UTILISATION OF ENERGY STORAGE TO IMPROVE DISTRIBUTED GENERATION CONNECTIONS AND NETWORK OPERATION ON SHETLAND ISLANDS

Fulin FAN
University of Strathclyde – UK
f.fan@strath.ac.uk

Han XU
University of Strathclyde – UK
han.xu@strath.ac.uk

Ivana KOCKAR
University of Strathclyde – UK
ivana.kockar@strath.ac.uk

ABSTRACT

The Northern Isles New Energy Solutions (NINES) project on the Shetland Islands seeks to trial the application of alternative solutions, including demand side management and battery energy storage to increase the integration of renewable generation and smooth the demand curve. As part of the NINES project, a 1MW, 3MWh Battery Energy Storage System (BESS) has been installed in the Shetland network and initially operated by an Active Network Management (ANM) system and then brought under the manual scheduling. The main objective was to reduce peak demands to be met by conventional generation and also to increase the demand at off-peak times which may provide additional headroom for non-firm distributed generation, i.e. ANM Controlled Generation (ACG). This paper aims to present experiences and findings from the NINES project regarding the BESS's operation, utilisation and efficiency (energy losses). Furthermore, the constraint rules that limit the ACG export are discussed alongside practical issues around charging the BESS in response to the ACG curtailment.

INTRODUCTION

A growing range of energy storage technologies are used for grid support either in distribution or in transmission networks to realise the future low carbon networks. The energy storage technologies fall into five main categories distinguished by the form the energy is stored in, as shown in Figure 1, which details classifications of energy storage technologies [1].

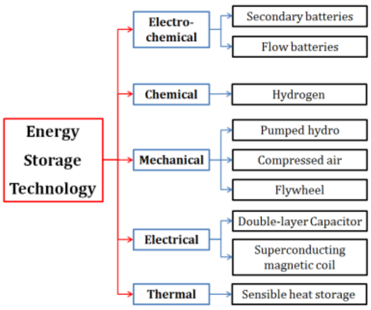

Figure 1: Classifications of energy storage technologies [1].

Grid-scale Battery Energy Storage Systems (BESS) that provide longer storage duration and fewer cycles per day are frequently applied to time shift of renewable energy and conventional generation. One of the most important contributions of the BESS is the deferral in reinforcement of electricity networks. For conventional generators, the BESS can be charged at off-peak times and inject the stored energy into the grid during peak demand periods, which leads to flatter power outputs and thus a more efficient operation of generating units and a reduction in the use of fossil fuel.

Another significant advantage of BESS is that they allow the accommodation of renewable generation [2]. Wind generation is known to cause considerable fluctuations to the system due to variation of wind speed during the day. In addition, wind turbines may produce more power than is needed in a specific period of time requiring the wind farm operators to turn the turbines off. However, a grid-scale BESS could assist in coping with these issues by storing the excess power produced by wind farms during high wind periods and then delivering the power back to the grid at times when wind farms are unable to produce energy. Furthermore, fluctuations can be reduced since the energy stored can be smoothly distributed to the grid when the battery discharges. Therefore, the time shift enabled by the BESS can offer a cost-effective means to reduce conventional generation costs for utility companies and increase the utilisation of renewables [1].

BESS has been applied to a number of projects in the UK and proves its ability to improve network utilisation. A 6MW, 10MWh BESS has been trialled in the Smarter Network Storage (SNS) project of UK Power Networks (UKPN) [3] to shift the peak loads so to defer the need for network reinforcement, to regulate frequency stability, to support reactive power, etc. (as illustrated in Figure 2). In addition, the Orkney Energy Storage Park project carried out by Scottish and Southern Electricity Networks (SSEN) [4] looks to encourage third party storage owners to provide BESS services to a distribution network operator, so to facilitate connections of new renewable generation in the constrained Orkney network.

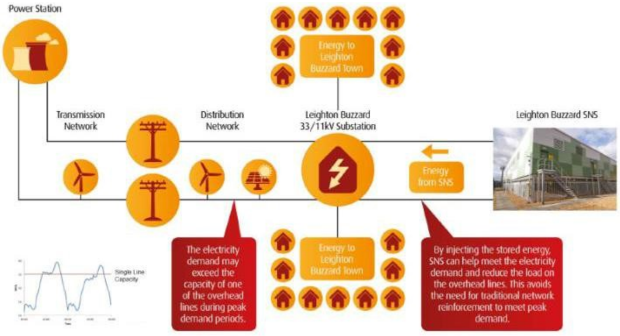

Figure 2: SNS in UKPN network [3].

NINES PROJECT ON SHETLAND ISLANDS

The Shetland Network

The Shetland Islands are located 130 miles from northern

Scotland and have a population of 23,200 with electricity demand varying between 11 and 47 MW. The Shetland Islands are not connected to the main GB electricity network and, as such, face unique electrical challenges – but also a unique opportunity to decarbonise electricity supply because of the very high potential of wind in that geographical area.

In the past the supply and balancing of the network relied mainly on synchronous generation from the Lerwick Power Station (LPS) and Sullom Voe Terminal (SVT), but that had the potential to change with the emergence of the renewable generators. The renewable source on Shetland is some of the best in Europe, with the existing wind farm on Shetland typically producing an annual capacity factor of 52% [2]. However, the islanded network is sensitive to sudden changes in the availability of generating capacity or electricity demand, requiring sufficient synchronous generating reserve to maintain system stability. In addition, network constraints relating to the system voltage and frequency stability limit the capacity for accommodating renewables on Shetland.

The NINES project and ANM system

Despite significant renewable resources, before the start of the NINES project just 7% of all consumed energy was produced by renewables. The two main principle objectives of the NINES project were to (i) help accommodate renewable generation customers and reduce reliance on fossil fuels and (ii) reduce peak demand and smooth the demand curve to minimise peaks and troughs in Shetland system demand. To achieve the above goals the NINES project integrated a grid-scale BESS and Domestic Demand Side Management (DDSM) with an Active Network Management (ANM) system, as shown in Figure 3 [2]. The architecture in Figure 3 indicates that the SSEN distribution network in Shetland is supported by three main generation stations: LPS driven by mostly diesel engines, SVT consisting of gas turbines, Burradale (BUR) wind farm which has a firm (i.e. 'must-take') network connection. In addition to 3.68MW BUR, a total capacity of 8.545MW non-firm wind and tidal generation, i.e. ANM Controlled Generation (ACG) is connected under flexible contracts to the network. These are: Garth (4.5MW), Luggie's Knowe (3MW), North Hoo (0.5MW), Shetland Tidal (0.5MW) and Cullivoe Tidal (45kW). The output of non-firm ACG is limited by a set of constraint rules (CTRs) that are designed to preserve the network stability [5]. In addition, the ANM system manages DDSM enabled appliances installed in a total of 234 homes which are scheduled to charge at times that suit the Shetland network. Finally, one of the integrated elements within the ANM system is a 1MW, 3MWh Valve-Regulated Lead Acid (VRLA) BESS installed at LPS [2].

The functional ANM system consists of (i) Smarter Grid Solutions (SGS) Balance which utilises wind forecast data to determine profiles for ACG and allocates controllable demand (i.e. DDSM and BESS) to alleviate constraints on ACG identified in the scheduling process and to smooth the demand curve and (ii) SGS Power Flow that monitors the CTRs and ACG output in real-time to determine set points for ACG [5]. The ANM system manages operation of all components connected via NINES on the Shetland network in an efficient and reliable manner to meet energy demand while maintaining the system stability subject to the specified network constraints.

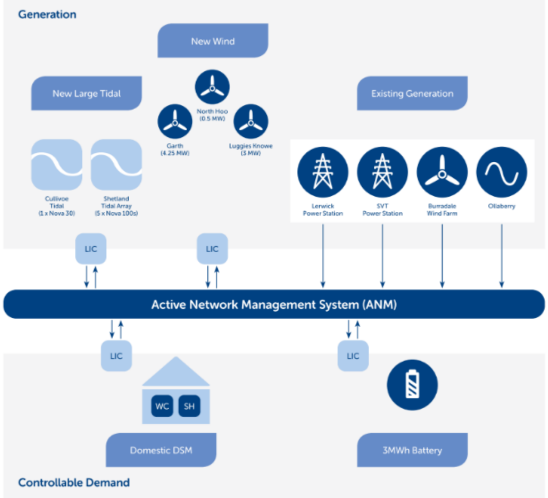

Figure 3: ANM system architecture on the Shetland network [2].

This paper reviews the BESS's operation and assesses its performance in terms of utilisation and efficiency (energy losses) based on the power outputs of the BESS measured at the 11kV circuit breaker every 15 minutes during its first full year operation from Sep. 2014 to Aug. 2015. Furthermore, the CTRs used to determine the constraints on ACG are discussed alongside practical issues around charging the BESS in response to the ACG curtailment.

OPERATION OF BESS

The BESS installed at LPS was limited to one cycle per day and provided up to twelve 1MW 15-minute discharge periods (3MWh in total) at peak times per cycle subject to a minimum 45% state of charge (SOC). During charging periods, which typically occurred at times of low demand, 4MWh of energy was required to recharge the BESS. The charge rate of VRLA BESS was dependent on the SOC of battery. An initial charge rate of 1MW was limited to 0.66MW and 0.33MW when the battery reached 80% and 90% SOC respectively. Figure 4 shows the BESS's outputs within a complete cycle from 07:00 on 3/9/2014 to 07:00 on 4/9/2014 along with the corresponding variation in SOC. How the system demand to be met by generators varied with the BESS's operation is shown in Figure 5. In this case, the minimum demands occurred at around 03:00 – 05:00 in the morning, where the optimum charge rates of the BESS would be 1MW. However, the BESS required about 7 hours to charge and would not be fully charged before the morning peak. To compromise the BESS was charged at the times of minimum demands but the charge rates which depended on the SOC may not be 1MW [6].

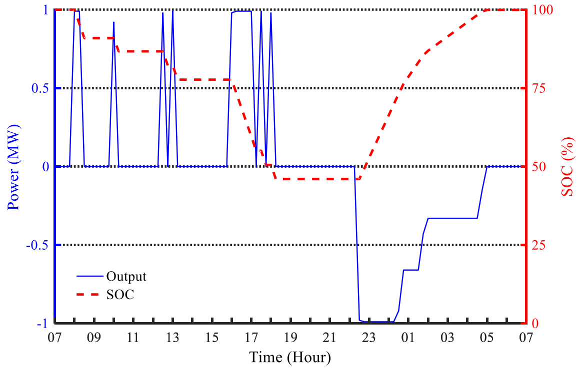

Figure 4: Outputs (MW) of the BESS (discharge rates are positive and charge rates are negative) and corresponding variations in SOC (%) within a complete cycle over a particular 24-hour period.

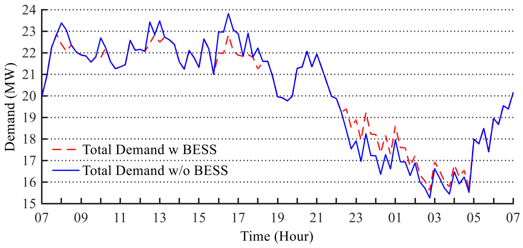

Figure 5: Variations in the system demand (MW) met by generators following the operation of BESS over a particular 24-hour period.

The BESS was integrated with the ANM system and operated by ANM calculated schedules over four months from Feb. to May 2015 to lop peaks, fill demand troughs and alleviate the constraints on ACG export. However, the deficiencies of the scheduling algorithm used in the ANM system [5] meant that the BESS was not reaching a fully charged state and the daily discharged energy (DDE) could not reach 3MWh, which led to an unsatisfactory utilisation of the BESS. While the revision of the scheduling algorithm was on-going, the BESS's operation beyond Jun. 2015, in the main, was based on a manually derived schedule which aimed to fully charge the BESS at off-peak times and discharge the BESS at peak times [6].

PERFORMANCE OF BESS

Utilisation of BESS

The BESS at LPS had completed 288 cycles in the first full year during which the total import and export of the BESS were about 826.6MWh and 629.7MWh. Given that the BESS was expected to complete 300 full cycles per year, **96%** of the expected number of cycles and approximately **70%** utilisation (i.e. 629.7MWh/900MWh) were achieved in the first full year, meaning that the DDE did not reach 3MWh in several days. The number of days with different DDE volumes is plotted in Figure 6. It shows that (i) the BESS was not cycled for 77 days including, e.g. the weekends during the first period of operation at which the BESS was not cycled for operational reasons and the biannual maintenance carried out in Mar. and Sep.; (ii) the DDE exceeded 2MWh for 175 days; (iii) the BESS provided an expected 3MWh DDE for 150 days; and (iv) the BESS was not largely utilised (0 – 2MWh DDE) for around 113 days, most of which were due to the ANM calculated schedules. Exclusive of the BESS outages, the manual schedules were evaluated to achieve a higher utilisation (about 86.1%) of the BESS than the ANM calculated schedules which led to a 47.2% utilisation [6].

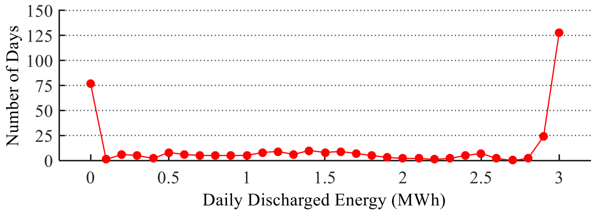

Figure 6: Number of days with different volumes (MWh) of daily discharge energy (DDE) in the first full year.

Operational efficiency of BESS

An important characteristic of the BESS is the round-trip efficiency which represents the capability of electricity transmission from charging state to storing state and then from storing state to discharging state. It is directly affected by energy losses that occur at the battery bank, power conversion system, cables and transformers and can be estimated as the ratio of the discharged energy injected into the network to the energy used to charge it within a complete cycle. The round-trip efficiency of the BESS at LPS was estimated to be 75% based on the efficiency test carried out at the 11kV circuit breaker where the energy losses were all included [7]. The round-trip efficiency η_{rt} can be considered as the product of a charging efficiency η_{cha} and a discharging efficiency η_{dis}. Though there was no test carried out to examine the efficiency for each phase, an approximate estimation of η_{dis} is made by assuming that 3MWh electricity injected into the grid from the BESS would reduce the SOC from 100% to the minimum limit of 45%. In other words, the electricity up to 55% of the nominal capacity discharged from the battery bank is decreased to 3MWh export to the grid due to energy losses. The VRLA battery that consists of 3,168 cells, each having a size of 1,000Ah specified at the 10-hour discharge rate and a nominal voltage of 2V [7], has a nominal capacity of around 6.336MWh. Therefore, η_{dis} and η_{cha} of the BESS are calculated as:

$$\eta_{dis} \geq \frac{3MWh}{6.336MWh \times 55\%} \times 100\% = 86.1\% \qquad (1)$$

$$\eta_{cha} \leq \eta_{rt}/\eta_{dis} = 87.1\% \qquad (2)$$

There are two ways to estimate the total volume of energy losses: an actual estimate equalling the difference between total export and import in practice was 196.9MWh; and a theoretical estimate equalling the product of total charged energy 826.6MWh and a coefficient of $(1 - 75\%)$ was 206.7MWh. The actual volume of energy losses being slightly smaller than the theoretical value means that the round-trip efficiency of the BESS was slightly higher than 75% during its first-year operation.

The theoretical value of the total energy losses can also be evaluated as a sum of the energy loss at each of discharging and charging times which was determined by multiplying the discharge and charge rates by the coefficients of $(1-\eta_{dis})/\eta_{dis}$ and $(1-\eta_{cha})$ respectively. Figure 7 shows the cumulative volume (MWh) of energy losses of the BESS's operation in the first full year. The energy loss estimated at each time step can be used to evaluate the energy-related operating cost based on the time-varying electricity price.

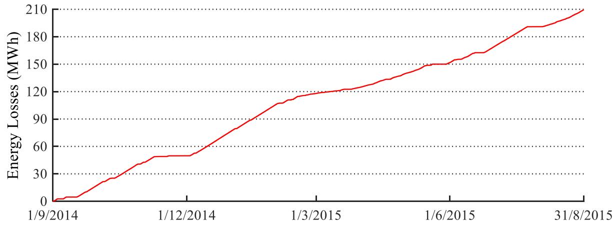

Figure 7: Cumulative volume (MWh) of energy losses of the BESS's operation during the first full year.

CONSTRAINTS ON NON-FIRM ACG

Constraint rules (CTRs)

SGS Balance and Power Flow in the ANM system use the same set of CTRs with inputs derived from forecasts or real-time data respectively. The scheduled set-points for the non-firm distributed generation, i.e. ANM Controlled Generation (ACG), would be replaced by the active set-points that were determined based on the real-time data combined with CTRs. The initial CTRs monitored: the SVT status ($CTR0$), frequency stability ($CTR1$), spinning reserve ($CTR2$), and network operation ($CTR3$) [5, 6]:

$$CTR0 = \begin{cases} 0 & SVT\ offline \\ 1 & SVT\ online \end{cases} \tag{3}$$

$$CTR1 = 14.3 - P(BUR) - Margin1 \tag{4}$$

$$CTR2 = 20 - P(SVT) - P(BUR) - Margin2 \tag{5}$$

$$CTR3 = 0.6 \times (Total\ Demand) - P(SVT) \\ - P(BUR) - Margin3 \tag{6}$$

where $Total\ Demand$ was calculated to be the sum of power outputs $P(\cdot)$ of all generating plants on the network and all the configurable margins were initially set to one. Due to the operational issues experienced with both $CTR2$ and $CTR3$ they have been negated through the use of negative margins and an additional $CTR4$ was introduced since Sep. 2015 [6]:

$$CTR4 = P(SVT) + P(ACG) - P(SVT_c) - Margin4 \tag{7}$$

where the minimum-take export limit for SVT is denoted by $P(SVT_c)$ and $Margin4 = 0$. The constraint on ACG export is usually determined by a Binding Constraint BC that is the lowest value of the CTRs listed in equations (4) – (7) if SVT is online and 0 otherwise:

$$BC = CTR0 \times \min(CTR1, CTR2, CTR3, CTR4) \tag{8}$$

where $CTR4$ is currently the dominant limit due to that the minimum value for $CTR1$ is higher than the total capacity of connected ACG and both $CTR2$ and $CTR3$ are negated by negative margins.

Due to the limited down-turn flexibility of LPS, the fast-acting governors at SVT would reduce output to accommodate the high ACG export, which may violate the minimum-take export limit for SVT without $CTR4$. Once $P(SVT_c)$ was exceeded, the reverse power flow protection at SVT would be triggered, which would lead to $CTR0 = 0$ and curtail all ACG export according to equation (8). The implementation of $CTR4$ can prevent the violation of the minimum-take export limit for SVT in the cases of high ACG exports [6].

Charge in response to ACG curtailment

Charging the BESS at a rate of 1MW could lead to 1MW growth in total generation output which would be taken by the fast-acting governors at SVT. Under the up-to-date representation of CTRs, the ACG limit determined by $CTR4$ would then be increased by the same volume as the charge rate, providing an additional 1MW of headroom for ACG to generate. If the ACG was curtailed at this moment, the SVT's fast-acting governors would release the load up to 1MW to allow additional ACG to be put onto the grid, therefore alleviating the ACG curtailment.

As was noted above, in the main, the BESS was manually scheduled to charge at times of low demand. This may have alleviated the ACG curtailment although the manual schedule was not optimised for this objective. Under the existing control architecture, a real-time algorithm has been developed by SSEN which primarily aims to charge the BESS at the times ACG is curtailed. Since charging the BESS will increase the ACG limit by the same volume as the charge rate, the real-time algorithm determines the charge rate P_{cha} as the lower value of ACG curtailment ACG_{curt} and the maximum limit on the charge rate P_{cha}^{max} which is dependent on the SOC of the battery [6]:

$$P_{cha} = min\{ACG_{curt}, P_{cha}^{max}(SOC)\} \tag{9}$$

$$P_{cha}^{max}(SOC) = \begin{cases} 1MW & 45\% \le SOC < 80\% \\ 0.66MW & 80\% \le SOC < 90\% \\ 0.33MW & 90\% \le SOC < 100\% \end{cases} \tag{10}$$

Figure 8 compares the ACG limits derived from the real-time data and the available powers of ACG during a particular 8-hour off-peak period where the BESS was not charged and the ACG had a total capacity of 3.5MW (prior to Mar. 2017). (The ACG was assumed here to generate in proportion to 3.68MW BUR that had a firm connection to the grid). In this case, the ACG had to be curtailed for most of the time, except for the time points of 01:00 and 05:00.

Assuming that 4MWh of electricity was required to charge the BESS to reach 100% SOC, the charging times and the corresponding P_{cha} would be determined by the real-time algorithm based on equations (9) and (10), as shown in Figure 9. The BESS was charged at 0.84MW which was equal to ACG_{curt} at 23:30 though the corresponding P_{cha}^{max} was 1MW as the SOC had not reached 80%. Furthermore, the BESS was not charged at 01:00 due to that ACG was not curtailed. In addition, P_{cha} at other time points reached the SOC-dependent P_{cha}^{max} since ACG_{curt} was greater than P_{cha}^{max}. Under the schedules calculated from the real-time algorithm, all the energy absorbed by the BESS would be supplied by the ACG export which would otherwise be curtailed in this case, which efficiency alleviated the ACG curtailment [6].

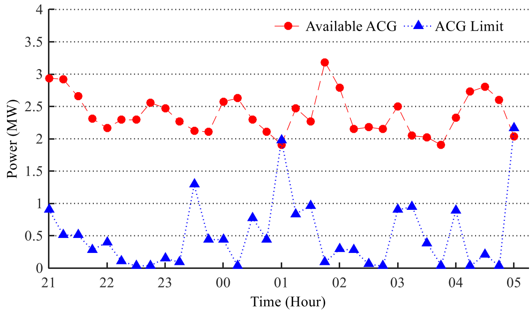

Figure 8: Available powers (MW) of ACG and limits (MW) on ACG at off-peak times during which the BESS was not charged.

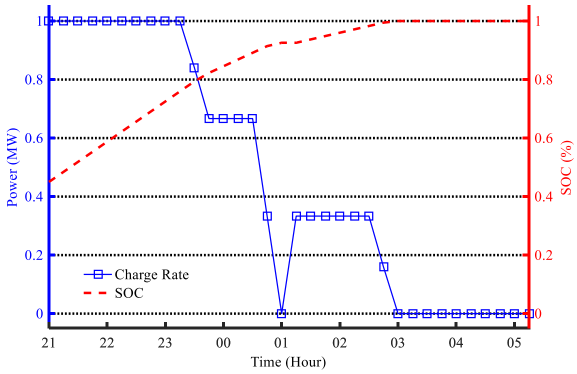

Figure 9: Charge rates (MW) of the BESS determined by the real-time algorithm and the corresponding variations in SOC (%).

CONCLUSIONS AND FUTURE WORK

This paper has reviewed the first-full-year operation and performance of a 1MW, 3MWh Battery Energy Storage System (BESS) that was installed in the Shetland network and integrated with an Active Network Management (ANM) system to facilitate the connection of distributed generation and smooth the demand curve, reducing peak demands to be met by conventional generation. Since the ANM system calculated schedules led to an unsatisfactory utilisation of the BESS (47.2%), the BESS was manually scheduled for most of the time which achieved a utilisation of 86.1% evaluated exclusive of the BESS outages.

The BESS completed 288 cycles in the first full year over which it discharged 629.7MWh and absorbed 826.6MWh from the network in total. Given an expectation of 300 full cycles per annum, the BESS achieved 96% of this and the utilisation reached 70% of the expected 900MWh. The difference between total export and import, i.e. 196.9MWh of energy losses of the BESS's operation, was slightly smaller than a theoretical estimate that was derived from the total import and a 75% round-trip efficiency. This reveals that the BESS was cycled at a satisfactory round-trip efficiency greater than 75% on average.

Charging the BESS can alleviate the limits on non-firm distributed generation, i.e. ANM Controlled Generation (ACG), and provide additional headroom for ACG. A new real-time algorithm has been designed by SSEN under the existing control architecture to charge the BESS in direct response to ACG being curtailed. Future work will assess the BESS's operation scheduled by the real-time algorithm which will be included into an upgraded ANM platform.

ACKNOWLEDGMENTS

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REFERENCES

[1] Market Strategy Board, 2011, "Electrical energy storage", International Electrotechnical Commission, Geneva, Switzerland. https://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

[2] S. Adams, A. Howison and S. Reid, 2017, "NINES project closedown report", Scottish and Southern Electricity Networks (SSEN), Perth, UK. http://www.ninessmartgrid.co.uk/library/nines-closedown-report/

[3] P. Papadopoulos, 2015, "The Smarter Network Storage project", presented at *The Mathematics of Demand Side Management and Energy Storage*. http://mcs.open.ac.uk/energymeeting/energymeeting2015/slides/Panagiotis_Papadopoulos_WMDSMES_June_2015_slides.pdf

[4] A. Urquhart and D. MacLeman, 2012, "LCNF Tier 1 close-down report, Orkney Energy Storage Park", Scottish and Southern Energy Networks (SSEN). https://www.ssen.co.uk/WorkArea/DownloadAsset.aspx?id=7305

[5] SSEN, 2017, "NINES ANM: Functional design, infrastructure and comms learning report". http://www.ninessmartgrid.co.uk/library/4a-nines-anm-fdi-comms-learning-report/

[6] F. Fan, H. Xu, I. Kockar, S. Adams, and N. Coote, 2017, "NINES 2A Battery operational effectiveness", University of Strathclyde, and SSEN. http://www.ninessmartgrid.co.uk/library/2a-nines-battery-report/

[7] N. Coote, 2014, "LCNF Tier 1 close-down report, 1MW battery, Shetland", SSEN. https://www.ninessmartgrid.co.uk/library/nines-1mw-battery-shetland-close-down-report/