations are expected to reduce, as experience in operating energy storage devices is gained and operating cost is optimised, the result of this particular project is that a loss was incurred when solely considering the tariffs involved in import / export costs, ignoring the value of network benefits.

In addition to the purchase and installation costs, a number of additional costs should be considered by ESS operators.

- Operating cost (excluding energy import cost and labour):** The anticipated annual operating expenditure associated with the operation of the Hemsby energy storage device is presented in Figure 17. Most of the cost was associated with the ESS maintenance and includes emergency response by ABB, inspection and trip tests, plant and cooling system maintenance, and battery maintenance by Saft. Auxiliary power consumption was the second largest contributor. It is expected that some of these costs (more specifically the maintenance cost, auxiliary power consumption and DNO field staff required to support the operation of the device) would reduce for future installations, as experience in operating such network devices is gained and operating costs are optimised. A particular area of optimisation is in deciding which of the infrequent maintenance procedures are sufficiently complex to continue to need support from the manufacturer, as opposed to the more frequent maintenance procedures which can be brought in-house.
- Energy import cost:** The cost associated with charging the energy storage device also needs to be taken into account, as it was not being treated as losses, but as an operational requirement. The relatively small size of the device meant that it was challenging obtaining competitive tariffs for energy import/export from suppliers. The inability to predict scheduled operating profiles and time of use prior to the installation of the device, meant

that suppliers typically were not prepared to offer even standard energy tariffs. The import price of the seasonal tariff used at Hemsby varies between 6.2p / kWh to 27.8p / kWh.

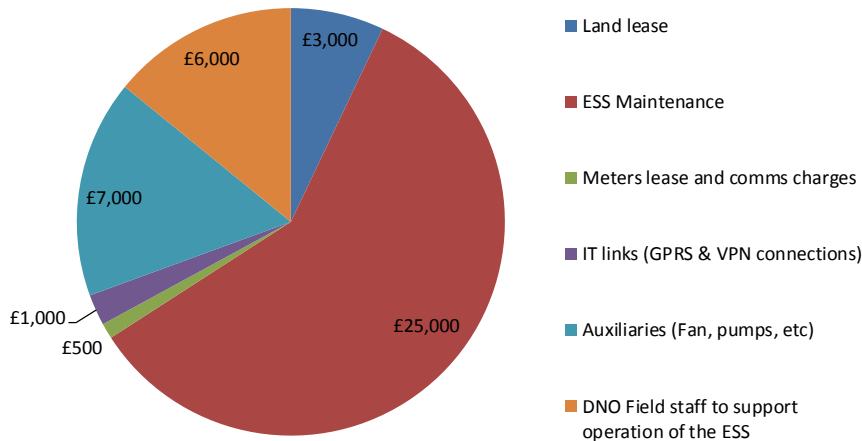


Figure 17 Breakdown of operating cost (excluding energy import cost and labour) – total: £42,500

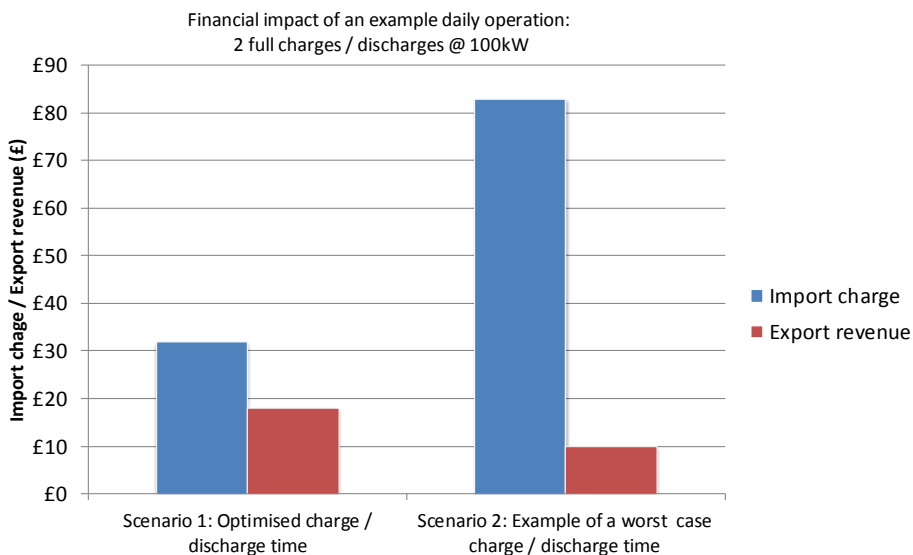


Figure 18 Cost of charging and discharging the ESS

Although an income could be expected from the energy exported back into the network (approximately 80% of the system sell price for the Hemsby energy export contract), for this particular project only the import charge and export revenue were considered, which resulted in a loss per cycle. Depending on the time of day selected to charge/discharge, this net cost could be minimised. Furthermore, other income streams could be explored, as suggested in chapter 8, ‘Lessons Learned’. This is illustrated for two opposing scenarios in Figure 18 above.

4.7.3 Study on impact of ESS on distributed generation capacity

Result:

- Increasing the energy capacity and power limits of the ESS does not necessarily



lead to an increase in benefit.

- The main benefit to the network when managing voltage rise is due to the reactive power being exchanged by the STATCOM.

One of the aims of this project was to understand the ability for this ESS to increase the amount of distributed generation capacity on Martham-Winterton and Ormesby-Hemsby feeders. To achieve this objective a separate study was carried out. The full study findings are presented in Appendix F with a summary presented below.

The study found that the key factors that limit the amount of DG that could be connected to the network are the voltage profiles, the thermal limits of the installed assets and the increase in fault level caused by the extra generation. For any additional installations of generation a check was required to ensure that the primary substation could accept any increase in reverse power flows.

As the ESS could help with both the voltage profiles and thermal limits, these were the two main constraints that were evaluated as part of the network simulations. Several scenarios were developed to understand the relationship between the capacity of ESS and the increase in DG capacity. The simulations resulted in two key findings:

- In the case of the Hemsby network configuration, increasing the energy capacity and power limits of the ESS does not necessarily lead to an increase in the ability to influence voltage profiles or available capacity.
- The main benefit to the network when managing voltage rise was due to the reactive power being exchanged by the STATCOM.

5. PERFORMANCE COMPARED WITH PROJECT AIMS, OBJECTIVES AND SUCCESS CRITERIA

Key message

- The trial successfully demonstrated the benefits of energy storage on a distribution network.

5.1 Introduction

The project was considered successful as the main aims and objectives were delivered. The following two tables summarise the performance of the project.

5.2 Performance compared with project aims and objectives

Objectives	Objective met?	Details
Perform validation of the storage device's capabilities with respect to data sheet performance, when installed on a real network. Specifically, the efficiency of the device will be measured	✓	The accuracy, efficiency and auxiliary power consumption were tested and assessed. Two key issues were presented for further consideration: <ul style="list-style-type: none"> Potential issues with metering and revenue settlement when the accuracy of the system is unknown and the system remains un-calibrated, (See section 4.4.1) How to define and report efficiency
Demonstrate load-shifting within the limits of the device capability (200kWh, 1 hour discharge duration)	✓	The load-shifting capability of the device was proven in various degrees of complexity ranging from manual scheduling to more advanced automated algorithms such as wind-following.
Understand the extent to which these interventions could be scaled up to manage larger quantities of demand or generation	✓	Network simulations were carried out to assess the benefits and impact of energy storage on the distribution network. A study considering energy capacity, power rating and location of installation was undertaken (See Appendix F). The 'Wind following with network switching and automatic voltage control' algorithm demonstrated that by installing an ESS between two feeders with different demand patterns and by operating the ESS using the

		<p>‘wind following and switching’ control, the ESS could manage larger amounts of wind than the capacity of the ESS would normally allow.</p> <p>The outcomes of this project were clearly relevant to Smarter Network Storage, which will demonstrate the benefits of an energy storage installation with a larger energy capacity in real life.</p>
<p>Validate a number of existing use-cases which have been proposed and simulated, rank their usefulness and understand their relative value to the DNO and to an intermittent generator</p>	✓	<p>The project demonstrated the network impact of the uses cases developed around voltage control and power flow management with various levels of automation.</p> <p>A ranking of their usefulness has been carried out and is presented in section 8.2.</p>
<p>Understand the potential lifetime of the device</p>	✓	<p>The adaptive peak-shaving control algorithm and a voltage control algorithm were used to generate representative operation profiles for the ESS.</p> <p>These profiles were used by Saft, the battery manufacturer, to carry out a lifetime assessment of each operating regime.</p>
<p>Embed the learning into a design tool for network planners, and into dissemination material for the UK DNO community</p>	✓	<p>A planning tool has been developed. It allows UK Power Networks planning engineers to evaluate both the impact of energy storage and additional distribution on the Martham / Ormesby distribution network. This tool is presented in this report and is available free of charge to other DNOs as stated in chapter 10.</p>
<p>Propose next steps</p>	✓	<p>Next steps to advance this technology to economic viability have been proposed.</p>

Table 7 Original project aims compared with results

5.3 Performance compared with project success criteria

Success criteria	Objective met?	Details
Validate, and if necessary update and re-run existing network simulations of a number of use cases	✓	<p>Simulations and system models were continually validated against network tests, and updated to reflect the tests' results.</p> <p>The simulations in turn assisted with planning the network tests and enhanced the resulting learning.</p>
Report on any practical difficulties encountered and new operating practices required to manage a storage device on the 11kV network	✓	<p>The practical difficulties associated with the management of a storage device are described in this report and have also been reported through an early learning report and conference publications (listed in Appendix B:). This will ensure that potential operators of energy storage systems learn from issues already encountered and will reduce the risk of future storage projects.</p> <p>As part of the 'Early learning from an electrical storage installation on an 11kV distribution network, Oct 2012', an Engineering Instruction was published detailing the various aspects of the operation of the device, including the type of protection used. This engineering instruction can be used as a guide to other DNOs wishing to install similar equipment on their distribution networks.</p>
Categorise use-cases for storage on the 11kV network into those of most value and those which only offer diminishing returns	✓	<p>A ranking of the value of use cases has been carried out and is presented in section 8.2.</p>
Indicate the conditions under which storage may present a compelling option (such as network characteristics, and the level of fund-sharing with other actors).	✓	<p>Based on the modelling, trial methods and use cases, conditions are presented (in Chapter 8) when storage could become a compelling option as a network intervention.</p> <p>Economic viability was one of the areas of future recommended work and fund-sharing could be one of the future options. UK Power Networks decided over the course of this trial that a higher storage capacity than Hemsby ESS would be required to attract sufficient interest from third parties to investigate the</p>

		financial business case for storage. The Smarter Network Storage innovation project was started with this objective.
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Table 8 Original project success criteria compared with results

6. REQUIRED MODIFICATIONS TO THE PLANNED APPROACH DURING THE PROJECT

Key messages

- Four significant modifications to the planned approach were required over the duration of the project and these were agreed with Ofgem
- The project duration was extended beyond three years and UK Power Networks funded all additional project costs after the project's third anniversary

6.1 Introduction

During the course of the project, several situations which required a change to the planned approach were encountered. Ofgem were notified when appropriate.

6.2 Modification to the ESS software

Situation	Revised Approach	Benefit
<p>The network data available to the project turned out to be inadequate for the purpose of controlling the ESS in real-time.</p> <p>Initially, the measurements at each 11kV feeder were limited to half hourly average measurements.</p> <p>Whilst the initial situation was sufficient to start the studies, the data measuring requirements had to be revisited to progress the trial.</p>	<p>The primary substation RTUs at both Martham and Ormesby substations were set to record raw analogue data.</p> <p>To further increase the clarity and resolution of this data, a modification to the ESS was completed in January 2012. This enabled for voltages and power exchanges with the network to be recorded in .csv format, in 1 minute intervals. It also enabled detailed information on the state of charge, status of the protection devices and network switches and details on the settings of the voltage control system to be recorded.</p>	<p>The increase in sample rate increased the accuracy and effectiveness of the controller. The ESS could now respond to real time network measurements.</p> <p>Data from the wind farm and wind turbine, installed on the Martham primary network were also initially available in half hourly format.</p> <p>By installing remote monitoring equipment at those sites, 1 minute interval data could be obtained to enable further understanding of the impact that energy storage could have on distributed generation, in terms of managing excess energy generation and voltage deviations.</p>

6.3 Remote alarm for CO₂

Situation	Revised Approach	Benefit
<p>The activation of the CO₂ fire suppression system caused the Mach2 control system to disconnect the storage device from the network.</p> <p>The Energy Storage System was not initially connected to the UK Power Networks SCADA network and this activation was only detected when an operator logged in manually to the ESS Mach 2 control software. No remote alarms were implemented to notify the Control Room and other relevant staff.</p> <p>The ESS remained disconnected until a full investigation, battery health diagnosis and associated remedial works could be completed.</p> <p>The investigation found that the cause of the CO₂ release was a mis-fire of a smoke detector located inside the battery room.</p> <p>The battery manufacturers, Saft, were contracted to attend the site and perform a diagnosis of the health of the battery. Their report detailed that the CO₂ had not caused any damage to the cells, and that they could safely be returned to operation.</p>	<p>The following actions were recommended and implemented to avoid future incidents:</p> <p>A second smoke detector was fitted in series with the existing one to reduce the risk of a false alarm.</p> <p>A remote alarm to the control centre was implemented to enable UK Power Networks control engineers to quickly react to any future “fire suppression system activated” or other alarm.</p>	<p>Whilst this event did not alter the testing regime or intended operation of the ESS, UK Power Networks did incur costs in order to rectify the problem. These costs would be avoided in the future and are an important lesson for future installations as they are one-of-a-kind costs. The activation of the CO₂ alarm highlighted the requirement for a robust alarm and reporting system.</p>

6.4 Extension of project duration – Delay in commissioning

Situation	Revised Approach	Benefit
<p>When the project was registered, it was expected the ESS would be commissioned in September 2010, but this was delayed until April 2011.</p> <p>In addition, several teething issues such as intermittent tripping of the circuit breaker connecting the battery to the voltage source converter, a number of spurious alarms from the control system and protracted development of the maintenance and energy contracts caused operational delays.</p>	<p>A change request was agreed with Ofgem to extend the project duration from October 2012 to the 31 October 2013.</p> <p>As part of this change request, UK Power Networks offered to cover all costs incurred beyond the 3 year anniversary (June 2013) of the project.</p>	<p>This extension was necessary to be able to complete the trials.</p>

6.5 Extension of project duration – Fire suppression system

Situation	Revised Approach	Benefit
<p>Investigation and remedial work was necessary following the activation of the fire suppression system. This included CO₂ bottles recharge, battery health diagnosis and implementation of an alarm function.</p> <p>As a consequence, the device was offline between 30 January 2013 and 23 April 2013.</p> <p>During this period, the ESS was not operational and therefore minimal operational learning was gained.</p>	<p>A change request was approved by Ofgem to extend the project duration from 31 October 2013 to the 31 January 2014.</p> <p>It was also agreed to postpone the submission of the close down report until after the conclusion of the project, as minimal learning had been developed since the submission of an early learning report in October 2012.</p>	<p>This extension was necessary to be able to complete the trials.</p>

7. SIGNIFICANT VARIANCE IN EXPECTED COSTS AND BENEFITS

Key messages

- As the preceding AuraNMS innovation project funded the ESS device, the purchase and installation costs are not included in this project
- The project cost was £388,433.
- UK Power Networks funded all the expenditure incurred after the three year project anniversary, a total of £69,647. The key benefits achieved are proving the concept of network benefits, suggesting next steps to enable large scale application and contribute to de-risking future projects.

7.1 Introduction

The site was originally procured and installed as part of the AuraNMS research project. That research project started in 2007, and was commissioned in 2011. For completeness, the purchase and installation costs will be presented in this chapter, but are not part of this trial.

7.2 Purchase and installation costs (as incurred as part of the AuraNMS previous project)

The total UK Power Networks project cost for the installation was just over £2 million. Purchase of the energy storage device contributed the vast majority of the total project cost (73%). Civil works was the second largest cost at 21%. The remaining 6% of the cost comprised mainly design, auxiliary supplies, connectivity, contractors and security.

7.3 Project cost and variance

The estimated project expenditure for the project was £340,000, comprising £250,000 LCNF funding and £90,000 partner contribution from ABB as direct payment to Newcastle University, covering half of the academic partner costs.

Table 9 Final Hemsby demonstration project costs

LCNF Tier 1 project funding details		
Funding for trial period	Project budget:	£340,000
	LCN Funding budget:	£250,000
	Partner (ABB) Contribution:	£90,000
Cost of trial	Total project cost:	£388,433
	LCNF eligible cost:	£228,786
	Partner (ABB) Contribution:	£90,000
	Funded by UK Power Networks:	£69,647

The final project expenditure came out higher at £388,433. This included the costs beyond the third year project anniversary which were borne in full by UK Power Networks as agreed with Ofgem in the change request presented in Chapter 6. A breakdown of the costs is shown in the tables above and below.

Table 10 Break-down of the eligible trial costs (during 3 year trial period)

Cost categories	Predicted	Actual	Variance	
Academic partners	£90,000	£84,385	-£5,615	-6%
Maintenance and decommissioning	£80,000	£41,061	-£38,939	-49%
Operational costs, including CO ₂ restoration	£55,000	£80,264	£25,264	46%
Modification to ABB Mach2 system	-	£23,076	£23,076	-
Contingency	£25,000			
Total LCN project expenditure	£250,000	228,786	-£21,214	-8%

Costs incurred beyond the three year anniversary and funded by UK Power Networks, as presented in Table 10, included internal costs of project management and field staff, operational costs such as specialist contractors for remedial activities in case of ESS and IT issues and the last payment to the academic partner.

Table 10 presents the cost categories of the LCN project expenditure during the 3 year trial period. The variances between predicted and actual cost were due to:

- The project had a slight underspend on **academic partners** as the last milestone payment fell outside the 3 year trial period.
- **Maintenance and decommissioning** has a substantial underspend due to change in future use of the installation. Originally the budget included some provision for decommissioning of the site. This expenditure has not been incurred as UK Power Networks is currently exploring options for continuing to use the Energy Storage System.
- There was an overspend on **operational costs**. The two key contributors to this overspend were:
 - **Internal costs:** As the project was extended for 15 months beyond its original end date, the internal costs increased accordingly. These include project management time as well as field staff attending site. The figure presented here excludes costs beyond the 3 year anniversary.
 - **Cost to restore CO₂ system:** The CO₂ release delayed the project by three months, and required several remedial works to restore the site to full and safe use. These included simple actions such as recharging the CO₂ bottles, as well as integration of the ABB

Mach2 control system with UK Power Networks' control system to enable remote alarms.

- **Modifications to the ABB Mach2 system** (described in chapter 6). This was a necessary expenditure to further develop the Mach2 system and allow for data logging at high resolution.

7.4 Project benefits

The aim of the project was to demonstrate the benefits of energy storage on an 11kV network and to develop practical operational learning. The key aims and objectives were achieved, as described in chapter 5 'Performance compared with project aims, objectives and success criteria'.

The main project benefits were:

- **Proof of Concept.** The trial provided the 'Proof of concept' for the DNO community and energy storage industry that 11kV connected storage can deliver network benefits – this knowledge will have a beneficial impact on industry developments to progress this technology.
- **Next steps to enable large scale application.** The trial suggested the next steps required for this technology to become a financial viable smart alternative to traditional network interventions. More details are given in Chapter 9 'Planned Implementation'.
- **De-risking of future projects.** The trial delivered practical learning on commissioning and operating energy storage – this learning has already been applied to de-risk the 'next generation' of energy storage projects, such as Smarter Network Storage, as also presented in Chapter 9.

The project was not set out to provide direct financial benefits and none have been achieved, as no traditional network reinforcements have been postponed or avoided due to the operation of the Hemsby ESS.

Indirect financial benefits include the financial value of de-risking future energy storage projects as mentioned above. At completion of the trial, ABB estimated that **savings of up to 15% could be expected on a similar project**, based on lessons learned from Hemsby and technology now available.

Based this estimation, the potential saving for repeating the trial would be:

Hemsby purchase and installation cost	£2,061,194
Installed ESS cost (excl. connection etc.)*	£1,943,364
Hemsby ESS repeat cost saving	£291,505

Furthermore, based on early understanding of the potential benefits, risks and mitigation measures, UK Power Networks was willing to invest in the larger storage demonstration trial: Smarter Network Storage.

8. LESSONS LEARNED FOR FUTURE PROJECTS

Key messages

- This trial was an early demonstration of the impact and benefits of energy storage on distribution networks. Through its challenges and its successes, this trial generated a wealth of knowledge, and has advanced the readiness of this technology as a smart solution.
- System reliability was an issue, partly due to frequent loss of communication with the remote monitoring and partly because the technology used was not sufficiently mature.
- Selecting remote sites for innovation projects caused operational issues and reduced appetite for knowledge dissemination site visits from stakeholders.
- The Smarter Network Storage trial was launched to better understand the economics of energy storage; a key barrier for large scale application.

8.1 Introduction

This chapter presents the summary of the lessons learned over the course of the project. This trial is part of a larger UK Power Networks roadmap to understand and develop energy storage as a viable smart solution. As stated previously, the journey started with the AuraNMS research and development project proving the technical viability of this smart solution.

This trial built on that learning and was designed to take the readiness of the solution to the next level by demonstrating the benefits of storage for an 11kV network. To achieve this outcome, the trial focussed on voltage control, power flow management and validating of the manufacturer's data sheet.

This chapter presents the lessons learned from this trial. It first assesses the outcomes of the trial and its potential use for DNOs. Secondly, it presents the operational experiences gained during the trial. It finally makes recommendations on what is needed to further progress this technology towards efficient and large scale deployment.

8.2 Assessment of outcomes

The trial provided the 'proof of concept' for the DNO community and energy storage industry that 11kV connected storage can deliver network benefits. The trial Methods focussed on voltage control, power flow management and validating of the manufacturer's data sheet, as presented in Chapter 3 'Details of work carried out' and summarised below.

All Methods served a purpose in demonstrating the benefits as the trial was designed to start with basic local manual interventions and gradually add complexity to provide autonomous control. Going forward, some of these Methods, or Use Cases, will prove more beneficial to DNOs or Intermittent Distributed Generation (DG) connected to the network than others.

The table below presents the assessment of each Use Case. As the true value to DNOs or DGs is dependent on local network and generation conditions, the assessment below is based on their relative value under generic conditions, and Use Cases were categorised using three rankings; ranging from high value to diminishing returns.

These three rankings are:

- √√ high value
- √V some value
- √ limited value

Table 11 – Assessment of the value of each use case.

Method	Category	Use for DNOs	Use for DG	Comment
Method 1: Voltage control (STATCOM)	a) Scheduled	√	√	Built-in Automatic Voltage Control proved effective in managing voltage by regulating reactive power. This use case only considered local voltage, limiting its use.
	b) Algorithm (secondary monitoring points)	√√	√√	This more advanced use case could regulate voltage based on remote network measurements increasing its use to the DNO. This could reduce reactive power imports through the primary substation and impact network losses, although other technical solutions such as switched capacitors might be a more suitable to achieve this effect.

Method	Category	Use for DNOs	Use for DG	Comment
Method 2: Power-flow management	a) Scheduled (no measurement points, based on expected power)	√	√	This Use Case to influence power flow by manually charging and discharging mainly served the purpose to prove the concept. The manual nature meant that this Use Case should not be considered as a viable solution on its own to manage capacity issues, unless it was combined with a very predictable generator.
	b) Algorithm			
	i. Peak shaving	√√√	√√√	This Use Case proved that energy storage can operate autonomously without instructions from a centralised control room, a vital step in building the smart grid and an application that will see further use.
	ii. Reactive power following	√√√	√√√	This Use Case utilised the STATCOM mode to deliver reactive power locally to alleviate upstream capacity issues. This is considered highly beneficial for DNOs under network conditions with a high reactive power demand or DGs with a high reactive power requirement.

Method	Category	Use for DNOs	Use for DG	Comment
	iii. Wind following with network switching and automatic voltage control	√√	√√√	This Use Case could increase the utilisation of an ESS which would increase the economic viability of energy storage for DNOs and/or third-parties. The use of storage could result in faster and cheaper connections for DGs, if it were deemed to make economic sense or was paired with other benefits. However its applicability depends on the availability of two feeders with different generation and demand profiles.
Method 3: Manufacturer's data sheet validation	a) Set point control accuracy & efficiency	√	n/a	Efficiency considerations are an important part of building the whole life cost investment case. When discussing or comparing efficiency figures, it is important to understand and explain how those figures were derived, as there are many different ways of calculating and testing efficiency which can produce vastly different figures.
	b) Auxiliary power consumption	√√	n/a	The auxiliary power consumption had a significant impact on the operational cost of an ESS. Understanding the auxiliary systems in order to minimise consumption would increase future economic viability of energy storage.

Method	Category	Use for DNOs	Use for DG	Comment
	c) Determine expected lifetime of batteries	√√	n/a	The batteries formed a major cost of an ESS installation. Understanding the expected lifetime of the batteries in relation to its operating regime is a crucial component to building a whole life cost investment case.

From this assessment, it could be concluded that Method 2 is most beneficial to both DNOs and Distributed Generators, in particular the use cases ‘Peak-shaving’ and ‘Reactive Power Following’. Of the use cases involving controlling voltage or capacity (Methods 1 and 2), the use cases which require manual intervention or involve local control only were considered to have diminishing returns (1a: Voltage Control – Scheduled’ and ‘2a:Power-flow management – Scheduled’).

8.3 System reliability

Over the course of the trial, full system reliability (of both the ESS and the remote monitoring network) was one of the major challenges. Although all components are commercially available, when combined in to one system reliability is not guaranteed. The trial experienced numerous reliability issues, some less critical, such as loss of communication to remote monitoring sites, and others more critical resulting in a disconnection of the ESS from the 11kV network.

A log file analysis of January 2013 to January 2014, when most of the trialling occurred, indicates 10 trips that caused the ESS to be disconnected from the network during this period. The causes of these disconnections can be categorised as follows:

- **One trip triggered by a mis-fire from the fire suppression system (site disconnected for 78 days).** The cause and mitigation actions of this event are presented in chapter 6 ‘Required Modifications to the Project Approach’.
- **Three trips triggered by malfunctions of the ESS (average duration of disconnection was 10 to 15 days).** Several malfunctions of the ESS caused the internal protection to trigger and the ESS to be disconnected. The main causes were a failing fibre optic cable causing inaccurate readings from the cooling sensors and over-sensitive ‘battery over-voltage’ protection. All these incidents required intervention from ABB on site.
- **Six trips from the G59 protection relay (average duration of disconnection was 3 days).** This protection relay was installed as physical back-up protection as UK Power Networks had yet to gain experience and confidence with software protection solutions as offered by ABB’s Mach2 system, run on a secure version of Microsoft Windows. Each trip required a site visit from a field engineer to perform a visual inspection and reset the protection relay. During each visit, no local cause could be found for the trip and it was suggested that the protection relay was set too sensitive. To increase site reliability the settings of this relay would have to be reviewed and coordinated with other protection devices.

The trial was further hindered by frequent loss of communication with the remote monitoring sites needed for the control algorithms. Whilst these incidents did not cause the ESS to trip, it slowed down the trials if that monitoring point was needed for the control algorithm. The main causes of these instabilities were:

- **Poor GPRS connection.** This is covered in the ‘operational experience gained’ section below.
- **Freezing of the Remote Terminal Units (RTU).** This caused the unit to stop monitoring and transmitting data. These incidents required a field engineer to go site and reset the unit.

Although problematic during the trial period, these challenges did contribute strongly to the operational experience gained as presented in the next section.

8.4 Operational experience gained

One of the key objectives of running this early demonstration project of energy storage was to gain operational experience. This section presents the lessons learned and what would be done differently if the trial was repeated. The lessons cover a variety of trial aspects from site selection to stakeholder engagement and finally business implementation.

8.4.1 Site selection

Lesson learned	Details
<p>Choosing a location for an innovation trial in a less remote area will improve operations and can strengthen the educational value</p>	<p>Due to their very nature, innovation projects require more attention and site visits than proven BAU technologies. Selecting a remote location such as rural Norfolk can pose operational issues, as the number of technical staff available for inspections and interventions will be limited.</p> <p>Distance to site from the main transport hubs also has an impact on the number of visitors willing to attend dissemination events.</p> <p>Other operational issues include the availability and reliability of communication channels such as GPRS and the suitability of road infrastructure, as roads can be too small to transport large equipment.</p>
<p>When selecting the site location, planning, building and operational issues should also be considered</p>	<p>To use the location selected for Hemsby, the land was to be leased and planning consent was sought. When possible, it would be preferable to locate the equipment on land already owned by the DNO as this could speed up the process.</p>

8.4.2 Network planning

Lesson learned	Details
Enhanced planning methodologies are necessary to represent energy storage accurately	The methods of planning used by UK Power Networks prior to the trial could not accurately predict the benefits that energy storage can offer. This is primarily due to the lack of representation of time , which is required to simulate the energy storage system's limited energy capacity. This has been demonstrated with the energy storage planning tool released as part of this project.

8.4.3 Operation

Lesson learned	Details
The location of the site should be considered when selecting communication channels to increase reliability Communication channels suited to the location of the site should be selected to increase reliability	The GPRS connectivity between the Martham primary, and some of the secondary remote monitoring locations was poor and resulted in loss of signal. To identify and mitigate such issues from the start of the project, it is recommended to perform a signal strength survey prior to installations. As a mitigation measure for this trial, directional high-gain antennas were installed to boost the signal strength and increase the reliability of the communications.
Remote control for operational staff and remote alarms that are visible to control room staff should be implemented to increase site flexibility and availability	Initially the ESS could only be controlled locally by staff that were not based at the site. This limited the frequency of operations. Implementing secure remote control increased site flexibility. The same applied for the alarms from the ESS, which were initially only visible when logging in to the system. This did not work well, as system trips were not always picked up. It is recommended to implement remote alarms visible to control room staff . Email notifications should be used to distribute alarms to those involved with the trial. The alarms should be grouped and filtered to not spam users.
The use of CO₂ fire suppression systems should be avoided	Although it has been used for this project, UK Power Networks are working with local fire brigades to phase out CO₂ fire suppression systems , as they are not safe for staff. The Smarter Network Storage project is expected to use an Argon Nitrogen fire suppression system.
Enabling remote control of relays will increase availability of the ESS	As stated earlier in this chapter, system instabilities and G59 protection trips caused frequent disconnections. The relays in Hemsby could not be reset remotely by the control tool. Implementing remote control would have increased availability.

<p>The trial design should ensure specifications of the hardware match the requirements of the software when developed by different parties</p>	<p>The version of the ABB COM600 used was constrained in memory and disk space. This occasionally caused disruptive issues for the control software provided by Newcastle as it ran out of disk space for logging system performance and network measurements during the trials.</p>
<p>It was challenging to secure suitable cost effective energy contracts for small scale installations. Work with energy suppliers (and other stakeholders) to develop suitable energy contracts for storage</p>	<p>At the time of commissioning, the suite of contracts available to the Hemsby installation was limited, due to the limited capacity available that could be of value to an energy supplier and novel nature of the installation for most suppliers. Where available, the contracts were typically either developed for demand or generation. These do not always fit the characteristics of a storage device, particularly when the charge/discharge pattern is unpredictable. Exploring suitable commercial arrangements with an energy supplier is part of the Smarter Network Storage project.</p>
<p>Operational staff should be aware that the batteries cannot be turned off completely</p>	<p>Batteries will remain 'live' even when fully discharged, and a residual voltage remains. Due to the unfamiliar nature of the technology UK Power Networks operational staff had to be familiarised with the risks and safety requirements surrounding working with live equipment by training.</p>
<p>Requirements for authorised staff should be revisited when experience with the ESS installation increases</p>	<p>Precautions were needed to re-energise the ESS. The original requirement for two authorised persons proved onerous; especially in remote locations with limited staff. Experience and confidence increased during the trial and it was recommended to relax the requirement to one authorised person.</p>

8.4.4 Maintenance & warranty

Lesson learned	Details
<p>Clarify with the technology providers what is classified as corrective maintenance, preventative maintenance and that is covered by the warranty, at the beginning of the project.</p>	<p>As the operation of this ESS installation was not critical to system stability and customer service levels, the site only had a preventive maintenance plan plus call-out via service line for corrective maintenance. The site also came with a 5 year warranty. Occasionally there was confusion about whether a fault resolution (e.g. rectify a malfunctioning cooling pump) should be considered corrective maintenance or whether it should be covered by the warranty.</p>

Maintenance of the ESS may require external expertise	This was a unique installation for UK Power Networks and as such, the required skills to perform the maintenance of the system were not able to be sourced internally. These were subcontracted to ABB and Saft.
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8.4.5 IT & communication

Lesson learned	Details
Involve the IT department during trial design	The Hemsby IT infrastructure is bespoke as is with many innovation trials. Earlier involvement of the IT department would have simplified the integration into the corporate network infrastructure
Appropriate access & rights for users should be agreed	Due to the bespoke nature of the IT architecture of the trial, managing access rights to system, both for UK Power Networks, manufacturers and contractors proved difficult. Firewall & VPN user accounts and access rights need to be coordinated.

8.4.6 Implementation & integration: transition to the business

Lesson learned	Details
A full integration into corporate processes is necessary to ensure a successful transition into Business as Usual.	<p>To migrate the Hemsby ESS and communication architecture from ‘innovation’ status to ‘BAU’ status, the following topics need to be addressed:</p> <ul style="list-style-type: none"> • The financial business case and use case for maintaining and using the site has to be understood; how would the site be used and who controls its behaviour? • The planners understand the use cases and can apply them in their work • Control room visibility and integration; the control room needs to have visibility of the site, receive its alarms and understand the way it works and any possible peculiarities • The IT infrastructure has to be integrated in the Corporate Network, including access right management, firewalls and communication line contracts • The site reliability / availability has to increase <p>More detail is also available in Chapter 7 in the Project Benefits section and Chapter 9: Planning Implementation.</p>

8.5 Storage as a compelling option

The trial demonstrated that storage could be a compelling option worth considering if there is a need for:

- **Peak-shaving:** if correctly sized, ESS could provide real power peak shaving to manage peak power flows. In a network with a thermally constrained asset, this approach could avoid reinforcement costs. This is being taken forward in SNS. The contribution to the business case was avoided reinforcement, which will be different in each network where storage is being considered.
- **Voltage-control:** in a network constrained by voltage, both real and reactive power could be used to assist with keeping the network within statutory limits. A radically different voltage management approach would be needed to incorporate the benefits brought from energy storage, but ultimately using ESS could enable greater quantities of DG to connect to the 11kV network. For the networks in this trial, long-term voltage control relied upon the (continuously available) reactive power capability of the ESS, although (time-limited) real power voltage control was also demonstrated. In the case of this network with this ESS 300-600kW of additional DG could be connected. The contribution to the business case was the difference in connection charge between an ESS based solution in comparison to an alternative connection arrangement (i.e. longer or reinforcement based).
- **Power-factor control:** by controlling reactive power flowing onto the network, the apparent power supplied from the upper network could be reduced. This has benefits in losses reduction. The mechanism for rewarding this loss reduction is weak (calculated at a macro level) and at present cannot be introduced into a balance sheet of tangible financial benefits.
- **Wind-power with thermally constrained connection:** testing the scenario of a wind-farm operating with an upstream constrained connection showed that using the normal open point in this network could allow up to 50% of energy that would normally be curtailed to be exported. This is particular to this or similar network configurations. If energy cannot be transferred to an unconstrained network, then the storage capacity used in this trial would provide very little benefit to a wind-farm developer. Orders of magnitude larger storage capacity would be required.
- **Reverse power flow:** if network congestion or constraints on substation equipment (such as tap-changing transformers) result in an inability to accept power into an upstream area of the distribution network, energy storage could be used to manage this. The underlying cause for reverse-power flow is low demand coinciding with high distributed generation output. Treating reverse-power flow directly acts on the resultant effect rather than e.g. operating in response to a generator output, which may not cause a problem if the local demand is sufficiently high. Use of energy storage in this role would be rewarded by avoided reinforcement costs.

The conditions will be different for each situation and any individual network will have different costs/benefits associated with each action that an ESS can perform. The choice of actions needs to be considered on a case by case basis and the ESS capabilities need to be sized to match. The overall economic viability of storage as a smart solution is discussed later on in this report.

8.6 Potential for large scale application

The Hemsby ESS trial demonstrated that energy storage is a key source of flexibility that can help address some of the challenges associated with the transition to a low-carbon electricity sector. The UK energy sector echoes this sentiment. The Smart Grid Forum, co-chaired by DECC and Ofgem, have identified storage as one of the key smart interventions likely to be required in the future smart grid.

To facilitate knowledge sharing between DNOs and the energy storage industry, the Energy Storage Operators' Forum (ESOF) was established in May 2012. They provided an indication of growing momentum in their White Paper 'State of Charge GB' which states that in November 2013, 5.1 MW and 6.4 MWh of distribution network connected energy storage was commissioned with an additional 7.2 MW and 13.8 MWh either under construction or being planned. Figure 19 shows the location of these installations.

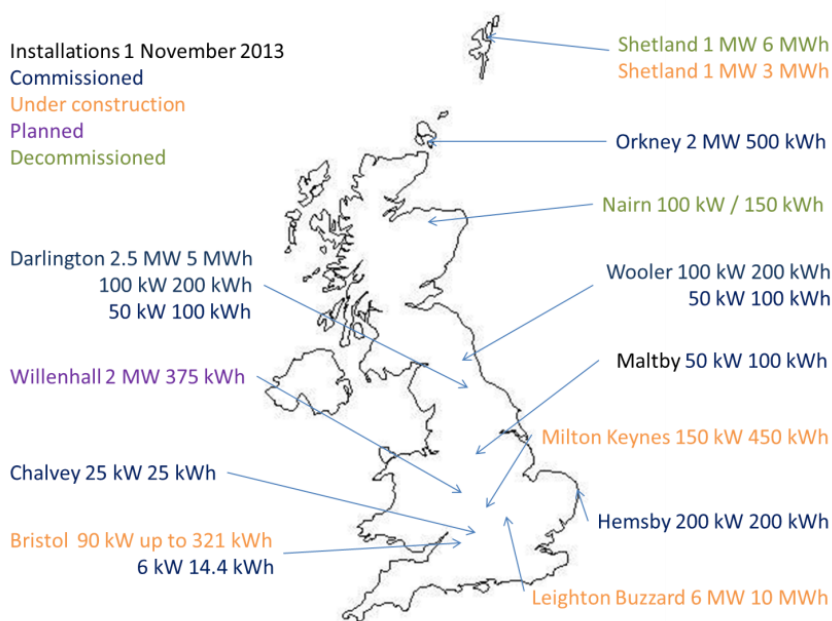


Figure 19 Locations of Energy Storage Systems (source: 'State of Charge GB' White Paper, Oct 2013, ESOF)

However, challenges in leveraging the full potential of storage on distribution networks to benefit other industry segments remain. The key challenge, improving the economic viability of storage, is presented in the next section. The other main challenges are presented in the following Chapter 9 'Planned Implementation'.

8.7 Recommendations for future projects

When Hemsby started delivering its first learning, UK Power Networks concluded that the storage technology itself, although not yet mature, was not the main barrier for large scale application of storage. It was UK Power Networks' view that the uptake was predominantly hindered by unclear economics and economic models of DNO owned energy storage.

Improving the economic viability of DNO owned and/or third-party owned storage can be achieved by the following methods:

- **Reduce the cost of installation and operation.** This is an area of continuous effort by the energy storage industry and academic community.
- **Increase benefits (income streams) by combining use cases.** This is an area of recommendation for the DNO community and Ofgem.

In response, the Smarter Network Storage project was proposed and awarded funding under the LCNF Tier 2. This project aims to carry out a range of technical and commercial innovation to tackle these challenges, and facilitate more efficient and economic adoption of storage. It is differentiated from other LCNF storage projects through the demonstration of storage applications across multiple functional boundaries of the electricity system, including the distribution network but also outside the boundaries of the distribution network. By demonstrating this multi-purpose application of 6MW/10MWh of energy storage at Leighton Buzzard primary substation, the project will explore the capabilities and value in alternative revenue streams for storage, whilst deferring traditional network reinforcement.

The project aims to provide the industry with a greater understanding and a detailed assessment of the business case with the full economics of energy storage, helping to accommodate increasing levels of intermittent and inflexible low carbon generation. The project was awarded funding of £13.2 million by Ofgem, under the LCNF scheme in December 2012 and will last four years, from January 2013 to December 2016.

9. PLANNED IMPLEMENTATION

Key messages

- DNOs need to improve economic viability by exploring combining different income streams – Smarter Network Storage is pursuing this area
- The industry needs to improve economic viability by reducing installation and operation cost
- Reliability and stability need to increase for storage to be a suitable alternative to traditional network interventions

Before this technology can be implemented, further development will be required from:

9.1 UK Power Networks & DNO community

9.1.1 Assessment of benefits

The uptake by DNOs and third-parties is predominantly hindered by unclear economics of energy storage, as presented in the previous chapter. Reducing the cost of installation and operation of an energy storage device is an area that industry and the academic community should explore. UK Power Networks and other DNOs should investigate how to increase benefits (income streams) by combining use cases. UK Power Networks' Smarter Network Storage project is focussing on this area.

We believe that an improved understanding and experience of the economic models will facilitate the faster adoption of storage from both DNOs and third-parties. Whilst there is uncertainty about the right commercial models for energy storage, there are an extremely limited number of non-DNO energy storage developers/operators in the market, due to the challenges and uncertainty in combining benefits and generating long-term value from storage.

9.1.2 Modelling of energy storage and their use cases

A current limitation of the UK Power Networks methodology when considering energy storage is the lack of representation of time derived variables such as the energy capacity, or the ability to model control algorithms and feedback loops' aspects. As such, current techniques will model a device with a fixed power rating for an indefinite duration; whilst in reality, this power rating would only be able to be sustained until the charge of the ESS is depleted. As part of this project, Newcastle University released a tool to enable UK Power Networks' planning teams to be able to give an accurate representation of energy storage on the Martham/Ormesby distribution network.

The network planning process will require enhancement when the results from Smarter Network Storage become available. The planners will need to understand the different use cases of the facility, their network impact and the financial benefits. Tools available will need to include financial benefit analysis so that network investments using either storage or traditional interventions can be compared more accurately by the network planners.

9.1.3 Control and operation

For the duration of the project, the operation of the ESS was performed by the project team. To fully incorporate this technology into the business, it would be required to migrate this function to UK Power Networks' control team. The control engineers will be best placed to understand the

configuration of the network as well as current levels of demand and generation which will affect the operational mode of the energy storage device.

9.1.4 IT Architecture

A full integration into corporate processes is necessary to ensure a successful transition into Business as Usual, including corporate IT arrangements such as access rights management, firewalls and communication line contracts. As part of this project, work has been carried out to start this process and the integration will be completed once a decision on the future use of the ESS has been agreed.

9.2 Non-DNO parties

9.2.1 Reduce the cost of installation and operation

As stated in the previous chapter, reducing the cost of installing and operating energy storage will have a positive impact on the economic viability of storage connected on distribution networks.

9.2.2 Improve system stability and reliability

Lessons have been learned by all project partners to improve system stability and reliability and it is reasonable to assume that any future system will prove more reliable and that the learning and improvements will continue as the technology and experience progresses over time.

9.2.3 Development or Clarity from Regulatory Frameworks

Whilst not explicitly explored in this project, there is currently uncertainty surrounding the ownership and operation of DNO-owned storage and the compatibility with EU and other regulatory frameworks.

This is unlikely to be an issue when used exclusively for network support, as in this project, but will have an impact if wider benefits are sought to improve the economic case. The Smarter Network Storage project is expected to generate additional learning in this area.

9.3 Conclusions

Based the findings of this trial, other DNO projects and the wider discussions with industry, UK Power Networks considers energy storage as a viable solution to have available to address changing network demand due to increased low carbon technologies and reduced generation flexibility.

10. FACILITATE REPLICATION

Key messages

- All components of the Hemsby ESS are commercially available
- The planning tool is available to other DNOs although it requires a network model developed in IPSA of the distribution network being studied
- The trial results, lessons learned and operating practices will be available free of charge for internal use

10.1 Replicating the solution

The ABB Mach2 controller platform, SVC Light, and Saft’s Li-ion batteries are fully developed and commercial products. These devices will enable other DNOs or users to replicate the physical components of this project. Newcastle University has confirmed that it will share the desktop planning tool with other DNOs via non-exclusive, royalty-free licences. The control algorithms created by Newcastle University will be specific to the Martham and Ormesby primary substations, and will not be relevant when replicating this project elsewhere, however the experience gained through developing them can be shared.

10.2 Components required

Components required	Details
Mach2 Control and Protection System	The Mach2 control and protection systems are available as a commercial product from ABB. This product was further developed for the purpose of this project to deliver an increased functionality when logging data at the ESS. The IPR for this component is owned by ABB.
Li-ion batteries	The li-ion batteries were sourced from Saft’s Intensium range. These are a commercially available product and no development has been performed as part of this project.
SVC Light	The SVC Light is a product available from ABB as part of their FACTS (Flexible AC Transmission Systems) range. This is a commercially available product, which can be installed with or without energy storage. The IPR for this component is owned by ABB.
Communications equipment	The communications equipment installed were not modified as part of this project. These were standard RTU based technologies, which are commercially available.

Table 12: Components required to replicate the project

10.3 Knowledge required

Knowledge required	Details
Operational experience	<p>The operational experience required to replicate this project has been disseminated through the following initiatives:</p> <ul style="list-style-type: none">• Early Learning Report: October 2012• LCNF Conference: October 2012, November 2013• ESOF meetings• This close down report <p>DNOs can contact the project team for further information using the contact details in Appendix C.</p>
Planning tool	<p>The planning tool, developed by Newcastle University, can be shared with other DNOs although it requires an IPSA model of the distribution network being studied.</p> <p>The user interface was written in php code and the user interacts with the simulation code from a web-browser. A mySql database is used to hold configuration and output data for querying after the simulation has completed. This solution means that the software can be installed on a local machine running a web-server or on a network web-server that users remotely connect to.</p>

Table 13: Knowledge required to replicate the project

Appendix A: FAQs

Q1. What is the lifespan of the battery installation?

Although the battery technology has a lifespan of up to 20 years, it is dependent on the number of charge/discharge cycles carried out, depth of discharges and calendar ageing. According to the manufacturer's guidelines, a constant depth of discharge of 80% would typically result in a life of approximately 3,000 cycles; whereas a depth of discharge of 40% would result in a life of approximately 10,000 cycles.

Our tests demonstrated an ageing effect of 1.5% per annum with a depth of discharge of 75%. This equates to a 20 year lifetime if end-of-life is taken to be 70% of the installed capacity.

Q2. How often did we use the energy storage device?

The frequency of operation of the ESS varied depending on external parameters (e.g. network conditions, wind farm output), and the control objectives. For example, if the ESS was set up to only reduce peak levels of consumption, one or two cycles of operation per day could be expected. If the device were set up to achieve a multitude of control objectives (voltage control, reduction of reverse power flows, etc.) and depending on the settings of the ESS, it would be entirely possible that many operations involving real and reactive power could have taken place every day. The modes of operation and settings were optimised to preserve battery life.

Q3. How were the losses modelled?

A modelling and simulation environment was built using physical network data (lines, cables, transformers) and operational data (voltages and currents). This included a load-flow capability that reported the losses that were present in the system under given operating conditions. By running the simulation with the ESS operating as defined in the trial cases, and then repeating the simulation without the ESS operating, the change in losses was evaluated. The storage and wider network monitoring deployment gave inputs and checks to the modelling system which provided verification of the model results and allowed a process of refinement to take place. Network losses information was combined with the parameters that described the ESS energy consumption (auxiliaries, battery charge characteristics, converter efficiency) that gave an overall assessment of the impact of the ESS on whole-system losses.

Q4. How was the battery connected?

The battery system was connected to the SVC Light voltage source converter, as well as to a harmonic filter. The voltage was then stepped up through a transformer to 11kV, and passed through a circuit breaker to act as protection for the entire ESS. A ring main unit connected the installation to the Martham primary 11kV network, with the option of feeding Ormesby.

Q5. What data was recorded?

Various metering devices were installed to record how much energy was being imported and exported, as well as the auxiliary power consumed and the local wind farm's output. In addition to this, data was available for the local primary network and monitoring equipment was installed at strategic points across the distribution network. Finally, all the parameters relating to the ESS

installation such as Real power (kW), Reactive power (kVAr), Voltage (V), Current (A), state of battery charge, settings, circuit breaker operation and other fault signals were logged.

Q6. What safety measurements were in place?

A circuit breaker controlled by the Mach2 control system protected the ESS, and was located on the 11kV side of the installation before connection to the distribution network. DC circuit breakers connected the battery stack to the power conversion system, and a G59 relay provided back-up protection should the software based protection have failed to operate.

The auxiliary systems were fed by two independent LV feeds. Should one supply have failed, an automatic changeover switch would have operated to maintain the auxiliary supplies. Access to the site was restricted, and only trained staff could obtain entrance to certain enclosed areas, such as the valve room. Further details on this can be found in Appendix 3 of the Engineering Instruction. Finally, the batteries were protected by a CO₂ fire suppression system, which was required to be disabled to allow access.

Q7. What was the physical size of the installation?

The installation consisted of a structure to house the battery system and control equipment, and external space for components of the cooling system and connection to the 11kV network. The footprint of the installation was approximately 625m² (25m x 25m).

Q8. Why was a Li-ion battery chosen?

This particular technology was chosen due to its lifespan and quoted high round-trip efficiency. All of these factors helped to increase and prolong the maximum levels of performance. Originally, a ZEBRA battery system was intended to be used, but upon considering the higher operating temperatures and after sales support, the decision was made to use a Li-ion battery.

Q9. What was the construction/arrangement of the battery?

The system was based on Li-ion cells (ranging from 3V - 4V depending on charge level). 14 of these cells completed a module (42V - 56V) and 13 modules completed a unit (546V - 728V). There were eight units in this system, which could deliver 200kWh of energy at approximately 4.3kV - 5.8kV DC.

Q10. Was there a solid financial business case for the ESS at Hemsby?

The installation of an ESS at Hemsby was not intended to have a strong financial return (given its relatively small scale), but to be an opportunity to further understand the effects of energy storage on the 11kV network and hence the potential for future larger scale devices, with sufficient economy of scale, to be economically viable as network support devices. As such, the main outcomes of this project have been learning and understanding.

Q11. How was the charging of the battery paid for?

Rather than considering the energy used for charging the battery as network operational losses, it was decided to measure the kWh required during charging and discharging, and enter into a supply agreement with an energy supplier. This enabled us to gain a better understanding of the relationship between financial energy charges and usage patterns.

Appendix B: KNOWLEDGE DISSEMINATION

B.1 Reports

- Early learning from an electrical storage installation on an 11kV distribution network, Oct 2012
- Demonstrating Energy Storage/Hemsby, information flyer, October 2013

B.2 Events

- LCNF Conference 2012, Cardiff
- LCNF Conference 2013, Brighton
- Wade, N.S., et al., Evaluating the benefits of an electrical energy storage system in a future smart grid. *Energy Policy* (2010).
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Appendix C: DETAILED SYSTEM OVERVIEW

C.1 Introduction

Although originally designed and built for the AuraNMS project, the original storage device's proximity to wind farms and its location between two feeders in rural Norfolk made it ideally suited to create a test bed to demonstrate the benefits of 11kV for distribution network operators.

The complete trialling environment comprised:

- The Energy Storage System (ESS)
- The Controller of the ESS
- The 11kV Network
- Remote communication architecture

This appendix presents each in detail.

C.2 The Energy Storage System

Designed and built by ABB and commissioned by UK Power Networks in 2011, the device was capable of exchanging **real power** with the network at 200kW nominally (1hr) or up to 600kW peak (15 min) and exchanging **reactive power** +/- 600kVAr for unlimited durations using the SVC Light. The ESS and its associated switchgear, protection and cooling equipment were housed in an open air compound, as illustrated below.

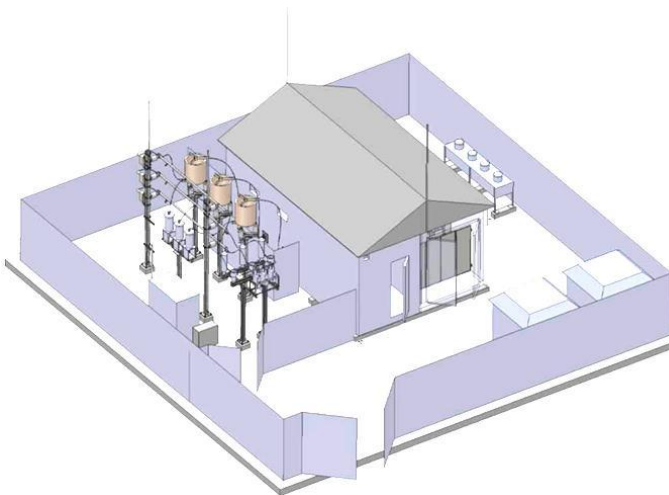


Figure 20 Drawing as planned



Figure 21 Site as built

The main components of the facility were:

- **Battery:** The basic component of the battery was the Saft Lithium-ion Intensium cell, which was rated at 3 – 4 VDC. 14 cells comprise a rack (42-56 VDC) and 13 racks build a unit (546 – 728 VDC). The entire energy storage system installed at Hemsby used a string of 8 units, which was rated at 4,368 – 5,824 VDC and had the capacity to store 200 kWh of energy. The continuous rating of the battery was 200kW with a short-term peak rating of 600kW.

- **SVC Light:** The SVC Light was an IGBT based power compensator and converter, and was a FACTS device. The system had a continuous maximum rating of 800kW. This was connected to the battery, and converted the DC power into AC for use on the network. The voltage at the output of the system was 2.2 kVAC. It was able to both manage the real power exchanges on the network and also the reactive power compensation to help to control the voltage. The SVC Light was controlled by the Mach2 control and protection system. There was a harmonic filter installed on the 2.2kVAC side of the SVC Light, which aimed to reduce the harmonic by-products of the conversion process.
- **Transformer:** The output from the SVC Light was 2.2kVAC and was connected to a transformer to allow power to be exchanged with the network at 11kV. A transformer with a rating of 1MVA and an air cooled resin encapsulated design was selected, as this type of design has little thermal latency.
- **Protection device:** The Mach2 control and protection system identified fault conditions and causes a circuit breaker to open. Whilst this system used an active and back-up computer to increase robustness, UK Power Networks decided to include further protection in the form of a G59 relay.
- **Auxiliary transformers:** The power required for energising the cooling and control systems came from a 50kVA pole mounted transformer. There was also a 100 kVA pad mounted transformer, which was housed in a GRP enclosure and provided back-up power should the primary supply have failed. These transformers were fed from Martham and Ormesby respectively, and a fault on the active feeder network would have caused the automatic changeover to operate.
- **Cooling requirements:** Temperature control was provided by two coolant pumps and four external heat exchangers.
- **Fire Suppression:** A CO₂ fire suppression system was installed in the battery room to act as protection in the event of a fire. There were smoke and temperature sensors, which fed into the fire control panel.

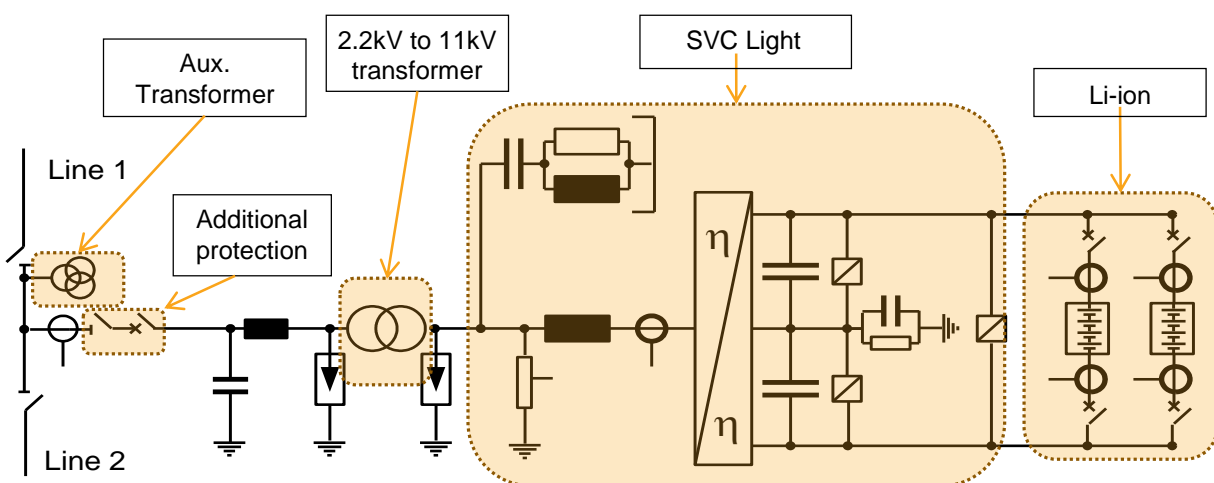


Figure 22 Single Line Diagram ESS

C.3 The 11kV Network

The Martham-Winterton and Ormesby-Hemsby 11kV sites were chosen because they have some significantly different characteristics. Ormesby-Hemsby is a relatively short feeder that mostly supplies the holiday parks on the seaward side of Hemsby, while Martham-Winterton supplies a diverse collection of farms, residential areas and holiday parks with around twice the length of conductor. Martham-Winterton also has more low-power distribution transformers than Ormesby-Hemsby. The most frequently occurring load (mode) is quite similar on both feeders at 1.15 MW and 1.30 MW on Martham-Winterton and Ormesby-Hemsby respectively, but a much higher peak is found on Ormesby-Hemsby at 4.3 MW compared with 2.3 MW on Martham-Winterton.

Only one feeder was connected to the ESS at any one time, allowing for different operational situations, which maximised the learning gained.

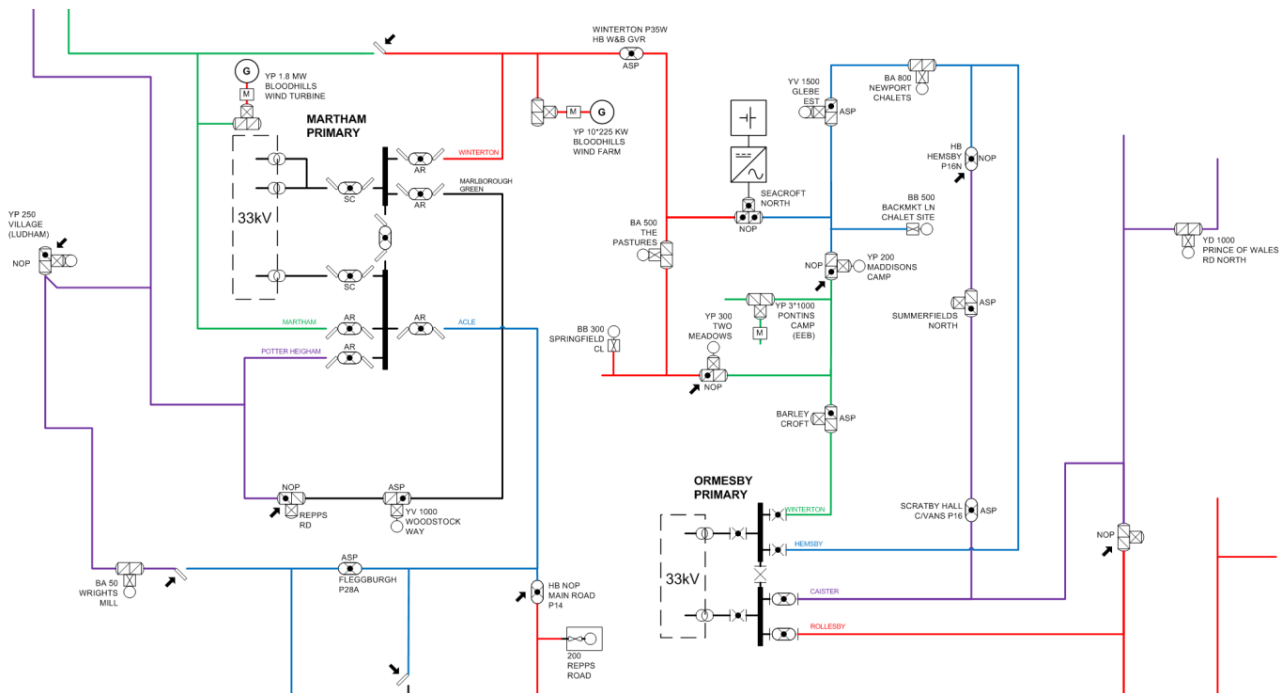


Figure 23 Single line diagram of Martham and Ormesby networks with ESS at Hemsby and secondary monitoring systems in place

C.4 Communication architecture

To allow for the ESS to react to real-time network measurements, and also to allow for remote control of the device, it was crucial to establish a secure and robust communication network. This involved additional installations at both primary locations, Martham and Ormesby, as well as installations at secondary locations across both 11kV feeders to provide measurements at remote locations across the feeders. An overview of the communication architecture can be seen below:

- **ESS:** The ESS had an ADSL line installed to allow for remote connection to the device for controlling and analysis functions.
- **Ormesby Primary:** This 33/11kV substation recorded Voltage, Real and Reactive power and the position of the tap changer on the transformers. This site had an ADSL connection to allow it to connect to Martham.

- **Martham Primary:** This 33/11kV substation also recorded Voltage, Real and Reactive Power and the position of the tap changer on the transformers. This site collected all data from the primary secondary sites into the COM600 controlling device. Using the appropriate algorithm, this device then sent control signals to the ESS to determine the mode of operation.
- **Secondary sites:** Equipment was installed at a number of remote secondary sites to record a variety of parameters, such as voltage and power levels. These were sent via GPRS to the COM600 at Martham, and fed into the control algorithm.
- **Firewall security:** It was essential that any access to the device was restricted to approved users who were suitably trained and authorised to control the ESS to ensure correct operation and minimise risk. All access was over a secure VPN, which passed through the UK Power Networks firewall.

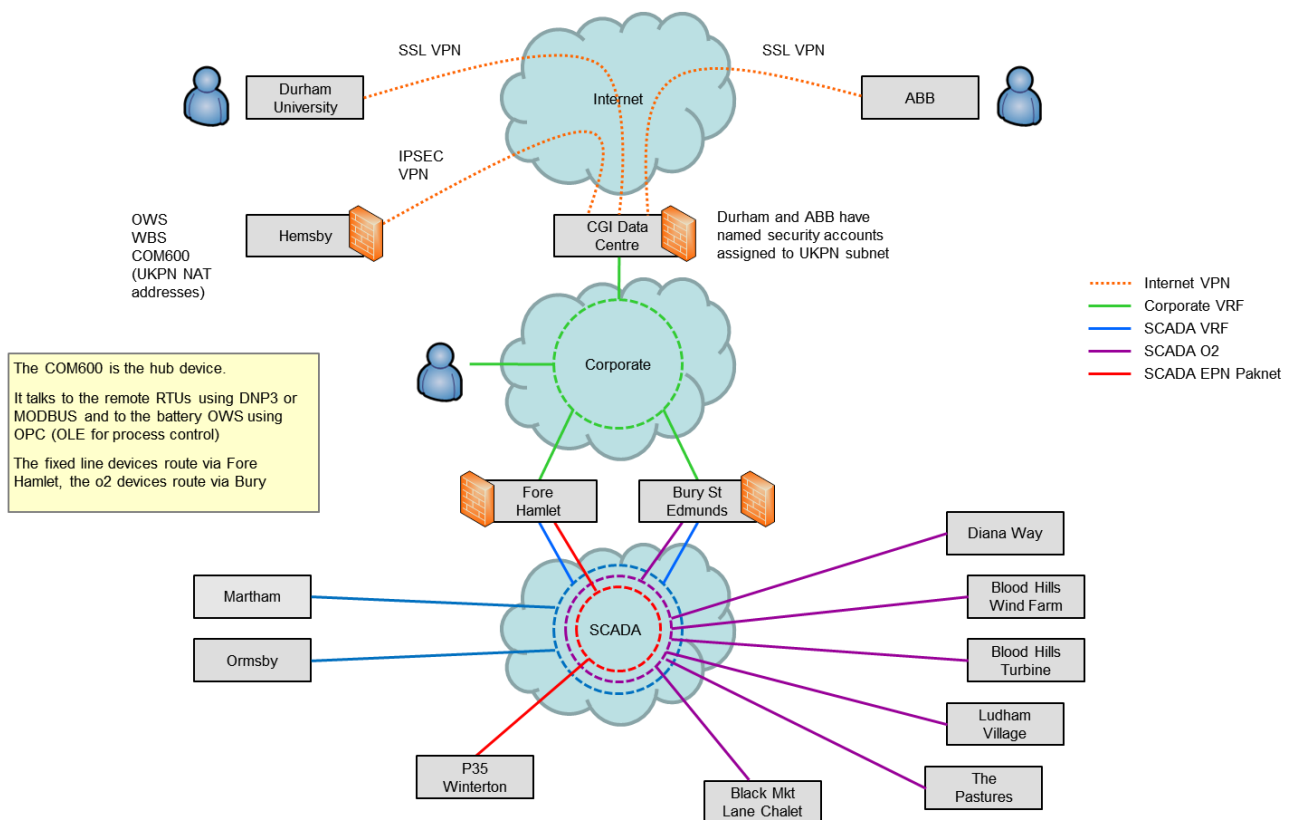


Figure 24 IT Architecture for the Hemsby project

C.5 ESS Control System

The ESS plant was managed by ABB’s Mach2 control system, which comprised both hardware and software specifically developed for power applications. Mach2 was built around an industrial PC with add-in boards and I/O racks connected through standard type field busses. The ESS could be controlled from a local interface, the Operator Work Station (OWS), located in the control system enclosure and via a Web Based Support (WBS) for remote connections.

The purpose of the control system was to:

- Provide voltage/reactive power control at the 11kV bus
- Transfer energy accumulated in the battery system to the 11kV network
- Re-charge the battery system by temporarily drawing active power from the 11kV network

The ESS plant could be operated in an automatic mode where local voltage measurements were used to determine the required injection of reactive power to stabilise the voltage at the ESS. In order to make decisions on ESS control from a wider range of measurements taken from across the network, such measurements would be collected and processed by algorithms on a central control system. Decisions would then be issued as ESS set points for active and reactive power control.

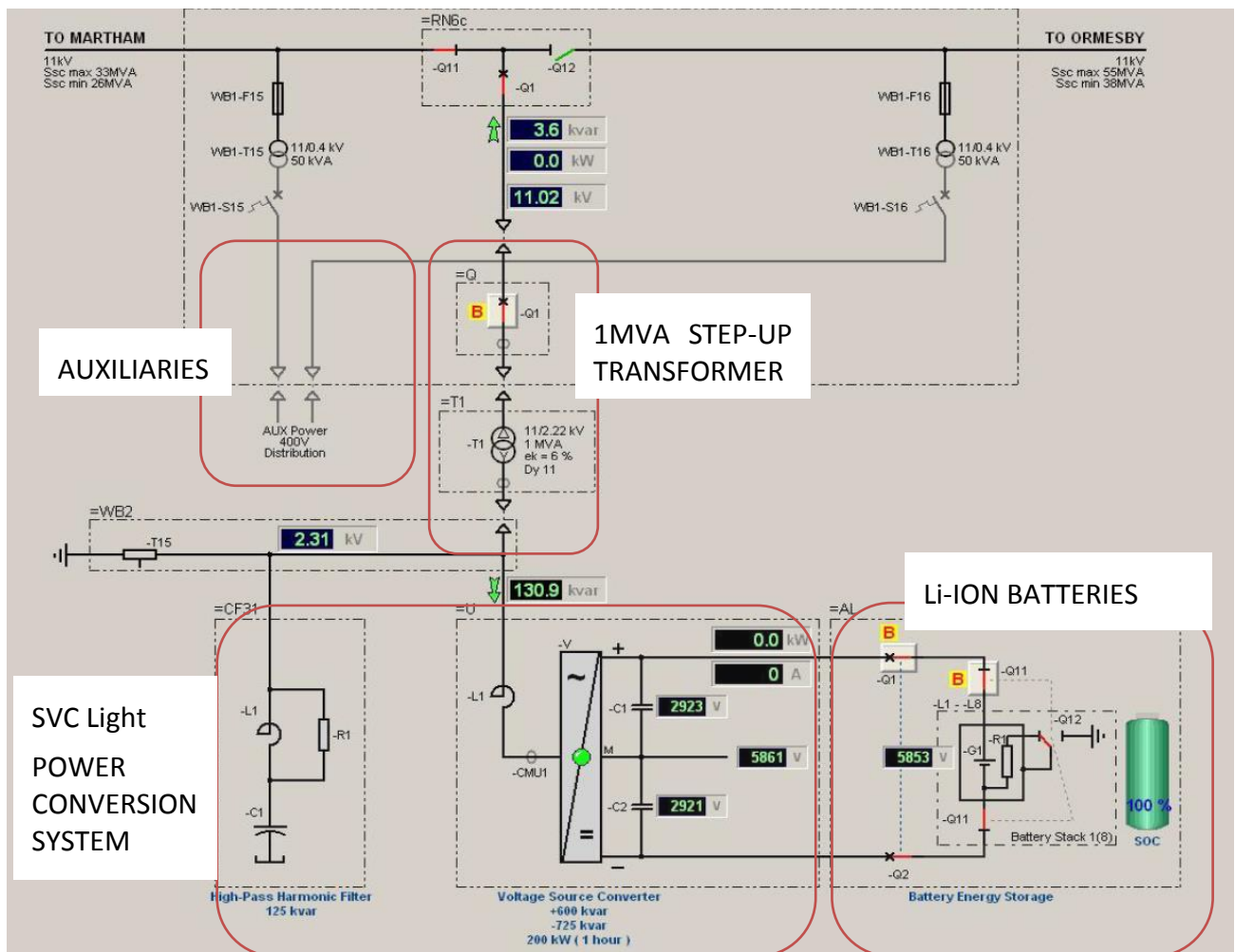


Figure 25 MACH2 control system single line diagram and main components impacting the efficiency



Heat Exchangers

- Share duty



Battery Room

- CO2 fire extinguisher nozzle (above and below)
- Observation window to check DC disconnect has opened

Appendix D: DETAILED RESULTS

D.1 Introduction

Trials on the Martham and Ormesby networks have been conducted with increasing levels of complexity since the device was first commissioned on the network at Hemsby. Initially, only local control of the Active and Reactive Power set-points by UK Power Networks staff was allowed. Following this, control of the set-points was carried out by UK Power Networks staff remotely. Once confidence in the performance and stability of the system was sufficiently high, control of the system by set-points determined by a computer control algorithm was allowed.

The results given here show how these trial phases were able to test a wide range of operating modes for energy storage on an 11kV distribution network. Control of network voltages and power flows using measurements local to the ESS and from primary and secondary sites were trialled. The performance of the ESS was tested, independently from its interaction with the electricity network, to determine the efficiency of the battery system and the auxiliary power demand of the overall system.

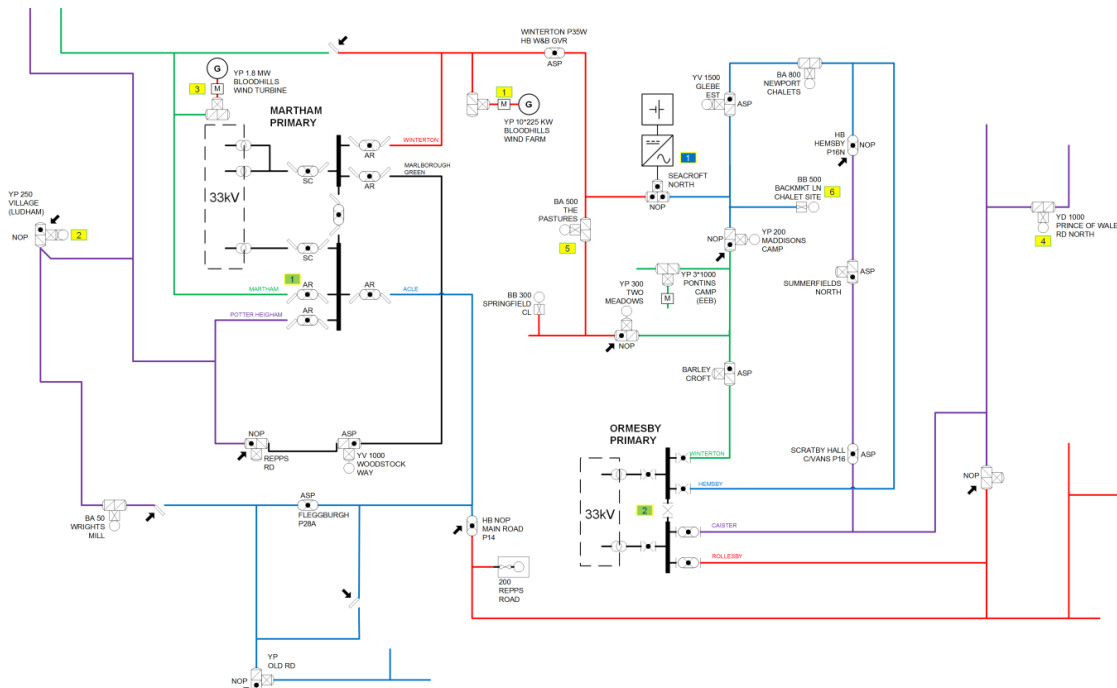


Figure 26 Single line diagram of Martham and Ormesby networks with ESS at Hemsby and secondary monitoring

D.2 Methodology

D.2.1 Measurement

To make anything but a very basic control decision, some information about the prevailing conditions on the network was required. This information included busbar voltages, branch power flows, generator output, and transformer tap positions. A communication and instrumentation system was installed to retrieve the measurements from transducers at primary substation and secondary sites. Both secondary transformers and embedded generators (wind) were included in

the secondary sites. Information that was available at the ESS, including power flows, voltage at point of common coupling (PCC) and battery statuses were also included in the instrumentation system. The locations of measurement points are shown on the network single line diagram in Figure 26. Measurements updated at a 1-minute interval were available for both control and analysis purposes.

D.2.2 Control

For manual control, the ESS was controlled by an operator either on-site or remotely. This allowed basic network control actions to be carried out, either by following a schedule, or through judgements based on the observed network conditions. An operator needed to be available and have visibility of all the information they needed to make a decision on the set-points for the ESS.

To carry out control actions that were more dynamic in nature, it was necessary to decide what to do within a control algorithm and issue the resulting set-points to the ESS. Such machine-to-machine control was exercised by exchanging commands or information by writing to or reading from an OPC server running on the Gateway Server of the ESS. This facility was used to implement dynamic, near real-time, control decisions based upon measurements taken from the network. Control algorithms run at a 1-minute resolution, in step with the update rate of the measurements.

After a trial had been run, analysis was required to understand what had taken place and evaluate the performance against expectations. Because the demand and network voltages have a significant stochastic component during the timescale over which the control system was operating, it was not possible to run any two tests with the same background network conditions. Voltage and demand cannot be expected to be the same in any ostensibly ‘similar’ trial. It was necessary to make a judgment as to what the effect of the ESS had been during a trial and make a comparison with what would have happened if the ESS had not been operating. Two approaches to managing this situation were available: either the trial must be repeated many times, with and without the ESS, to build a statistical picture of the effect of the ESS; or a modelling process implemented to artificially add or remove the effect of ESS.

A modelling and simulation environment was developed before the Tier 1 project started which has been used in analysis, both before and after trials, to decide what to do and assess what has happened respectively. This was composed of an IPSA network model that allows load-flow analysis to be carried out and programming code written in Python that simulates the behaviour of the ESS and the control system that reads network conditions and takes control decisions.

D.3 Voltage control: Using the statcom

The ESS Mach2 system controller has a built in voltage control algorithm that responds to the local measurement, at the PCC, of the 11kV network voltage. Reactive power is exported to boost voltage when low and imported to decrease voltage if it is high. The operation of this function was tested by varying the set points of the algorithm and recording the effect.

The voltage control algorithm was configured with the parameters in Table 14. Changes to the default settings were made as shown in the difference between ‘original setting’ and ‘revised setting’.

Table 14. Changes to voltage control mode programmable parameters.

Parameter	Description	Original setting	Revised setting (31/07/12)
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UAC,ref:	Voltage reference	11kV	11kV (no change)
Slope:	Scaling factor	2%	2% (no change)
UDB:	Dead-band	0.11kV	0.08 kV
iq,ref,max:	Converter current ref	156 A	78 A
iq,ref,min:	Converter current ref	-189 A	-111 A

The configuration can be interpreted as in Figure 27, which shows how the exchange of reactive power changed in response to the measured voltage at the PCC. A reduction in the maximum reactive power output (from 600 kVAr to 300 kVAr) was made to prevent excessive power flows taking place during this test. The main difference was a reduction in the dead-band, which means that smaller voltage deviations from the ‘voltage reference’ cause the controller to begin exchanges of reactive power with the network.

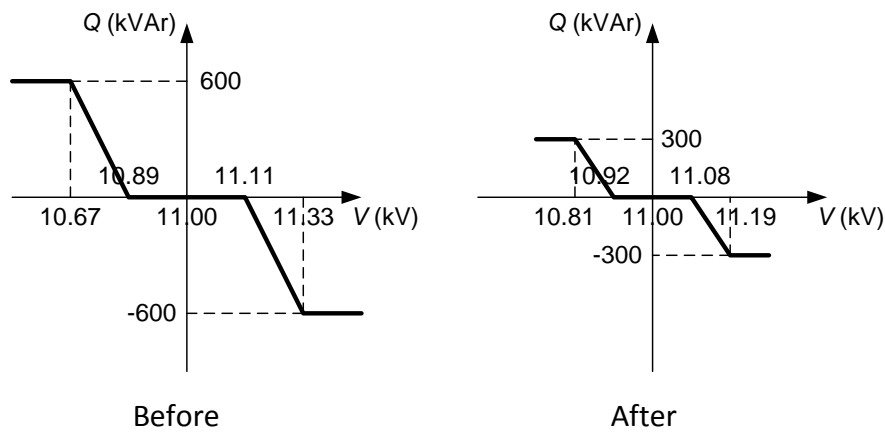


Figure 27. Changes to voltage control settings

Figure 28 shows the seven week period surrounding the SVC Light set-point change. For information, the feeder real power demand and windfarm real power output are given, as they are significant controlling factors for feeder voltage. Note for instance that the SVC Light voltage regulation worked to increase the voltage during the period of high demand in the week beginning 12 August 2012. In this graph ‘Vpcc—No ESS’ and ‘Vpcc-With ESS’ are modelled results. The ‘byKVARCalc adj’ dataset used the 30-minute-average kVAr flow at the ESS-PCC to reconstruct the voltage profile at the PCC. Feeder demand and wind farm output are also shown on the graph to give context to the pattern of voltage fluctuations that are seen.

To increase understanding of the results from this test, the measured data was also run through the network model to provide additional interpretation from the available information. ‘Vpcc—No ESS’ and ‘Vpcc-With ESS’ were modelled results using the SCADA 30-minute-average data as inputs to the IPSA model of the network. This result was corroborated by the ‘byKVARCalc adj’ dataset that used the 30-minute-average kVAr flow at the ESS-PCC to reconstruct the voltage profile at the PCC.

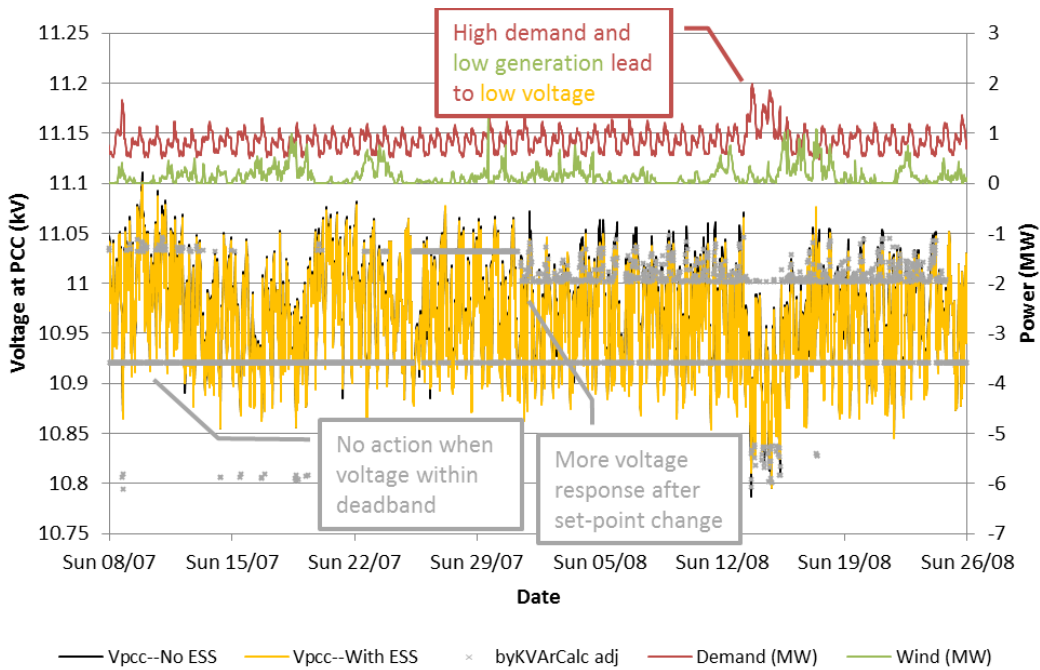


Figure 28 Seven week period surrounding SVC Light set-point change on 31 July 2012

A closer view of the effect of the set-point change is shown in Figure 29. In this graph, 'Vpp--No ESS' shows the voltage when no voltage control is in place and is compared with 'Vpp--With ESS'. After the deadband change, the higher voltages are frequently reduced. The grey line shows what the voltages would have been without operating the voltage regulation.

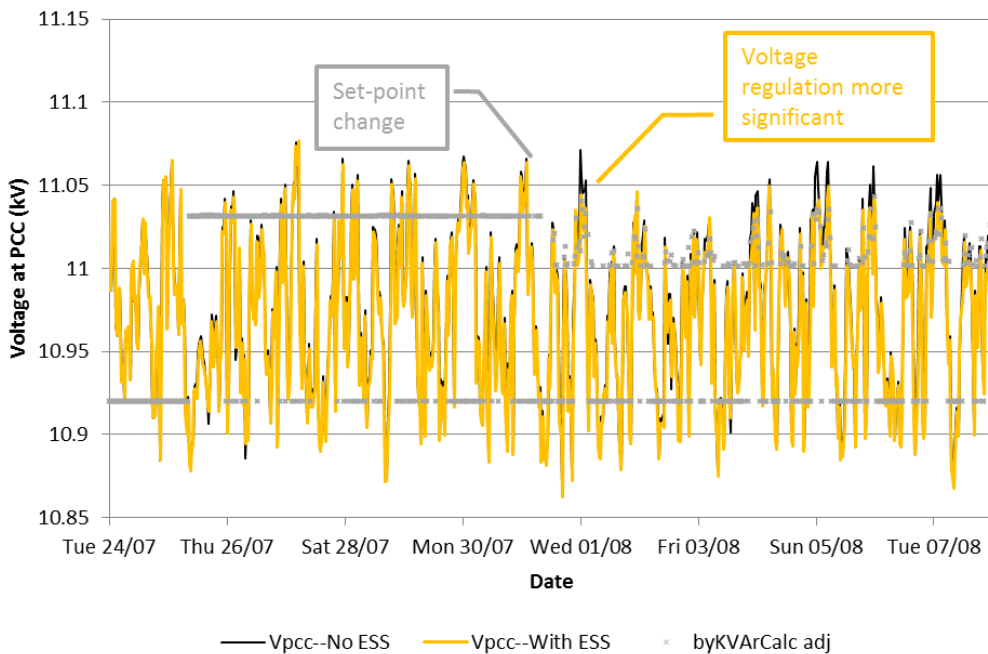


Figure 29 Close up of period before and after the deadband was changed from 0.11kV to 0.08 kV

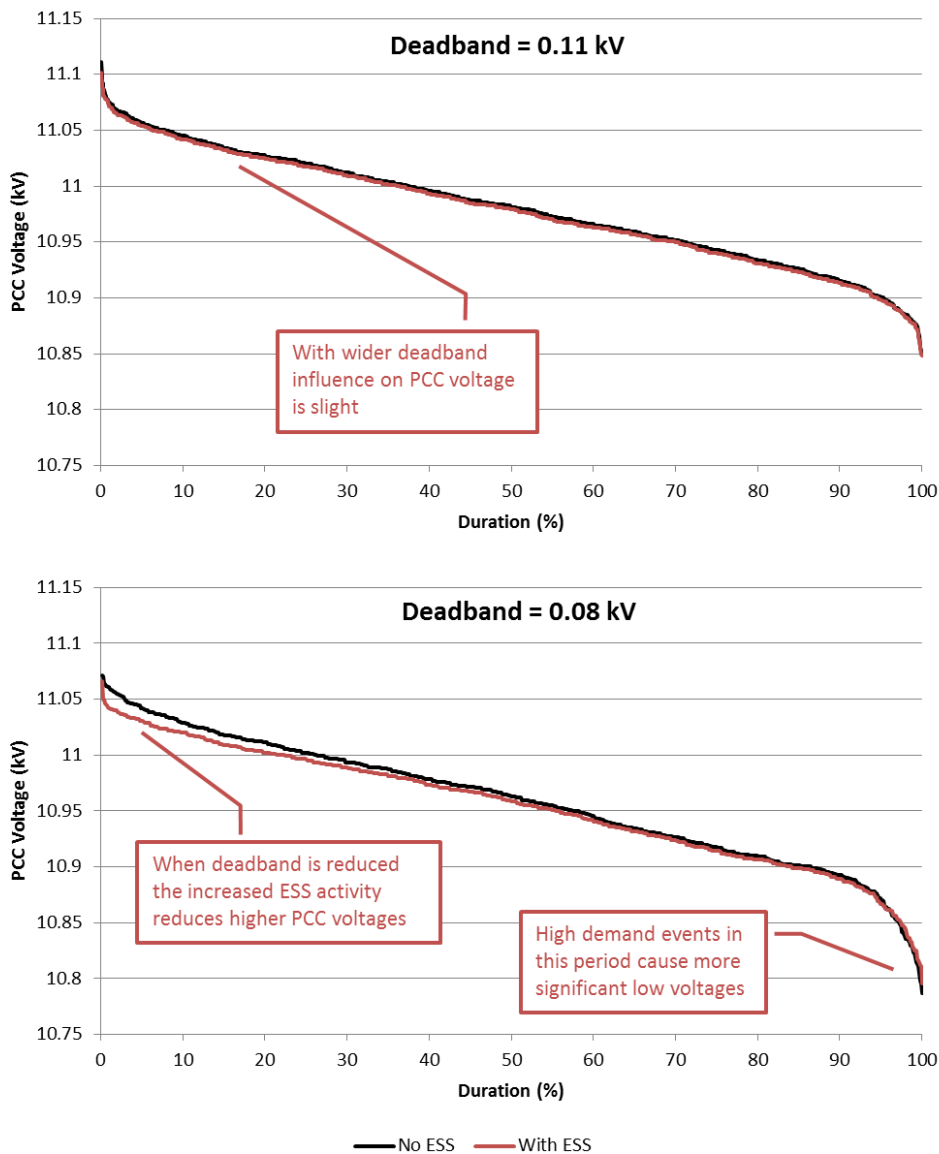


Figure 30 Voltage duration curves, before and after set-point change

To visualise the change to the voltage profile with time, duration curves before and after the set-point change are shown in Figure 30. This is a way of summarising the impact of the change to the voltage control deadband setting. These duration curves show the week before (upper) and week after (lower) the deadband change. There was a clear reduction in the upper limit of voltages that occurs in the later period. Reference to the demand and generation patterns in Figure 30 shows that the underlying network behaviour was similar in both of these periods; except for a period of high demand after the change where the voltage was particularly low.

D.3.1 Conclusions

The ABB supplied automatic voltage control provided a measureable effect on the ESS PCC voltage. In the period during which the test took place, the deadband of the control function was narrowed from 0.11kV to 0.08 kV, reducing the maximum recorded voltage by 0.025 kV.

A significantly higher load condition was experienced after the deadband setting change that resulted in a lower minimum voltage being observed.

D.4 Voltage control: Algorithmic operation using secondary monitoring sites

Instead of regulating voltage from the PCC measurement, the voltage was regulated from a secondary measuring unit at the furthest available point from the Primary Substation. The control algorithm read the voltage at secondary measurement location 5 (The Pastures) and used this to determine the set-point of the energy storage system. In this trial, the ESS output was set to zero in a deadband of 10.4-10.45 kV. When the voltage was beyond this deadband, power output was set in proportion to the difference between the measured value and the edge of the deadband. The result of this is shown in Figure 31, where the real and reactive ESS power exchanges, battery state-of-charge and remote voltage measurement are displayed. In addition to the measured quantities, the network model was used to determine what the voltage profile would have been without the storage system operating.

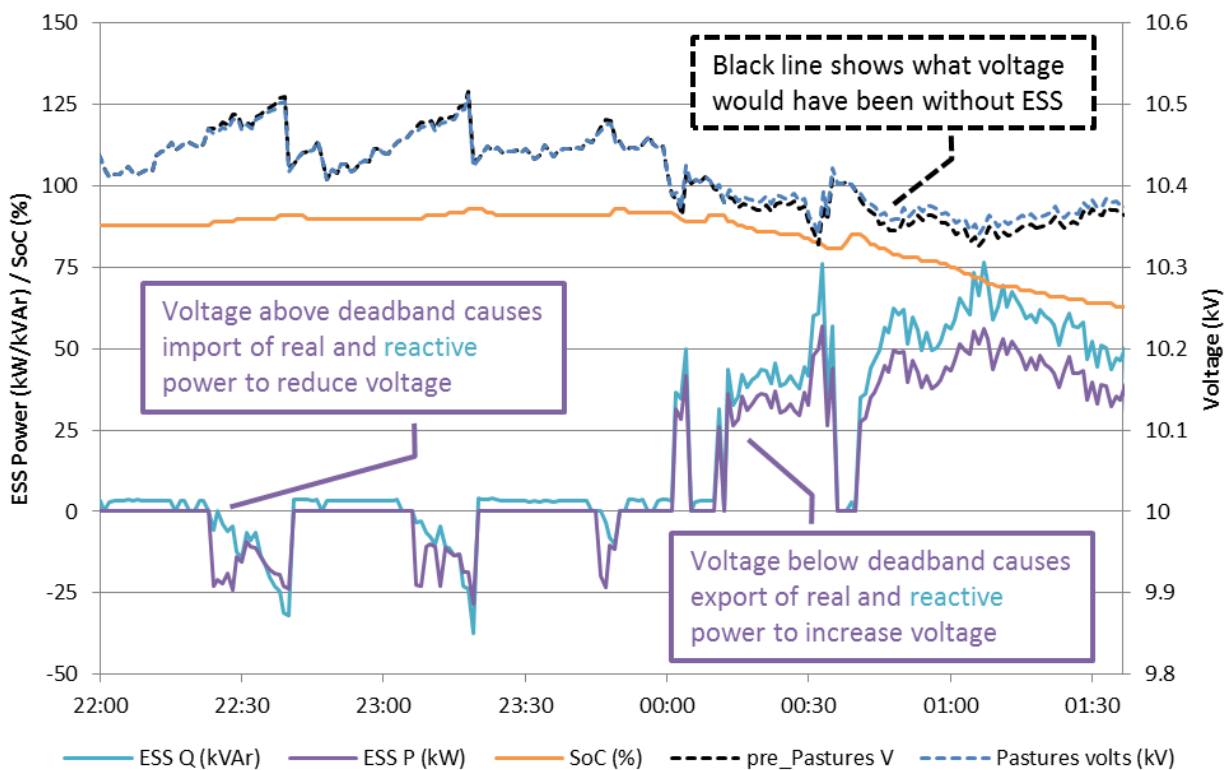


Figure 31 Voltage control in response to voltage measurement at far end of feeder

In the early part of Figure 31 the voltage was increasing, which at 22:39 caused the tap changer to operate, resulting in a step change in the voltage. Similar step changes can be seen later in the figure. While the voltage was above 10.45 kV (edge of deadband), real and reactive power was taken into the ESS to attempt to decrease the network voltage. The relatively small excursions resulted in a small power exchange and a correspondingly modest voltage reduction.

After 00:00 the network voltage began to decrease. This was driven by an increase in demand as night storage heaters began to turn on. The deviation from the bottom of the deadband (10.4 kV) was greater than was seen in the over-voltage condition so the power exchange and corresponding voltage correction was increased. Throughout this event, the power level was modulated in response to the actual network conditions. With the settings used in the test, the minimum voltage was raised by 0.014 kV.

D.4.1 Conclusions

A control algorithm was used to regulate the voltage at a different location to that of the ESS. Both under- and over-voltage were responded to by corresponding export and import power set-points at the ESS. A combination of real and reactive power was used to regulate the voltage.

A model of the network was used to calculate the effect of the ESS and indicate that the use of up to 60 kW of the ESS power capability has resulted in a 0.014 kV reduction in the network voltage deviation.

Higher levels of power could be used to increase the effect of this intervention, in this case each 10 kW of power used affected the voltage by 0.04%. The specific location of the busbar under control relative to the ESS changed the efficacy of this control mode.

D.5 Power-flow management: Manual scheduling

By analysing historical demand data, the expected demand profile for particular future days was determined. This was done for short periods of time (two to four weeks are sufficiently stable) so that a manual switching schedule could be specified and implemented by UK Power Networks staff. This process resulted in a schedule such as that shown in the table below. Information from the energy supply contract was used to calculate the cost of operating the trial and an estimate of the revenue that would be received from the sale of energy (not known in advance as revenue is a function of the System Buy Price, determined in the Balancing Mechanism).

Table 15 Pre-determined power exchanges for manual implementation

Week	Month	Day	Date	Time	Energy cost	Estimate of revenue	Setpoint change	
							Real power (kW)	
							Import	Export
3	Jan	Mon	21-01-13	13:00	£8.16		-43.3	-
3	Jan	Mon	21-01-13	16:00			0	-
3	Jan	Mon	21-01-13	17:00		£5.76	-	65
3	Jan	Mon	21-01-13	19:00			-	0

This example was valid as at 21 January 2013 and the results from the implementation are given in Figure 32. It can be seen that the demand profile was significantly flattened by this operation, even with relative modest power exchanges of -43 kW and 65 kW. In this case the evening peak was reduced by 45 kW. The battery state-of-charge varies from 16% to 83%.

D.5.1 Conclusions

It has been shown that with a good understanding of the daily demand profile, the peak real power flow on the feeder can be reduced. In this case, an output of 65 kW reduced the peak by 45 kW.

The limited available energy resource must be managed to provide the maximum peak power reduction, by operating over the peak demand period without running out of energy before the

peak has passed. Modulation of the power output would have the potential to produce an absolute power reduction closer to the maximum output level.

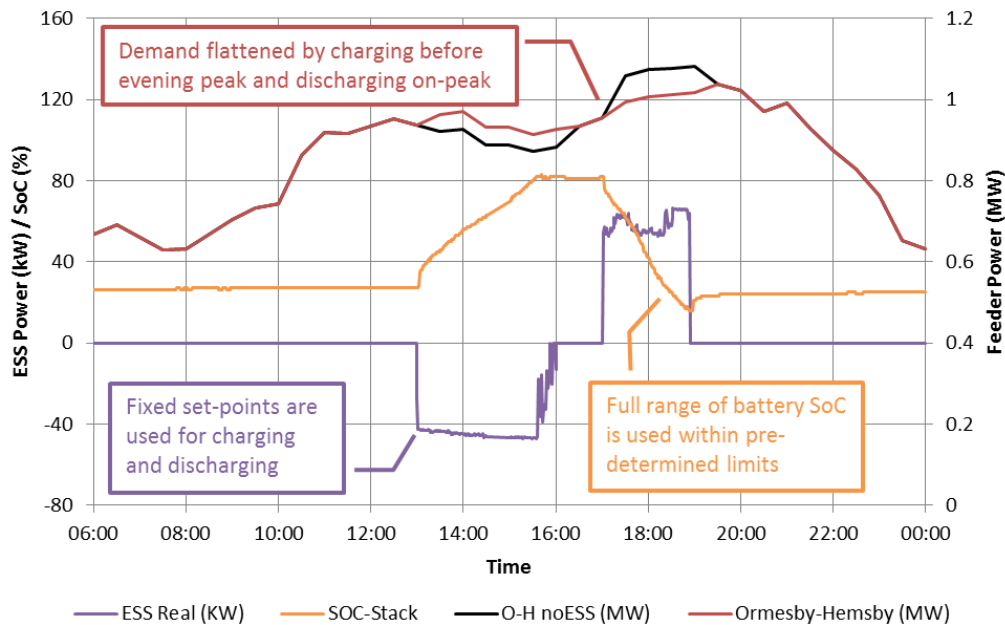


Figure 32 Scheduled real-power operations, timed to charge in afternoon lull and discharge during evening peak

D.6 Power-flow management: Algorithmic ‘peak shaving’

From day to day, week to week and season to season, the pattern of demand changes. In order to be able to assess the capability of the ESS to perform real-power peak-shaving an algorithm was developed that estimated the upcoming time and magnitude of the demand peak. This controlled the point in time and the power threshold at which peak-shaving started, to make the best use of the limited energy resource available in the ESS. For the three days of operation shown in Figure 33 (showing ESS power exchanges and State-of-Charge in upper part of figure and feeder power flow with (Hemsby_P) and without (Pre_Hemsby_P) ESS operating), a 98 kW reduction from 2.615 MW to 2.517 MW in peak feeder power demand was achieved with a 103 kW maximum power output from the ESS.

The 5 kW difference between the reduction and the maximum power output was due to the delay between reading the feeder power and adjusting the ESS output. In this implementation, up to one minute could have passed between the measurement being taken and the ESS set-point being calculated.

A one day period of operation is shown in Figure 34 to give increased detail of the operation of the peak-shaving algorithm.

D.6.1 Conclusions

An algorithm was used to demonstrate peak-shaving with a one-minute set-point update rate. This used the available power and energy efficiently to reduce the peak power flow onto the feeder in this trial, reducing the peak feeder power by 98 kW with a peak ESS output power of 103 kW.

An element of demand forecasting was required to prevent the algorithm acting too early and using all the available energy before the actual demand peak was reached.

An algorithm that tracked and reduced the daily peak feeder power, as compared with one that only operates when an absolute peak power threshold is crossed, served to reduce the network losses since these increase as the square of the current flow. However, the energy cost of doing so when factoring in the ESS round trip efficiency should also be considered.

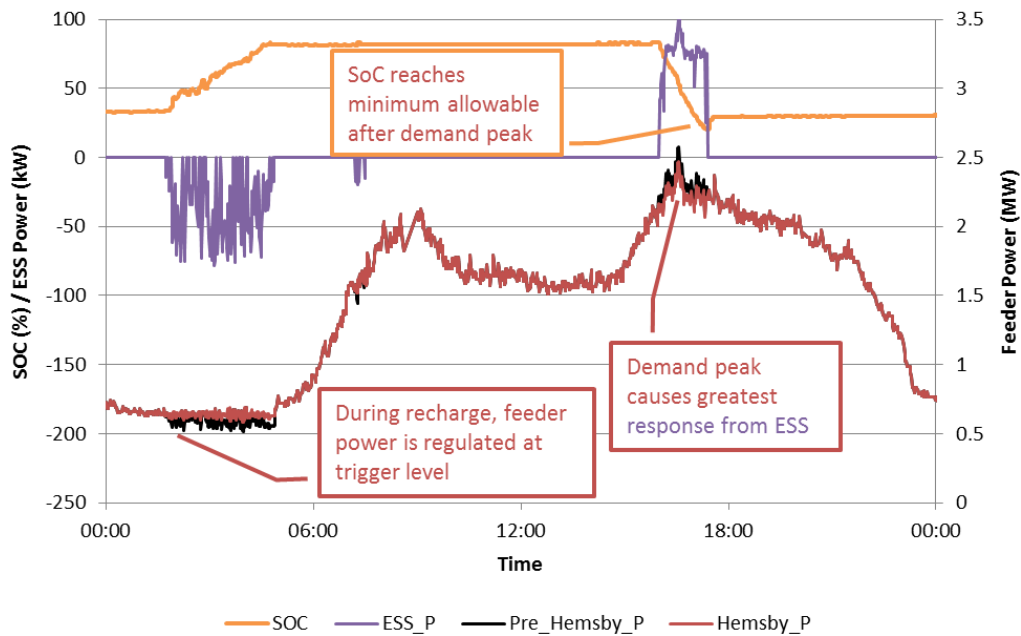


Figure 33 One day of adaptive peak-shaving operation

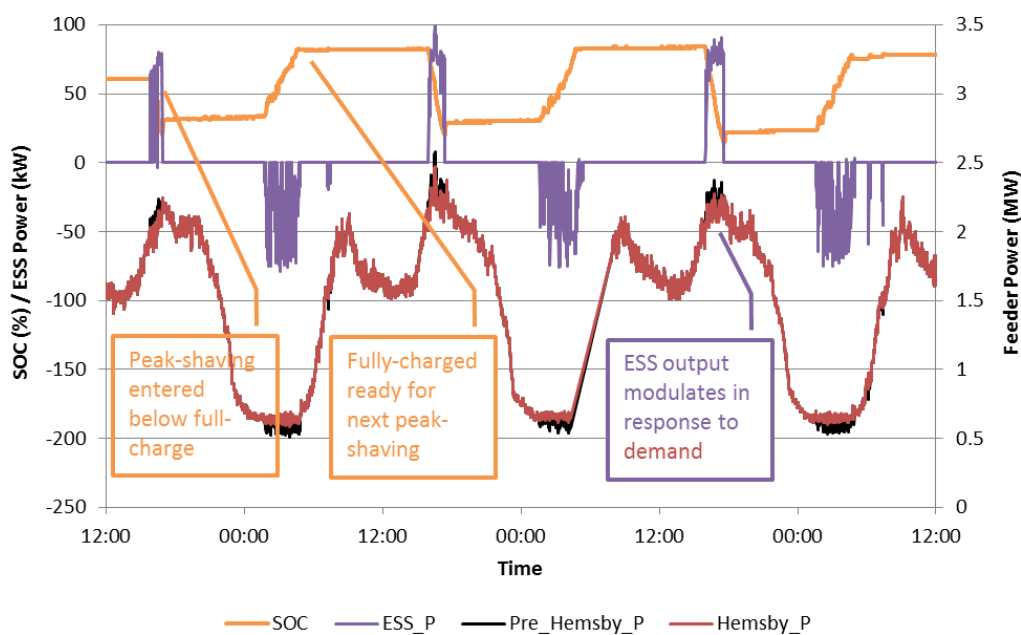


Figure 34 Three days of adaptive peak-shaving operation

D.7 Power-flow management: Reactive power following

Local supply of reactive power onto a feeder can benefit the network by reducing the reactive power demanded from the wider network. This reduces the apparent power flowing further up the supply system and thus the system losses. Voltage control can be simplified in some circumstances by adjusting reactive power flows. The Martham-Winterton feeder had a particularly significant reactive power demand due to the induction machines that generate power at Bloodhills Wind-farm. These draw up to one MVar of reactive power when generating at their rated capacity of 2.25 MW.

The charts in Figure 35 show the ability of the control algorithm to regulate the reactive power delivered onto the feeder at Martham Primary substation over a period of one day. In the lower charts the modulation of the ESS Reactive Power output can be clearly seen in the turquoise trace, resulting in a stable reactive power demand of 0.1 MVar (brown trace) until 12:00. If the ESS had not been operating, reactive power would have followed the black trace. Once the Wind-farm generated above 0.5 MW, its reactive power demand exceeded the 0.2 MVar output limit that was set on the ESS output. This is shown where the ESS output saturated just after 12:00.

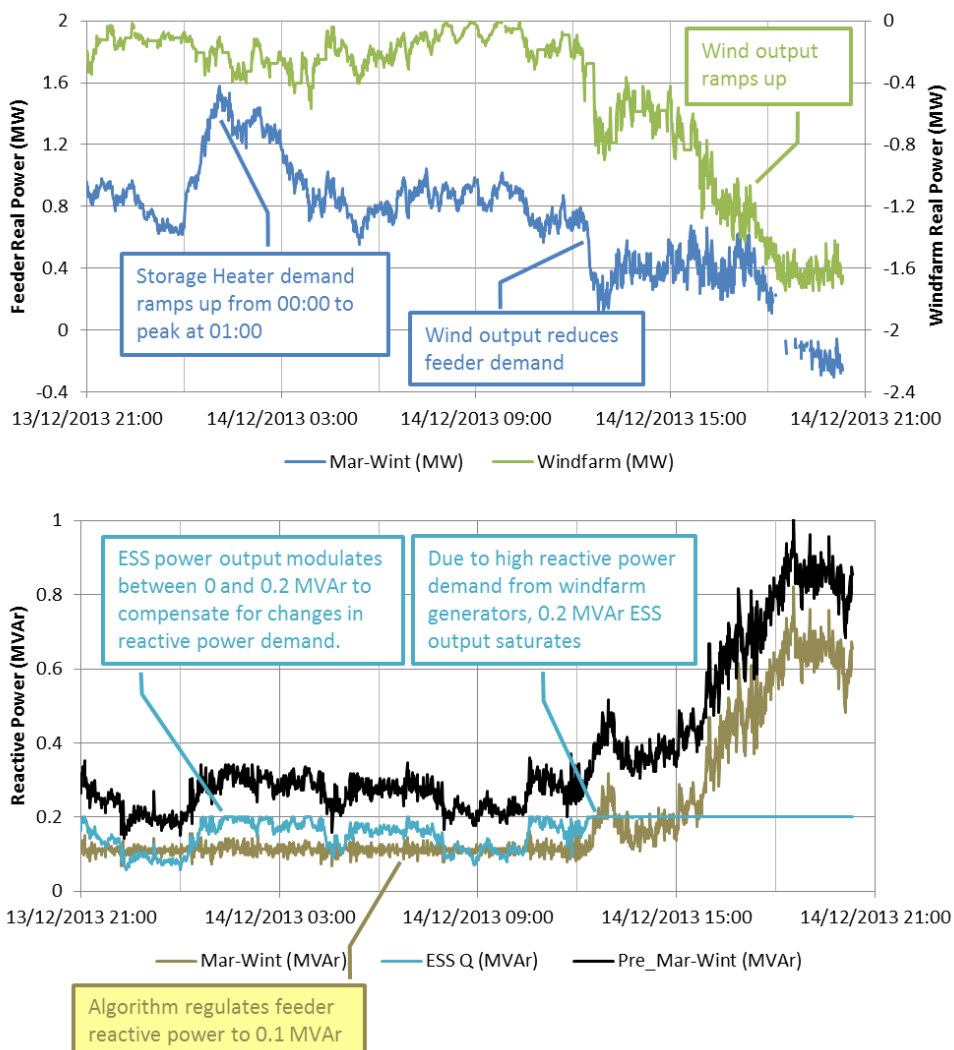


Figure 35 Reactive power compensation at primary substation for one day

The upper chart shows the cause of the reactive power demand; the increasing wind-farm output is shown by the green line becoming more negative. The corresponding reduction in feeder

demand is shown in blue, indeed becoming negative (exporting) after 18:00. As noted above, the wind-farm required a substantial reactive power supply to generate power.

D.7.1 Conclusions

Reactive power could be supplied locally by the STATCOM function of the ESS. In this trial, the output was limited to 0.2 MVAR, but a further 0.4 MVAR was available. The effect of this was to reduce the requirement of the upstream network to supply reactive power and thus reduce the apparent power flow.

D.8 Power-flow management: Wind following with network switching and automatic voltage control

The complimentary characteristics of the Martham and Ormesby networks were confirmed during analysis of historical data. This provided an opportunity to trial the idea of using both sides of the network during a prolonged network event for which the ESS energy capacity was overwhelmed. In this scenario, the wind generation was considered to be overloading the network and would require curtailment without any intervention. By charging the battery from the Wind-farm side, switching to the non-Wind-farm network and discharging, the ESS could be reconnected to the Wind-farm network to consume further wind generated power.

This process was successfully trialled, with the results shown in Figure 36, where the annotations describe the actions that have taken place. During this trial, the ESS was also operating in automatic voltage control mode so that the voltage variations that took place either due to the real power exchanges or general network conditions were compensated. This action is evident in the last chart in the figure.

In this case, the HV network switching was a manual operation actioned by a telephone call to the HV Control Engineer. In an enduring application, it is likely that an automated process and associated procedures would need to be developed.

D.8.1 Conclusions

The ability to expand the limited energy capacity of an ESS through the use of network switching has been demonstrated.

Wind following to increase generation output in a situation where the alternative would be curtailment was demonstrated. An isolated ESS would require a substantial capacity to have much effect in this situation. As demonstrated, pairing the wind-following function with feeder switching releases an infinite energy capacity.

While performing real power exchanges the ESS can simultaneously operate an independent voltage regulation function with the reactive power capability.

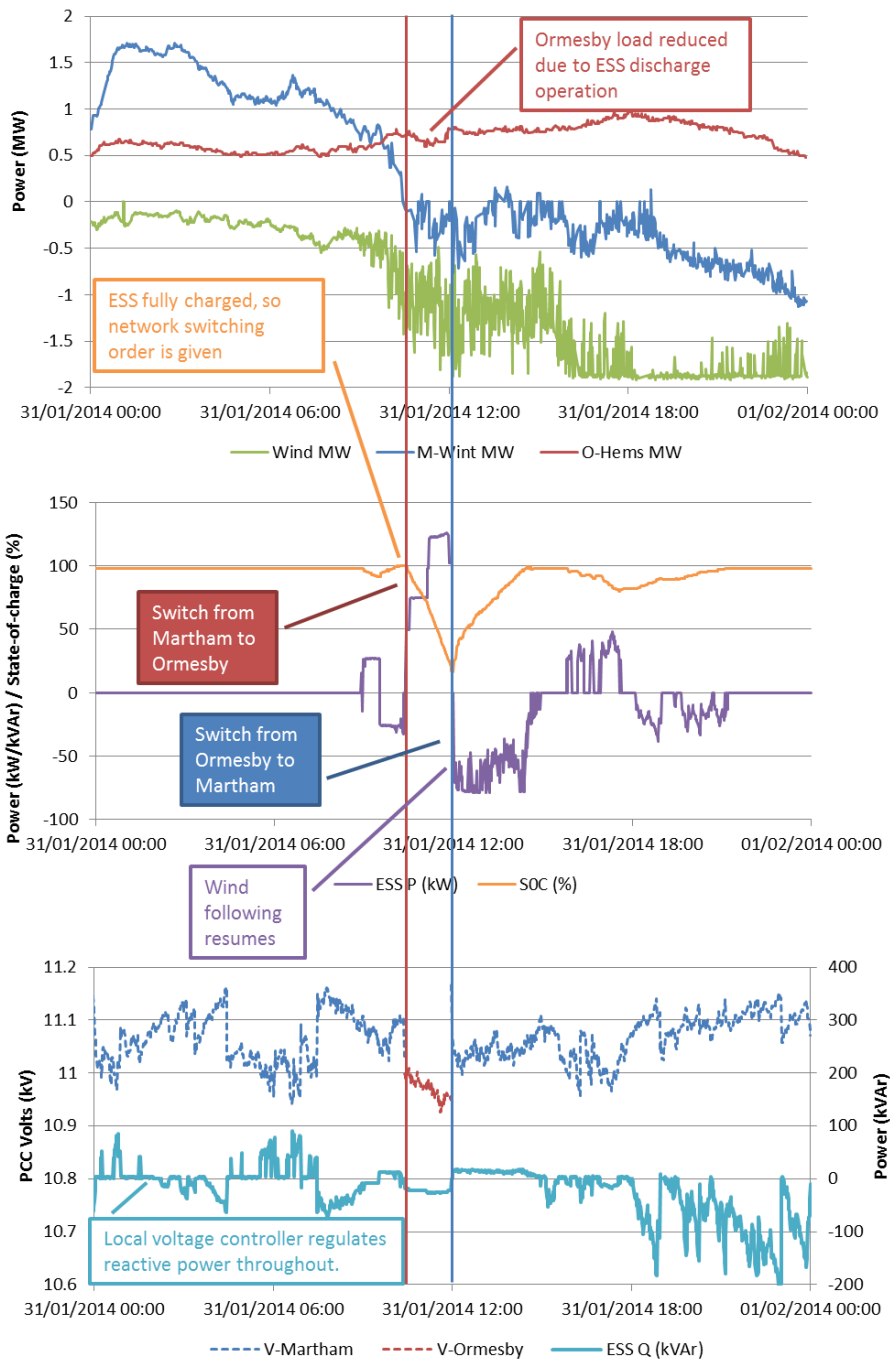


Figure 36. Use of two networks to exchange energy from windfarm to non-stressed network. Top: power flows on both networks and wind generation. Middle: ESS power exchanges and state-of-charge. Bottom: voltage of network connected to ESS point of common coupling (PCC).

D.9 Data sheet testing: introduction

A number of parameters were measured for comparison with expectations. The available measurement points are annotated on a view of the Mach2 control system Human Machine Interface screen in Figure 37. The auxiliary power measurement was not available in the HMI, so a standalone meter was used to take this measurement.

Efficiency and losses were impacted at a number of points in the system. These points are indicated in Figure 37 as standing/operational losses, transformer efficiency, power conversion

system (PCS) efficiency and battery efficiency. The measurement points that are available make it possible to isolate the battery efficiency and make an estimate of the overall system efficiency. It should be noted that the instrumentation on this system was not calibrated, so the results for overall efficiency can only be regarded as indicative. Furthermore, the technique used to measure the battery efficiency was reliant on the state-of-charge readings, which can be subject to variation due to a number of factors.

The accuracy of the output in relation to the real and reactive power set-points was also recorded using the measurements available in the HMI.

To test a large number of conditions, a control function was developed that scheduled the test points to be stepped through in an automatic process. This avoided the need for an operator to carry out these actions, which would have been an enormous task prone to human error.

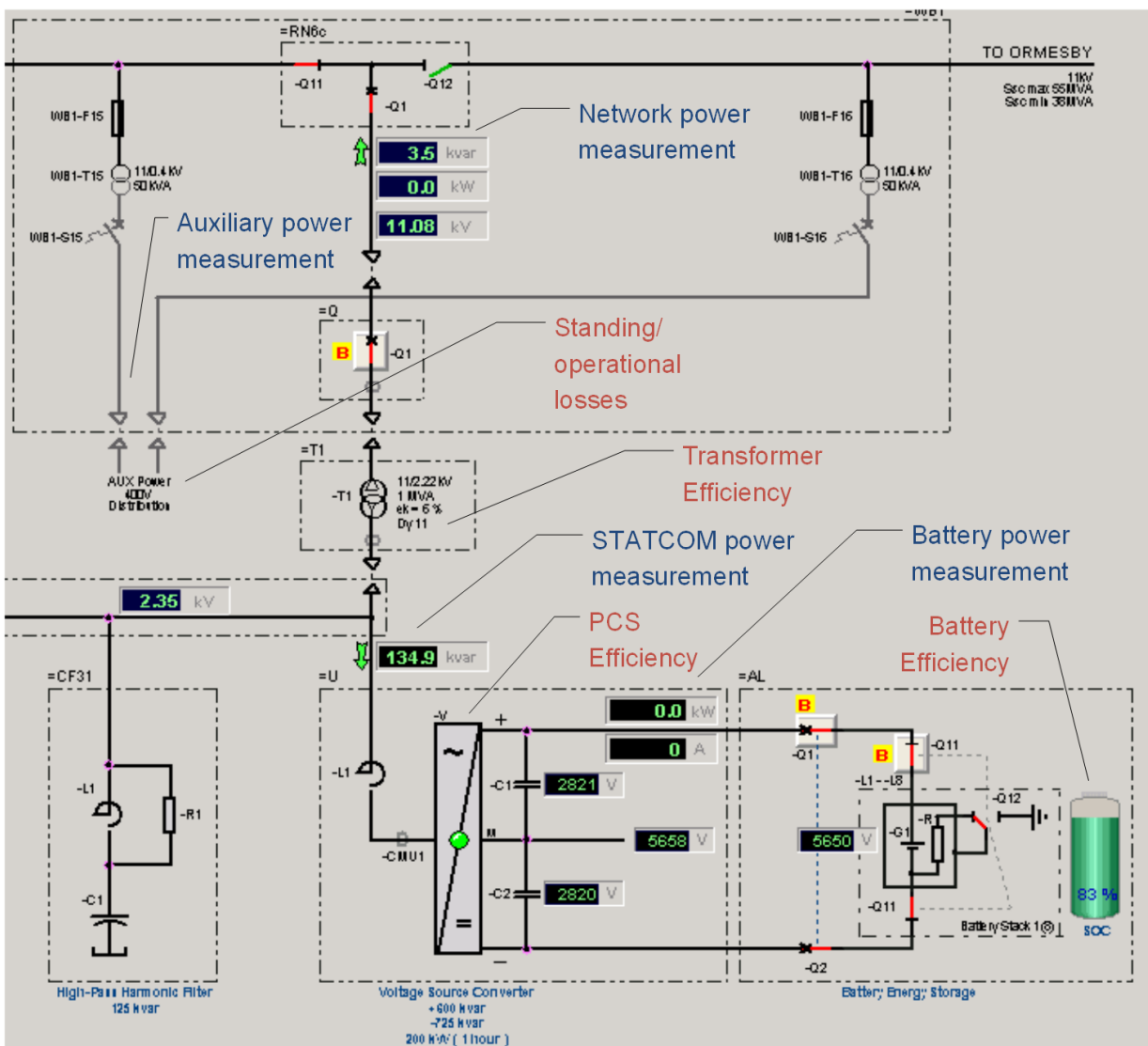


Figure 37 View of Mach2 Human Machine Interface (HMI) showing the available measurements and areas that impact on efficiency.

D.10 Data sheet testing: Auxiliary power consumption

The three-phase 400V auxiliary power circuit was fed from a transformer connected to the 11kV circuit and provided power for the ESS support systems which included climate control equipment, fans, pumps, control systems and computers. Metering of the auxiliary circuit was put in place for a limited period of time to determine the level and variability of demand that these systems placed on the auxiliary power circuit.

The complete trace for the period over which auxiliary power monitoring was in place is shown in Figure 38. Power consumption ranged from 7 to 15 kW and is generally around 8 kW. The red shading shows when the ESS was actively exchanging power with the network. No pattern can be seen to indicate that exchanging power with the 11kV circuit increases the auxiliary power draw. An event occurred on 24 Oct that caused a substantial increase in the power. No indication of the cause has been identified in the available data.

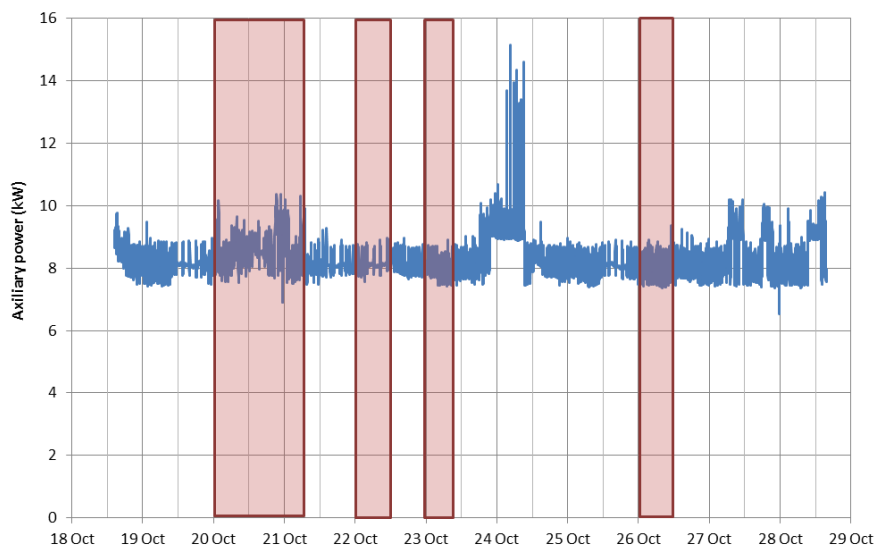


Figure 38 Auxiliary power draw from 18-29 October 2013, with highlighted blocks showing when the ESS was under active control.

The principal factor that was expected to drive changes in the auxiliary power demand was the requirement to cool the power conversion system (PCS) equipment. A scatter plot of coolant temperature and flow rate with respect to apparent power passing through the PCS is shown in Figure 39. It can be seen that the flow rate and thus pump power draw was not correlated with apparent power. The coolant temperature did vary between 25 and 37 degrees Celsius, and higher temperatures are seen when higher apparent power is passing through the PCS. The heat is dissipated by the cooling plant without any increase in effort. This could be interpreted as being configured with excessive cooling capability when operating at low (or zero) apparent power levels.

Other plant and systems also used the auxiliary power supply, but due to an absence of sub-metering it was not possible to ascertain the particular usage of these components.

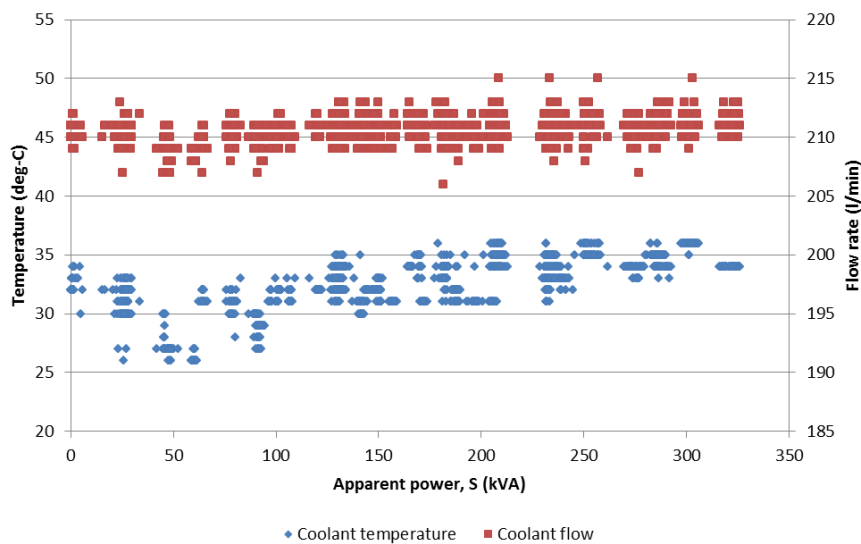


Figure 39 Cooling system characteristics as a function of apparent power passing through PCS.

D.10.1 Conclusions

The auxiliary power demand of this equipment can add up to a significant amount of energy. Careful assessment of the auxiliary energy demands should be made and where possible be reduced in similar equipment.

D.11 Data sheet testing: Set point control accuracy and stability

The ESS Mach2 control system had set-points available to control active and reactive power exchange between the 11kV network and ESS. Confirmation of the relationship between the set-points and actual measurements of power exchange with the network was carried out.

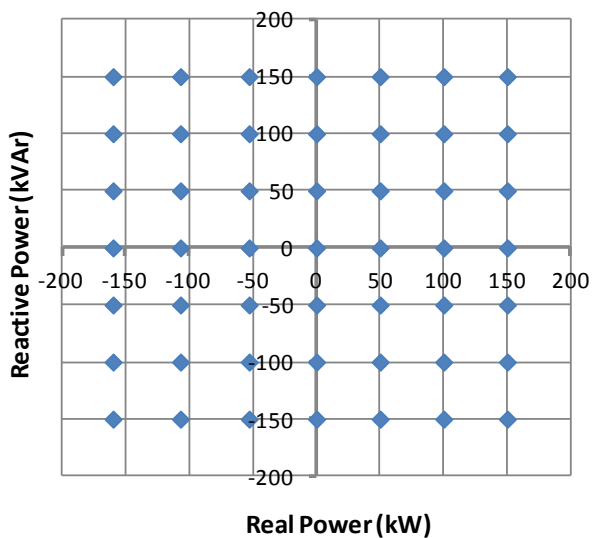


Figure 40 Four-quadrant test set-points

A series of tests were enacted to achieve this by issuing set-points to cover the four quadrants of power exchange as shown in Figure 40. The active power import (battery charging) set-point was higher than export (discharge) to account for system losses and maintain a steady peak state-of-charge throughout the course of the study.

The actual power delivered to the network deviated from the set-points as plotted in Figure 41. The groups of blue crosses would be expected to align with the crossing points of the red grid (the set-points).

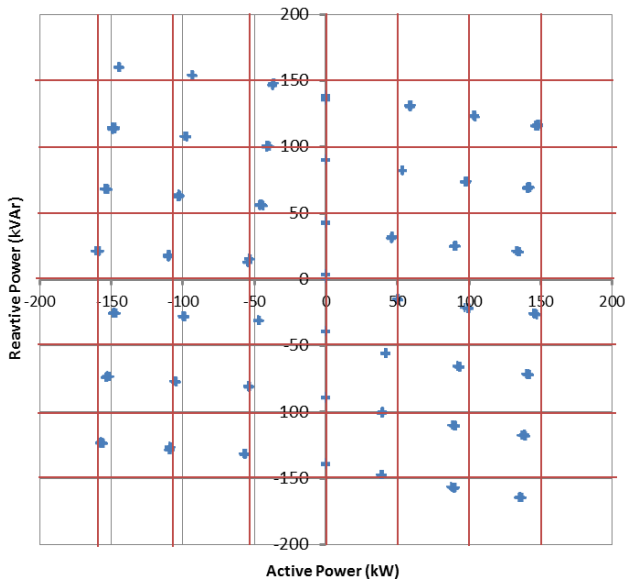


Figure 41 Measured set-point accuracy and stability.

Each quadrant is described below:

- First (top-right) quadrant: reactive power is always lower than the set-point, while active power is below, on and above the set-point, depending on the particular power combination.
- Second (top-left) quadrant: active power is always below the set point except at 0 kVAr, -100 kW. Reactive power is always above the set-point except at 150 kVAr, -50 kW.
- Third (bottom-left) quadrant: reactive power is always significantly below the set-point. Active power is below, on and above the set-point, depending on the particular power combination.
- Fourth (bottom-right) quadrant: all active power is below the set-point. Reactive power is on or above the set-point.

D.11.1 Conclusions

When commissioning equipment of this nature, testing procedures to validate the operation should be considered. Although not a priority in this project, for some applications the difference between the set-points and delivered power may be critical, such as if a contracted service has been arranged where revenue is dependent on exchanging a specific volume of energy at the meter point.

D.12 Data sheet testing: Round trip efficiency

Round-trip efficiency of the ESS, including losses from the battery system, power conversion system (PCS), transformer and auxiliary power demand have been measured. Fixed quantities of energy were repeatedly transferred in and out of the battery, during which the state-of-charge (SoC) was monitored. The difference between the SoC at the start and end of this process gave a measure of the amount of energy expended during the equal in/out energy transfers.

Measurement points on each side of the transformer/PCS, 'Network power measurement' vs. 'Battery power measurement' in Figure 37 are available, were used to determine the efficiency of these combined components. It should be noted that the measurements record an above unity efficiency when importing power and below unity when exporting power. The arithmetic mean of these records was used to produce a figure for the combined efficiency of the transformer and PCS. The resulting value was 98.8%.

The results can be expressed in a number of ways: the instantaneous efficiency of the battery system, the instantaneous efficiency of the battery system and PCS, the instantaneous efficiency including accounting for auxiliary power, or as an efficiency measure over a period of time in which the ESS was only operating for part of the time. This last measure accounts for standing losses in addition to the operational losses. These results are presented in Table 16 below.

Table 16. System efficiency by three different measures.

Power Exchange (kW)	Battery efficiency (%)	Round trip efficiency (no aux power)	Round trip efficiency (with aux power)	Round trip efficiency (4-hrs of ops per day)
50	95%	94%	78%	0%*
100	94%	93%	85%	43%
150	90%	89%	83%	53%

**more energy consumed by auxiliary systems and losses than the battery throughput*

D.12.1 Conclusions

Careful consideration has to be given to what is meant by efficiency. Individual components in the system can be considered in isolation, or combined together into a single figure for efficiency. How to account for the standing losses is open to interpretation. Whether these should be smeared across the periods of operation, or considered separately is a choice that has a substantial impact on the final quoted efficiency.

Efficiency depends on the amount of power being exchanged. Although the 11kV connected components see a reduction in efficiency due to the higher current, there is an economy of scale in relation to the auxiliary power demand.

D.13 Data sheet testing: Lifetime assessment

Two sets of representative duty profiles were sent to the battery manufacturer, Saft, who carried out a lifetime assessment of each operating regime.

The adaptive peak-shaving control algorithm was used to generate representative operation profiles for the ESS. The power exchanges and resulting state of charge are shown in Figure 42. The depth-of-discharge has a significant impact on the battery lifetime. In this simulation, three conditions were tested, where the allowed energy use was 100, 125 and 150 kWh, corresponding to a 50, 62.5 and 75% depth-of-discharge. The power exchange was limited to 100 kW.

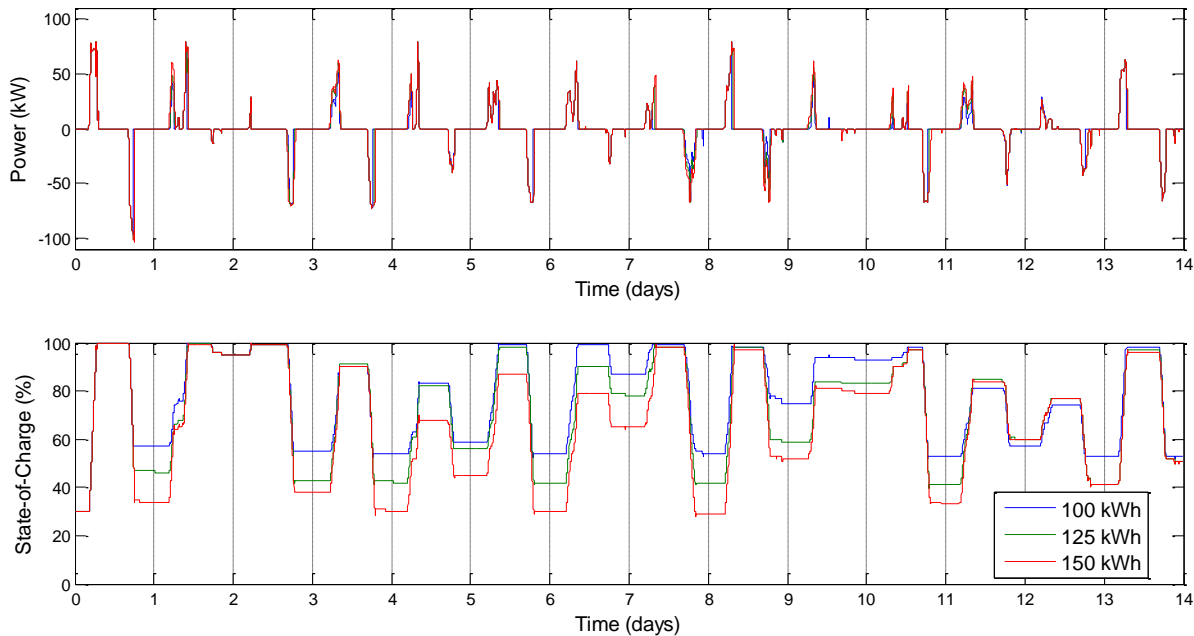


Figure 42 Power and State-of-Charge for three peak-logging simulations.

The impact on battery lifetime found by running this data through Saft's battery ageing algorithms gave the reduction in battery capacity for each scenario as:

- 100 kWh – 1.1% p.a.
- 125 kWh – 1.2% p.a.
- 150 kWh – 1.5% p.a.

This means that running the ESS in this peak-shaving mode allowing use of 50, 62.5 and 75% of the total energy capacity will reduce that capacity by 1.1, 1.2 or 1.5% per annum respectively. For 1.5% this equates to a 20 year lifetime if end-of-life is taken to be 70% of installed capacity.

In the second case, the battery was operating in voltage control mode, which results in a considerably more stochastic duty profile than the regular diurnal pattern seen in the peak shaving profile. The import and export power was allowed to reach up to 200 kW. The state-of-charge was typically in the 50-100% range, but a significant drop to around 10% was experienced within the profile. The battery capacity degradation from this profile is 1.21% per annum, comparable to the middle peak-shaving case above.

D.13.1 Conclusions

The battery lifetime for representative operating regimes needs to be understood when calculating the lifecycle cost of using an ESS. To evaluate the battery lifetime for a given battery technology, cooperation with the battery manufacturer is advisable in order to access their battery models, which vary for each kind of battery technology.

Appendix E: THE STORAGE MODELLING TOOL

E.1 Background

In the early stages of the Hemsby energy storage project it was identified that there was a need to simulate the ESS operating in the particular distribution network to which it was being connected. This was to allow the effects of differing ESS operations to be tested and explored before carrying out live network trials. The solution was developed as a research tool, and the ability of a DNO user to configure and interact with the code was not a considered as a requirement.

The underlying code uses an IPSA model of the 11kV network to perform load-flow analysis of the model, populated with time-series data comprised of historical demand and generation. Node voltages and branch power flows are monitored to determine the state of the network for making decisions on how to use the ESS to produce a favourable effect on the network conditions.

Having gained experience in using the code, consideration was given to the use that could be made of this facility by a DNO planning department. A version of code with a user interface giving access to the simulation configuration parameters would allow a range of ESS operating strategies to be explored, without having to understand the detail of the code structure. This requirement was taken forward in the development of the Storage Planning Tool.

E.2 Implementation

The user interface was written in php code and the user interacts with the simulation code from a web-browser. A mySql database was used to hold configuration and output data for querying after the simulation has completed. This solution meant that the software can be installed on a local machine running a web-server or on a network web-server that users remotely connect to. Note that to operate the IPSA load flow engine, a license was required to be installed on the machine running the simulation code.

In the original research use version of the simulation code, a configuration file governed the setup and behaviour of the simulation run. The Storage Planning Tool provides access to the required configuration parameters in a web form, so that the ESS configuration and network events to be considered could be altered. A user could then change the simulation characteristics, without needing to understand the configuration file structure.

The main configuration parameters are:

- Network model to be used
- Historical demand and generation dataset
- Duration of simulation
- ESS parameters (power, energy)
- Network events and the corresponding ESS response

Once configuration parameters had been specified, a user ran the simulation. An analysis page provided key information extracted from the results. The complete results were available to the user in a comma separated values file for them to perform any additional analysis using another tool of their choice, such as Excel.

E.3 Example use

The following figures show the forms that the user was presented with at various stages in the simulation process. A blank configuration form is shown in Figure 43. The completed configuration form in Figure 44 shows how events and the ESS response were configured. Figure 45 shows the key information that is presented in the results analysis page.

Storage Planning Tool

localhost/npt/NewConfig/index.php

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Home
New Configuration
Edit Configuration
Simulation
Result Analysis

Basic information

name

network

model

powerflow

weeks

woffset

ESS

initsoc

maxsoc

minsoc

maxP

minP

maxQ

minQ

Events

Add Delete

Submit Delete Back

Figure 43 New configuration page

Storage Planning Tool

localhost/npt/EditConfig/EditConfiguration.php

maxQ 0.2

minQ -0.2

Events

Delete

event overpower

location MARTHAM PRIMARY AUX TX 15 UG 0.1 CU

threshold 25

action p_source

priority 2

Delete

event reversepowerflow

location MARTHAM PRIMARY AUX TX 15 UG 0.1 CU

threshold -0.4

action p_sink

priority 3

Delete

event excessgeneration

location WINDFARM 10-225 HW

threshold 1.2

action p_sink_curtail

priority 4

Add Delete

Submit Delete Back

Figure 44 Event configuration section

Storage Planning Tool

localhost/npt/Analysis/Analysis.php

Apps Tasks Other bookmarks

Storage Planning Tool

Home
New Configuration
Edit Configuration
Simulation
Result Analysis

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ESS

Total energy out (MWh)	Total energy in (MWh)
0.400	0.4

Events

Event	Location	Threshold	Count
overpower	MARTHAM PRIMARY.AUX TX.15 UG 0.1 CU	25	6
reversepowerflow	MARTHAM PRIMARY.AUX TX.15 UG 0.1 CU	-0.4	0
excesspgeneration	WINDFARM.10-225 kW	1.2	0

Feeder duration curve

Windfarm duration curve

Feeder power above 1.2MW

count
0

Max vantage (%)

V_millroad	V_martham	V_windfarm	V_nopsn
2012-08-27 21:30:00	2012-08-26 21:00:00	2012-08-27 21:30:00	2012-08-27 21:30:00
0.760	1.920	1.310	0.900

Min vantage (%)

V_millroad	V_martham	V_windfarm	V_nopsn
2012-09-01 17:30:00	2012-08-27 13:30:00	2012-09-01 17:30:00	2012-09-01 17:30:00
-0.960	0.380	-0.270	-0.780

Max power rating (%)

AU_up_stm	AU_dn_stm	AU_ug_sec
2012-08-26 17:00:00	2012-08-30 17:00:00	2012-08-26 17:00:00
22.300	27.700	24.500

Figure 45 Analysis page

Appendix F: IMPACT OF ESS ON DISTRIBUTED GENERATION CAPACITY

One of the aims of this project was to understand the ability for this ESS to increase the amount of distributed generation capacity on Martham-Winterton and Ormesby-Hemsby feeders.

F.1 Constraints

Table 17 details the typical constraints that could limit the amount and position of DG installations on distribution networks. By considering these, we were able to further understand how the ESS can benefit the capacity for installations.

Table 17 Constraints when considering DG installations

Constraint	Details of constraint	Potential issue? on the Martham / Ormesby networks	Does the ESS help?
Voltage profiles	The voltages at the point of connection to the network, and at the local point of generation must not deviate by more than 2% and 3% respectively, as a result of the generation installation. Higher levels of DG installation will lead to higher deviations.	Yes	Yes – primarily by exchanging reactive power, secondly by exchanging real power.
Thermal limits	The maximum installed capacity of the generation must not cause any of the assets on the network to exceed their operation thermal limit.	No	Yes – by exchanging real power with the network, although this is limited by the energy storage capacity.
P2/6 compliance	These are a set of rules and considerations when planning for load connections to ensure security of supply on the network, and the ESS could be affected by these. If the output of a DG is reliable then its contribution can be considered in the P2/6 calculations. Wind has a very low persistence value that could be improved with storage.	No	No – Whilst all load and generation installations must comply with P2/6, the ESS cannot directly influence this.
Fault level (rating of the primary switchgear)	The amount of DG installed must not increase the prospective fault level beyond the designed limits. The ESS will not contribute to fault levels.	No	No – The ESS cannot reduce fault levels on the network.

Harmonics	Whilst this is not a major concern for planners, any harmonics introduced into the network as a result of the generation must be kept within defined limits (as defined in ENA Engineering Recommendation G5/4). As these networks are in rural areas, harmonic content likely to be low.	No	No – The ESS can only dampen harmonics caused by its own inversion process.
Reverse Power Flows	Care must be taken to ensure that the settings of the directional over current relay and the tap changers at the primary are correctly configured to cope with any reverse power flows. Martham-Winterton and Martham-Martham feeders have already shown reverse power flows on occasion; however, Ormesby-Hemsby feeder has not due to the lack of DG. The equipment can be upgraded to accept up to 100% reverse power flow.	Yes	Yes – By managing the real power flows on the network, although this is limited by the energy storage capacity.

In summary, the key factors that limit the amount of DG that could be connected to the network were the voltage profiles, the thermal limits of the installed assets and the increase in fault level caused by the extra generation. For any extra installations of generation, other checks would have to be carried out to ensure that the primary substation can accept increases in reverse power flows.

As the ESS could help with the voltage profiles and thermal limits, these were the two constraints that were evaluated using the network simulation; although all results were checked against all constraining factors to ensure that they are compliant. Allowed voltage rise limits are 2% at the point of connection to the network and 3% at the source of generation. It was assumed that the additional generation in these simulations were connected directly onto the network, as is the case with the 2.25 MW wind farm on Martham-Winterton, and therefore had to satisfy the 2% limit. These rules were derived from ENA Engineering Recommendation G59 Issue 2 2010, were adopted by UK Power Networks and are written into UK Power Networks’ Design Policy: EI 08-0106, specifically regarding New Distributed Generation Connections.

F.2 Simulation

To understand the potential for increasing the amount of generation, both UK Power Networks’ planning team and Newcastle University were contacted to simulate several scenarios.

A limitation of the UK Power Networks’ planning methodology was the representation of energy storage in the time domain. As such, this needed to be modelled as both traditional load and generation with a constant power rating and could not take into account the method of operation, i.e. when the device charges and discharges, nor the energy capacity of the system. The existing modelling system used in EPN is DigSilent Powerfactory, which could model the network down to the 11kV bus bars. To investigate the effect of adding generation onto a particular feeder, the feeder itself had to be manually built on the system. The practice was to model a lump load representing the maximum load on that feeder over the past 12 months, rather than investigating

the load at each substation. The reasoning behind this is that the voltage rise at the point of connection to the network and at the location of the generation were the key factors being investigated, and the effects at each substation were not required to be understood. All studies were run assuming unity power factor.

Newcastle University developed a network model which could run simulations based on user defined parameters, such as energy capacity and location of generation. This model was able to factor in the element of time, and can therefore represent the limited storage capacity of the device. It could also represent the individual loading of each substation along the 11kV feeder. A ratio of real power to reactive power was assumed based on typical power levels measured during normal operation, and there were no time constraints with the reactive power exchanges. In this regard, there were situations in the model where real power has been exhausted and the reactive power exchange from the ESS was the only interaction with the network.

F.3 Results – Martham-Winterton Feeder

F.3.1 Simulation Results

Eight scenarios were considered in this network simulation. The results are shown below in Table 17. The scenarios show how the voltage deviation and utilisation levels change with different magnitudes and locations of DG installations, as well as changes in ESS energy capacity and power limits.

Table 18 Simulation results for Martham-Winterton

Scenario	Windfarm output (MW)	Additional DG		ESS characteristics			Max voltage deviation at ESS (%)	Max voltage deviation at WINDFARM (%)	Max voltage deviation at MARTHAM (%)	Max power flow at Primary UGC (%)	Max power flow upstream of windfarm (%)
		Location	Size (MW)	Capacity (MWh)	Real power limit (MW)	Reactive power limit (MVar)					
1	0	none	n/a	0	0	0	n/a	n/a	n/a	50.6	45.7
2	2.25	none	n/a	0	0	0	1.44	1.56	0.18	50.6	45.7
3	2.25	ESS	300	0	0	0	1.98	1.76	0.21	50.6	45.7
4	2.25	ESS	400	0.2	0.05	0.2	1.97	1.68	0.2	50.6	45.7
5	2.25	ESS	400	0.4	0.05	0.4	1.97	1.68	0.2	50.6	45.7
6	2.25	WINDFARM	600	0	0	0	1.82	1.98	0.22	50.6	45.7
7	2.25	WINDFARM	850	0.2	0.05	0.2	1.81	1.98	0.22	50.6	45.7
8	2.25	WINDFARM	850	0.4	0.05	0.4	1.81	1.98	0.22	50.6	45.7

F.3.2 Observations on utilisation of installed assets

The Martham-Winterton feeder was not heavily loaded and had existing generation installed in the form of a 2.25 MW wind farm. From the Newcastle University simulation, the underground cable leaving the substation reached utilisation of 50.6% under maximum loading conditions and this did not change as the levels of DG were increased.

F.3.3 Observations on Voltage Rise

Table 19 Observations on Martham-Winterton based on Newcastle University simulation

Scenario	Observations
1	Scenario 1 is a baseline representation showing the existing network with no ESS and no DG installed and 0 MW output from the wind farm.
2	Scenario 2 shows the impact of adding the wind farm, which can sink reactive power when generating and cause voltage deviations seen at all three measurement locations.
3 & 6	Scenarios 3 & 6 show the existing capacity to add generation to the ESS location (300 kW) and the wind farm (600 kW) without the ESS being installed. The difference in these levels will be due to the higher voltage deviations at the ESS location, partially due to the remote location of this site.
4 & 7	These scenarios show the impact of adding the existing energy capacity of the ESS, which has a 50 kW and 200 kVAr limit. The results show that the generation capacity at the ESS can increase from 300 to 400 kW, an increase of 100 kW; and the generation capacity at the wind farm can increase from 600 to 850 kW, an increase of 250 kW.
5 & 8	<p>These scenarios show the impact of doubling the energy capacity of the ESS, and increasing the reactive power limits from 200 to 400 kVAr. The real power exchanges remain limited to 50 kW. The results show that by increasing the energy capacity of the ESS and keeping the DG levels as per the previous scenarios, no noticeable reduction in voltage deviation is seen.</p> <p>This indicates that there will be a limit beyond which increased energy capacity and power ratings of the ESS will not increase benefits to the network.</p>
Voltage deviation at Martham Primary	The voltage deviation at Martham Primary grows as DG levels are increased, from 0.18% to 0.22%.

F.3.4 Compliance to remaining constraints

It can be seen from Scenarios 4 and 7 that by having the existing ESS installed, we can increase the capacity for DG installed at both locations on Martham-Winterton. These results are based on the key constraining factor, voltage deviation, but it must be shown that all other constraints are satisfied. To ensure this, UK Power Networks' planners have used the model results in Table 17, along with their planning methodology to produce Table 19.

Table 20 Remaining constraints

Location	ESS Situation	DG (MW)	Voltage rise compliant?	Loading limits compliant?	Fault level compliant?	Reverse power flow compliant?	P2/6 compliant?
ESS	With ESS	0.4	Y	Y	Y	Y	Y
	W/out ESS	0.3	Y	Y	Y	Y	Y
Wind Farm	With ESS	0.85	Y	Y	Y	N	Y
	W/out ESS	0.6	Y	Y	Y	Y	Y

Key:

	These have been calculated by UK Power Networks' planning team as compliant.
	Whilst the simulation has shown a voltage deviation of <2%, UK Power Networks have calculated these as 2.18% (with ESS) and 2.09% (without ESS) due to not being able to model the reactive power exchanges from the ESS. Whilst it is agreed that the voltage rises associated with these DG installation are acceptable, this highlights that the differences in planning techniques and network assumptions.
	<p>Tap changers at Martham Primary substation have been modified to take 100% reverse power flow, but combining the peak output of 2.25 MW from the wind farm with an extra 850kW of generation at the same location causes the maximum power flow to exceed this 100% value. This was calculated in the worst case scenario of maximum generation, minimum load and is not compliant. We can therefore state that with the ESS installed, the amount of generation that can be added at the wind farm location is between 0.6 and 0.85 MW firm capacity.</p> <p>If 0.85 MW were to be installed, it would have to be curtailed when the wind farm achieved peak output to ensure that reverse power flows are not excessive.</p>

F.4 Results – Ormesby-Hemsby Feeder

Seven scenarios were considered in this network simulation with the results being shown below in the table below. The scenarios show how the voltage deviation and utilisation levels change with different magnitudes and locations of DG installations, as well as changes in ESS energy capacity and power limits.

Table 21 Simulation results for Ormesby-Hemsby.

Scenario	Additional DG		ESS characteristics			Worst voltage deviation at ESS (%)	Worst voltage deviation at GLEBE EST (%)	Worst voltage deviation at Ormesby (%)	Max power flow at Primary UGC (%)	Max power flow at pinch point (%)
	Location	Size (MW)	Capacity (MWh)	Real power limit (MW)	Reactive power limit (MVar)					
1	none	n/a	none	n/a	n/a	n/a	n/a	n/a	57.1	88
2	ESS	2.6	none	n/a	n/a	1.98	1.5	0.13	55.2	85
3	ESS	2.9	0.2	0.05	0.2	1.96	1.5	0.15	55	84.7
4	ESS	3.2	0.4	0.05	0.4	1.98	1.51	0.15	54.8	84.4
5	GLEBE EST	2.9	none	n/a	n/a	1.67	1.96	0.15	55	84.7
6	GLEBE EST	3.2	0.2	0.05	0.2	1.6	1.93	0.15	54.8	84.4
7	GLEBE EST	3.5	0.4	0.05	0.4	2.98	3.23	1.66	54.6	84

F.4.1 Observations on utilisation of installed assets

Ormesby-Hemsby feeder, like Martham-Winterton feeder is not heavily loaded, but does see a summer peak of 4.69 MVA, which is approximately double the normal peak. This is due to a holiday park. From the Newcastle University simulation, the underground cable leaving the substation reaches utilisation of 57.1% under maximum loading conditions in Scenario 1. As the levels of DG increase on this feeder (Scenarios 2 – 7), the utilisation naturally decreases based on the assumption that the DG is generating at the time of peak load. The utilisation at the pinch point reaches a load driven peak of 88% throughout the year when the Holiday Park is active. It is understood that at this location (Equestrian Centre), the section of underground cable is rated at 4.82 MVA, and therefore causes a constraint. As the DG is installed downstream (closer to the NOP) the maximum power flows reduce as DG output increases.

F.4.2 Observations on Voltage Rise

Table 22 Observations on Martham-Winterton based on Newcastle University simulation

Scenario	Observations
1	Scenario 1 is a baseline representation showing the existing network with no ESS and no DG installed.
2 & 5	These scenarios represent the maximum capacity for DG at both the ESS location and Glebe Estate with no ESS installed. It is worth noting that whilst this simulation shows that there is 2.6 MW available at the ESS, UK Power Networks' planners only allowed 2.25 MW (based on voltage constraints). Whilst this will need to be investigated, the relative increases in DG capacity are thought to be accurate and will be focused on during the observations.
3 & 6	These scenarios showed that by adding the existing ESS (limited to 50 kW and 200 kVar), DG capacity increased by 300 kW when installed at either the ESS or Glebe Estate. Attention should be drawn to the 1.93% voltage deviation at Glebe Estate as this headroom indicates that a slight increase in generation levels could be available to achieve a deviation closer to the 2.00% limit. The algorithm could be improved further to provide greater accuracy when determining the generation capacity available. This is complicated due to difficulties faced when trying to coincide the maximum reactive power exchanges with the peak voltage deviations, which are a

	moving target.
4 & 7	<p>These scenarios showed the impact of doubling the energy capacity of the ESS, and increasing the reactive power limits from 200 to 400 kVAr. The real power exchanges remained limited to 50 kW. The results show that whilst a larger battery can increase the DG capacity at the ESS location by a further 300 kW (i.e. from 2.6 MW with no ESS to 3.2 MW with an ESS), there is no additional benefit when installing at the Glebe Estate. In this situation (Scenario 7) a higher level of DG and ESS capability resulted in a 3.23% deviation at the point of connection to the network. This is non-compliant.</p> <p>This indicates that there will be a limit beyond which increased energy capacity and power ratings of the ESS will not increase benefits to the network.</p>
Voltage deviation at Ormesby Primary	The voltage deviation at Ormesby Primary caused by the changing parameters of the ESS and DG, varied from 0.13% to 0.15% during Scenarios 2-6. In Scenario 7, the high levels of DG have caused the load to drop, resulting in the primary voltage control to operate causing a deviation of 1.66%.

F.4.3 Compliance to remaining constraints

It can be seen from Scenarios 3 and 6 that by having the existing ESS installed the project can increase the capacity for DG installed at both locations on Ormesby-Hemsby by 300 kW. These results are based on the key constraining factor and voltage deviation. It must be shown that all other constraints are satisfied. To ensure this, UK Power Networks' planners used the model results in Table 20, along with their planning methodology to produce the table below:

Table 23 Remaining constraints

Location	ESS Situation	DG (MW)	Voltage rise compliant?	Loading limits compliant?	Fault level compliant?	Reverse power flow compliant?	P2/6 compliant?
ESS	With ESS	2.9	Y	Y	Y	Unknown	Y
	W/out ESS	2.6	Y	Y	Y	Unknown	Y
Glebe Estate	With ESS	3.2	Y	Y	Y	Unknown	Y
	W/out ESS	2.9	Y	Y	Y	Unknown	Y

Key:

	These have been calculated by UK Power Networks' planning team as compliant.
	Whilst the simulation has shown a voltage deviation of <2%, UK Power Networks have calculated these as 2.18% (at ESS location) and 2.27% (at Glebe Estate location) due to not

being able to model the reactive power exchanges from the ESS. Whilst it is agreed that the voltage rises associated with these DG installation are acceptable, this highlights that the difference in planning techniques and network assumptions.

To achieve these results, UK Power Networks had to use their own calculated maximum level of DG capacity, and then factor in the relative increase, 300kW in both cases.

It is unknown whether the tap changers at Ormesby Primary substation are able to operate with reverse power flow. This is being investigated. Providing that the maximum generation, minimum load situation does not exceed the maximum permissible reverse power flow, then this will be compliant.

F.5 Conclusions

- The ESS has shown to be able to marginally increase DG capacity on the feeders by being able to react and compensate for voltage rise at the point of connection.
- The voltage deviation at the point of connection onto these networks and the reverse power flows at the primary substations were the key constraints when planning for DG installations, although all other constraints must be considered.
- Increasing the energy capacity and power limits of the ESS did not necessarily lead to an increase in benefit.
- The main benefit to the network when managing voltage rise was due to the reactive power being exchanged by the STATCOM. It could be argued that only reactive power exchanges should be used to influence network voltage and the real power exchanges should be reserved for other uses such as arbitrage.

Glossary

ADSL	Asymmetric Digital Subscriber Line
AuraNMS	Autonomous Regional Active - Network Management System
BAU	Business As Usual
DECC	Department of Energy and Climate Change
DG	Distributed Generation
DNO	Distribution Network Operator
ENA	Energy Networks Association
EPN	Eastern Power Networks
ESOF	Energy Storage Operators' Forum
ESS	Energy Storage System
ESS P	Real power (P) delivered by the ESS
ESS Q	Reactive power (Q) delivered by the ESS
GPRS	General Packet Radio Service
HMI	Human-machine Interface
HV	High Voltage
IFI	Innovation Funding Incentive
LCNF	Low Carbon Networks Fund
LV	Low Voltage
NOP	Normal Open Point
PCC	Point of Common Coupling
PCS	Power Conversion System
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SNS	Smarter Network Storage
SoC	State of Charge
STATCOM	Static Synchronous Compensator
UKPN	UK Power Networks
Vpcc	Voltage at the Point of Common Coupling
VPN	Virtual Private Network