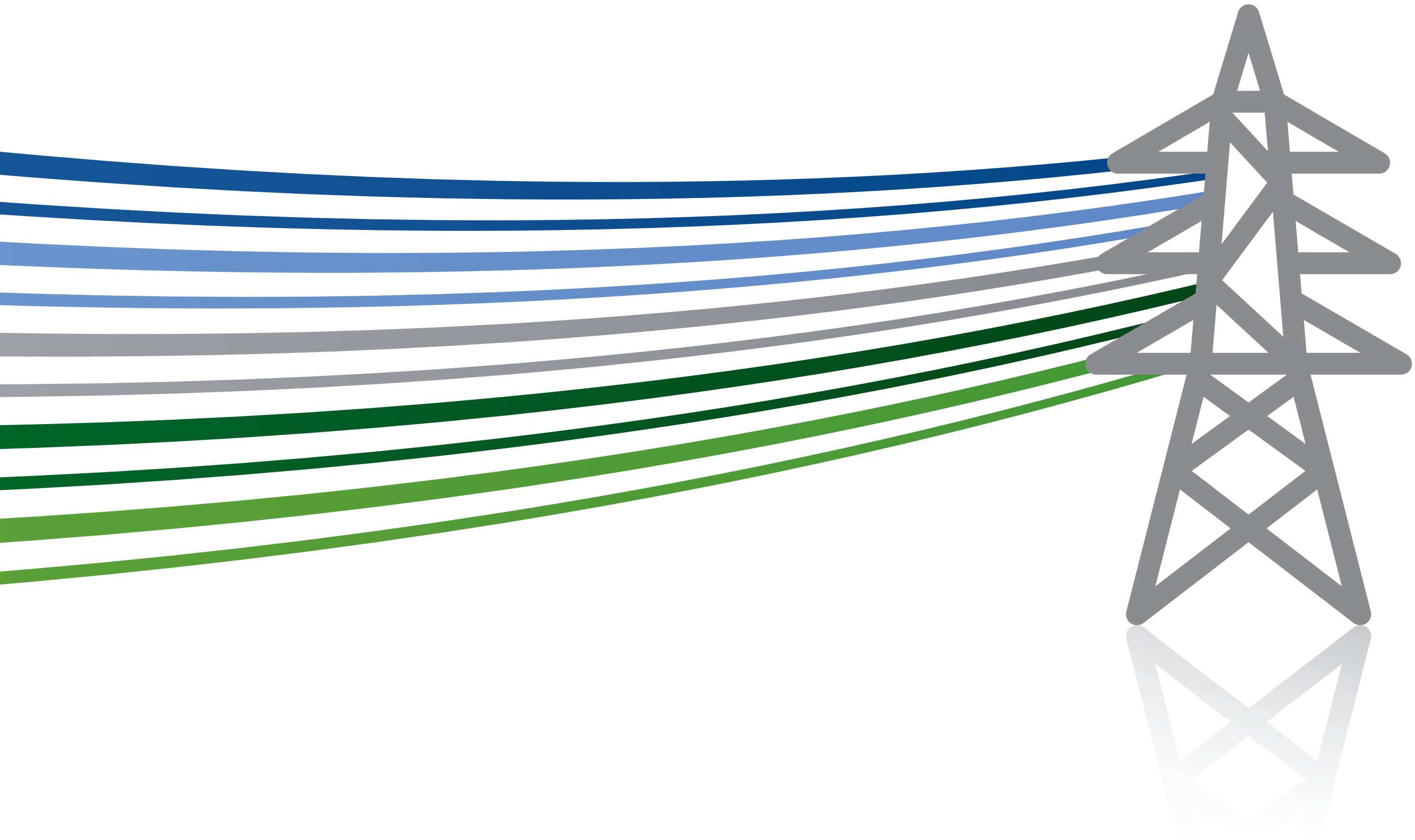
Scottish & Southern
Electricity Networks

University of
Strathclyde
Engineering

NINES

4B ANM Operational Effectiveness Report



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This report has described the commercial arrangements used by the Northern Isles New Energy Solutions (NINES) project for integrating the NINES elements into the Shetland network. Scottish and Southern Electricity Networks (SSEN) conducted the NINES project[1] from 2010-2016 as phase one of an integrated plan for Shetland repowering[2].

The project trialled a range of innovative solutions to inform the solution – including Active Network Management (ANM), Battery Energy Storage System (BESS) and Domestic Demand Side Management (DDSM). The project aims were to: reduce the maximum demand, reduce the units generated by fossil fuels, and maximise the renewable generation output.

As academic partner on the project, the University of Strathclyde (UoS) had responsibility for assessing the operational effectiveness and covering associated learnings of above technologies (i.e. DDSM, BESS, frequency response, ANM system, commercial arrangements and economics). A suite of knowledge and learning reports are produced by UoS, as listed in Table 1. These UoS learning reports are available publicly through the NINES website[1].

NINES UoS Reports	
1A	DSM: Customer Impact
1B	DSM: Infrastructure
1C	DSM: Network Benefits
2A	Battery: Operational Effectiveness
3A	Frequency Response: Customer Impact
3B	Frequency Response: Operational Effectiveness
4A	ANM: Operational Effectiveness
4B	ANM: Functional Design Report
6A	Commercial Arrangements and Economics Report
7A	UoS Knowledge & Learning Report

Table 1 NINES UoS learning reports

The ANM Operational Effectiveness report contributes to the following learning outcomes:

LO1: How can a distribution system be securely operated with a high penetration of renewable generation.

The NINES project tested the expanded use of ANM; for the first time an ANM system was configured to control demand sources including DDSM and a BESS, in addition to generation. An additional challenge included managing a closed electrical system prompting the development of a new set of constraint management rules. These constraint rules would be evaluated by the ANM system, both in real-time and via day-ahead scheduling, to define the limit of ANM controlled generation that could be accommodated while maintaining system stability.

An initial set of constraint rules were identified by the UoS in 2012 via modelling and simulation of the Shetland network, which informed the specification of parameters and constants that defined each of the constraint rules.

Rules for system frequency, spinning reserve and network voltage were defined, along with the availability of Sullom Voe Terminal (SVT), one of Shetland's primary conventional generation sources – and the main source of spinning reserve.

Operational experience by SSEN found issues with the spinning reserve and network voltage rules and sought to remedy this by the introduction of an additional constraint rule – asset protection. A variation of the network voltage rule, the asset protection constraint rule, recognised the ANM system could not directly influence the generation from Lerwick Power Station (LPS) engines and ensured renewable generation export did not cause excessive displacement of SVT export:

Asset Protection = P(SVT) + P(ACG) – P(SVTc) – Margin4

where

(*SVTc*) is the minimum-take export limit of SVT, a configurable parameter to specify the minimum SVT value

(SVT) is the output from SVT

(ACG) is the sum of output of ANM controlled generators

*Margin*4, a configurable parameter via the ANM HMI

The constraint rule became the prime mover for curtailing and releasing ANM controlled generation (ACG) on the network and has successfully demonstrated the ability to manage a high penetration of renewable generation while maintaining system stability.

LO2: What is the relationship between intermittent generation and responsive demand, including storage.

The Shetland ANM system was integrated with a BESS and DDSM, controllable demands that could be scheduled via day-ahead scheduling to alleviate constraints to ACG.

ANM calculated schedules were operated over four months from February to late May 2015. The objectives were to promote the utilisation of ACG on the Shetland network subject to the constraint rules and smooth the demand curve by filling troughs and lopping peaks. The expectation was that, when charging, controllable demand may alleviate the constraint limit and lead to a higher level of ACG export.

Analysis of the ANM calculated schedules uncovered deficiencies in the algorithm. This included non-optimal utilisation of the BESS – 47.2% in the period when it was scheduled by ANM, compared to 86.1% during manual scheduling – and examples of allocating charging of DDSM at peak times.

More importantly the research demonstrated the inherent limitations of using day-ahead scheduling to allocate responsive demand. The day-ahead scheduling algorithm utilised the same constraint rules however data sources were derived from forecasts and constants. In particular the use of a constant power value for SVT had a significant impact as this did not reflect actual system operation. This led to inaccurate forecasting of constraints, peaks and troughs and as a consequence, the allocation of controllable demand at sub-optimal times.

To maximise the benefit of the Shetland ANM and promote the efficient utilisation of responsive demand and intermittent generation, a new real-time algorithm was developed to schedule the BESS to charge in direct response to the ACG curtailment. Based on the battery completing 300 full cycles per annum, a 1.2GWh reduction in ACG curtailment may be achieved each year.

LO6: To what extent do the new arrangements stimulate the development of, and connection to, the network of more renewable generation and reduce the area's reliance on fossil fuels.

- Detail the 8.5MW additional renewable generation capacity facilitated by NINES.
- Detail the total GWh of renewable generation output facilitated by NINES.
- Detail the GWh reduction in conventional generation and associated CO^2 savings.

The experience gained from the operation and evaluation phase of the resulted in a list of enhancements in order to provide further benefit beyond the end of the NINES project into the business as usual life of the system. The main outcomes of this work were:

- Understanding inherent limitations in day-ahead scheduling prompting a major revision of the optimization algorithm.
- Understanding the value of real-time control and the ability to schedule controllable demand via existing control functionality.
- Updated ANM user interface.
- Building a level of confidence in the ANM platform to deliver further ANM systems under BAU.

It is anticipated that the upgrade to the Shetland ANM system will be completed in 2017. In addition to the capability to alleviate generator constraints by deploying controllable demand in real-time, the upgrade will provide a more robust platform to meet the future requirements of the Shetland repowering process while ensuring the benefits of the project are enduring.

1

Project Background

1. Project Background

In 2010, a licence obligation was put in place requiring SSEN to present an Integrated Plan to manage supply and demand on Shetland. 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 supply.

Under the licence condition, this Integrated Plan was required to demonstrate that it had identified a solution based on the lowest lifecycle costs, taking into account its environmental obligations.

As part of the Integrated Plan submission, consideration was given to, amongst other things, the upgrading or replacement of LPS, the impact of third party generation requirements, the abundance of renewable energy resources and the future demand on Shetland. The factors influencing the supply and demand issues on Shetland necessitated an innovative approach to their management. However, with innovation comes the need to trial solutions before reaching an answer. As a result, SSEN originally proposed to split the implementation of the Integrated Plan into two phases:

> **Phase 1 Shetland Trial** (Northern Isles New Energy Solutions 'NINES') – implementation of the infrastructure necessary to actively manage demand, generation, reactive compensation and energy storage assets. These elements were coordinated to maximise the amount of energy harvested from renewable generation while maintaining supply quality and security. In doing so, two principal effects are achieved:
>
> - a reduction in maximum demand; and
> - a reduction in the electricity units generated by fossil fuels
>
> **Phase 2 (Shetland Repowering)** – upgrading or replacement of LPS by SSEN, taking into account the learning acquired during Phase 1 and, where appropriate, extending the Phase 1 technology.

NINES Elements

NINES was originally designed and developed to operate in conjunction, and integrated, with LPS or its replacement operated by SSEN, and was developed with the main aim of informing the optimum repowering solution. Whilst its primary objective was to trial 'smarter' initiatives, importantly NINES has funded elements and infrastructure that are expected to endure. Central to the project has been the creation of an integrated set of models designed to anticipate the impact of NINES, covering the following themes:

- Dynamic Stability model
- Steady State model
- Unit Scheduling model
- Customer demand forecast model
- System Development optimisation model
- Strategic Risk and Operational risk model
- Shetland Economic model
- Commercial model

Facilitated by modelling and practical learning, the aims of NINES have been to:

1. Increase understanding of how best to accommodate Shetland's significant wind potential on a small distribution network; and
2. Increase understanding of how the existing and known future demand on the island can be best managed on a constrained, isolated system.

These models served to predict the behaviour of the energy systems on Shetland, and to validate each of the key elements of NINES as they were added. Following this validation process, these models have been used to inform the development of the New Energy Solution realised through the competitive process. With the successful operation of NINES, the infrastructure and knowledge to reduce the peak capacity requirement for any replacement solution to a level dependent on the particular assets connected, and the characteristics of the new solution has been determined. The NINES project assets are described below.

1. 1MW battery at Lerwick Power Station

A 1MW battery acts as an energy storage system on the Shetland Network. In addition to facilitating the connection of new renewables, the battery assists in optimising and stabilising the operation of the existing island network by helping to reduce demand peaks. The battery has helped to accommodate the connection of new renewable generation that would otherwise not have been able to connect.

2. Domestic demand side management with frequency response

SSEN has worked with Hjaltland Housing Association (HHA) to install advanced storage heating and water heating in 234 existing homes. These new storage and water heaters (which replaced existing traditional storage heaters) were provided through HHA and European Regional Development Fund (ERDF) funding and have been specifically designed to use a much more flexible electrical charging arrangement. This new charging arrangement is determined based upon the predicted demand, weather forecasts, availability of renewables and any other network constraints. This initial roll out was intended to help gauge the effectiveness of storage and demand side response at the domestic level.

The heaters incorporate additional insulation to minimise heat loss and are fitted with programmable timers to allow users much better control of temperature and operating times when compared with conventional storage and water heating systems. The new heating system is designed to be more efficient, while giving the customer full control of both temperature and operating time and allowing for charging at times that best suit the network.

3. Renewable generation

Shetland has some of the richest renewable resources in Europe and there is significant interest on the islands to connect a range of new renewable generators. There is a mix of wind and tidal generators currently connected that range in scale from 45kW up to 4.5MW. However, before the advent of NINES these generators could not connect to the network due to the underlying voltage and stability constraints. Connecting more renewable generation, which is unavoidably intermittent, would have exacerbated these problems.

To address this, NINES has trialled an active network management regime which has offered renewable connections to developers. In return, they are required to give their agreement to being constrained when the system cannot accommodate their generation. The measures that have been developed and trialled under NINES are reducing this constraint by being able to actively provide demand when there is renewable resource available.

Indeed, these arrangements could be necessary even if Shetland is to become electrically connected to the mainland at some point in the future. If a single mainland link is damaged, this could result in a prolonged outage, which would mean that Shetland would once again be electrically islanded. Therefore the prospect of and ability to constrain will remain for generators on Shetland, albeit on a less frequent basis.

4. ANM system

This is the NINES project's nerve centre: it monitors the different parameters affecting the network, including embedded constraints, frequency stability and weather and manages an appropriate response. It responds to, and tunes, the models which have been developed to monitor and understand how new storage assets will behave. By creating flexible demand on the island progress has been made in exploiting and maximising Shetland's wind generation potential on an islanded basis, and in reducing the generated output from replacement thermal generation.

A key driver for the trial has been to develop an understanding how these technologies work and interact in a real-life environment. The learning from NINES has demonstrated that in general terms (with the exception of additional renewables), all NINES technologies predominately involve energy shifting rather than energy reduction.

The following report is one of a number of related reports undertaken by the research team, led by the UoS and focuses on evaluation of effectiveness of the deployed ANM solution developed by Smarter Grid Solutions. Details related to the Functional Design, Infrastructure and Communication of the deployed ANM solution are provided in a NINES Learning Report 4A: ANM Functional Design, Infrastructure and Comms.

The document consists of the following sections:

- It provides a brief overview of ANM scheme and requirements posed by Shetland network operator
- Analysis of initial set of Curtailment Management Rules (CTRs) and assumptions
- Reasoning behind changes in the initial CTRs and development of new ones
- Effectiveness of ANM to manage controlled generator (ACG) outputs
- Integration of Battery Energy Storage into ANM system
  - Effectiveness of scheduling
- Integration of DDSM into ANM system
  - Effectiveness of scheduling to alleviate ACG curtailment

2

Brief Overview of the NINES ANM Solution

2. Brief Overview of the NINES ANM Solution

The Active Network Management (ANM) system is a real-time control solution that enables the co-ordination of the various elements of the NINES scheme and the Shetland system.

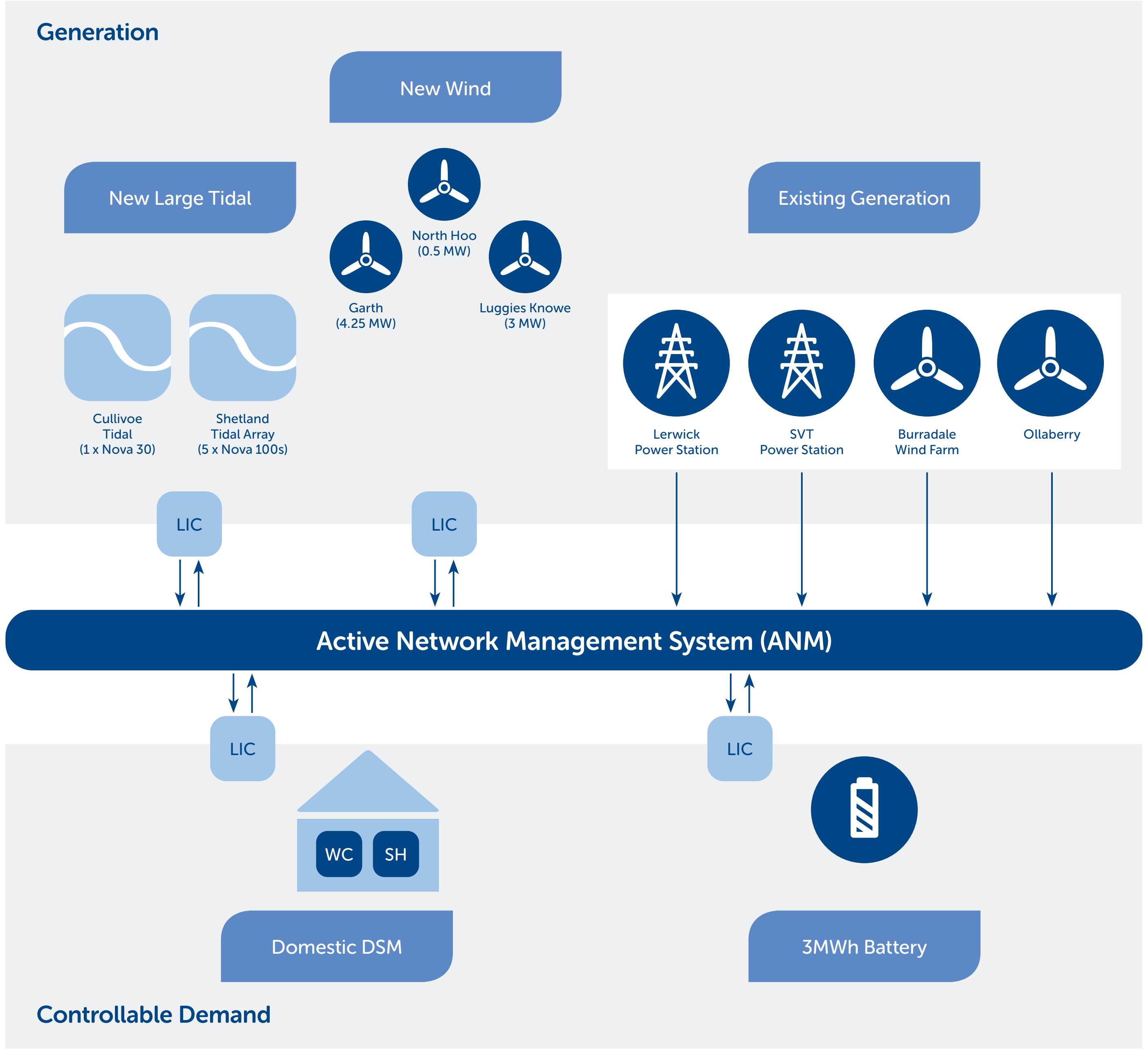

Figure 1: Schematic representation of ANM system architecture

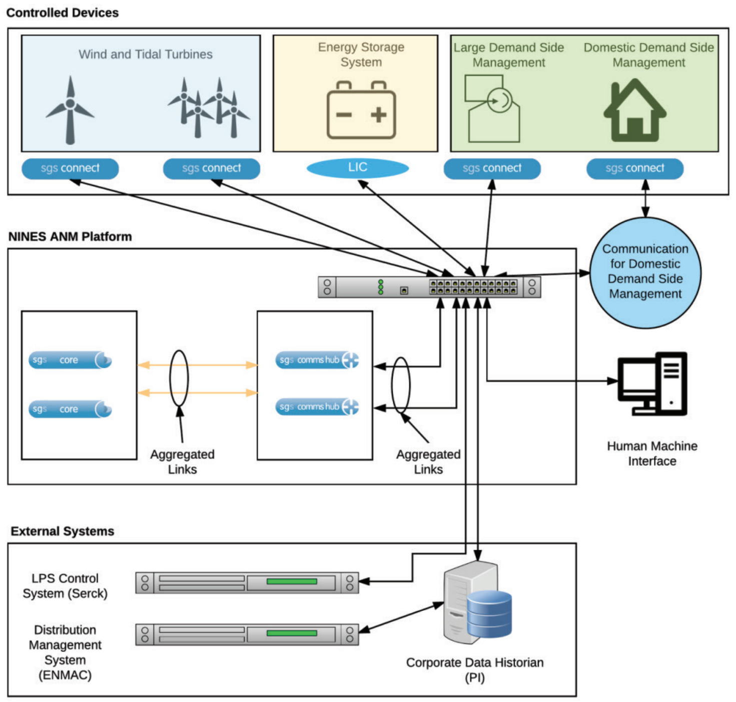

Figure 2: NINES ANM system logical overview

It includes a control platform that hosts algorithms which are designed to help system operation through network monitoring and automatic control of ANM elements including renewable generation, large-scale battery storage, and groups of domestic demand side management devices. The ANM system uses real-time data alongside forecast information to use flexible supply and demand at times that suit the Shetland network. A schematic representation of the ANM System architecture is shown in Figure 1.

Prior to NINES, the Shetland system had limited capability for control, measurement and automation of network operation, particularly regarding the integration of renewables. A SCADA system located in LPS is based upon the Serck SCX product, providing an indirect interface to the GE PowerOn Fusion SCADA/DMS system based at the SSEN Network Management Centre in Perth. SSEN identified the opportunity to use ANM as a means to accommodate additional renewable generation on Shetland, restricting export under conditions where stability constraints were binding. An overview of the ANM system deployed for NINES is presented in Figure 3.

Through active management of controllable network devices, the two high-level objectives of the NINES ANM system are to:

- Accommodate renewable generation customers and reduce reliance on fossil fuels;
- Smooth the demand curve to minimise the differences between peaks and troughs in the Shetland system demand.

More specifically, the objectives of the ANM deployment were to:

- Accommodate customers:
  - Enable the provision of ancillary services from a wider range of customers on Shetland.
  - Allow the maximum possible amount of renewable generation to be connected, and reduce the amount of fossil fuel consumption from the island's generation sources.

    - Accommodate the connection of new small generators on the network.
- Smooth the demand curve:
    - Provide network balancing by managing demand
    - Enhance the stability of the network with new generation and storage capabilities, including the management of network frequency via ANM.
    - Smooth the net demand profile seen by LPS (reduce the difference between minimum and maximum daily demand).
- Gain an understanding of ANM and improve control interfaces:
    - Test the expanded use of ANM, building on SSEN experience in Orkney, by implementing control of connected loads and generators for network constraint management.
    - Monitor power flow and voltage across the network and control devices in real-time to ensure that all points remain within limits.
    - Provide acceptable user interfaces in conjunction with existing systems for operators at LPS and Perth Network Management Centre.
    - Use real-time feedback from network monitoring and communication link health status to modify system operation.

The ANM functional requirements are presented across three areas:

1. **Stability Constraint Management:** Where network devices, such as generators, responsive loads and energy storage devices, are controlled in real-time in response to prevailing network conditions. This meets the objective of accommodating additional customers while managing the network constraints that may arise following their connection.
2. **Device Scheduling:** Where forecasts are used to derive and issue schedules to appropriate devices to meet the objective of smoothing the demand curve.
3. **Configuration and Interface:** The requirements associated with ANM user interactions, the capability to issue manual control commands, and interfaces with other SSEN systems.

In this report, ANM operational effectiveness will be evaluated for the following:

- ANM Constraint Management
    - Summary of initial constraint rules introduced in the first phase of the project
    - Revision of the original constraint rules and introduction of new ones
    - Influence of constraint rules on DG curtailments
- Battery
    - Evaluate Battery Schedule via ANM
    - Effects of Manual Schedule on ACG limits
- Flexible Demand
    - Effects of DDSM on ACG limits

3

ANM Constraint Rules

3. ANM Constraint rules

3.1 Specification of ANM Initial set of Constraint Rules

In addition to three main generation sources, i.e., Lerwick Power Station (LPS), Sullom Voe Terminal (SVT) and Burradale wind farm, the Shetland network is supported by non-firm distributed generation at North Hoo (0.5MW), Luggie's Knowe (3MW), Tidal Array (0.5MW) and Garth (4.5MW) under flexible contracts which were commissioned in November 2014, December 2015, December 2015 and March 2017 respectively. These generating plants together with controllable demand were all integrated with the ANM system. ANM includes constraint management necessary to ensure stable operation of the Shetland network. Connection of increased levels of intermittent renewable generation may affect system balancing and reactive support capabilities, leaving the system sensitive to sudden changes in generation or demand that cause an imbalance in supply. This is more challenging due to the nature of the Shetland network which is not connected with the mainland GB network, and where additional renewable generation displaces generation from the conventional synchronous plant at LPS and SVT.

To ensure that the operational tool accounts for the security constraints that may be caused by the connection of additional renewable generation, a number of constraints rules were identified by the University of Strathclyde[3], with support from SSEN engineers. These initial rules were identified via modelling and simulation of the Shetland network, which were used to inform the specification of parameters and constants that defined each of the constraint rules. These constraint rules have been implemented within the SGS Balance and SGS Power Flow algorithms when calculating the scheduled set-points and active set-points of ACGs based on forecasts and real-time data respectively.

The initial constraint rules (CTRs) were the following:

CTR0 – SVT Online/Offline Constraint

The gas-turbine synchronous generators at SVT provide both primary and secondary frequency response following loss of all renewable generation on Shetland. As such, SVT provides a significant contribution to the stability and operation of the Shetland system when there is high renewable output. SVT is also the main source of spinning reserve for renewable.

Therefore, when SVT is off-line, not exporting to the Shetland system, all ANM-controlled generators are to be curtailed entirely to a 0 MW set-point, and is defined as,

$$CTR0 = \begin{matrix} 0 \\ 1 \end{matrix} \begin{cases} SVT\ Offline \\ 1SVT\ Online \end{cases} \quad (1)$$

CTR1 – Frequency Stability Constraint

The key criterion for frequency stability is that the Shetland system frequency can be maintained within +/- 2% of nominal (+/- 1Hz) in the event of losing all renewable generation. The instantaneous loss of all renewable export will require sufficient primary frequency response pick-up from the online synchronous generators. The frequency stability constraint limits the export from additional renewables, ensuring there is sufficient demand met from synchronous generation to manage frequency deviation.

Dynamic simulation of the Shetland system, performed by University of Strathclyde[3], investigated the worst-case frequency deviations following loss of all renewable generators, including already-connected sites. The modelling and simulations identified a 14.3MW limit of instantaneous renewable generation that could be accommodated onto the Shetland system without breaching frequency limits following an outage.

Based on the above, the CTR1 is defined as,

$$CTR1 = 14.3 – P(BUR) – Margin1 \quad (2)$$

where *P(BUR)* is the output of the Burradale windfarm, while a parameter *Margin*1 is currently set at value of 1, but is configurable via the ANM HMI. This rule would never limit the ACG export due to the fact that the minimum value of *CTR1* is always greater than the export of 8.545MW ACG[4].

CTR2 – Spinning Reserve Constraint

Similar to the Frequency Stability Constraint, it is required that sufficient spinning reserve is provided by synchronous generation to meet demand following an instantaneous outage of all renewable generation on Shetland. Spinning reserve is provided primarily by the SVT generators, meaning that all lost energy exports from renewable generation must be displaced by SVT. At 23MW export from SVT, protection will operate disconnecting SVT from the network instantaneously, a 990 second trip counter commences at 21MW, and the LPS control room do not have visibility above 20MW export. Displacement of renewable generation export from SVT following an outage must therefore not allow SVT export to exceed 20MW.

This specifies a limit on instantaneous renewable generation export such that it, in combination with the instantaneous export from SVT, must not exceed 20MW.

The CTR2 is formulated as:

$$CTR2 = Constant2 – P(SVT) – P(BUR) – Margin2 \quad (3)$$

where

- *Constant2* = 20
- *P(SVT)* is the output from SVT
- *P(BUR)* is the output from Burradale wind farm
- *Margin2* is a parameter configurable via the ANM HMI

CTR3 – Network Operation Constraint

The town of Lerwick constitutes a relatively large proportion of the electrical demand on Shetland. This means that the supply from LPS is required to meet at least 40% of total system demand to ensure that the voltage profile to the South mainland is maintained within statutory limits. Note that 40% was provided as a guideline and is dependent on the type of network load, and the voltage of the South mainland is the key limiting factor. This requirement introduces the Network Operation Constraint, which specifies that the total exports from renewable generation and SVT must not displace LPS export below meeting 40% of system demand. Taking account of total system demand, the export from existing firm renewables and SVT, it is possible to define a limit of additional renewable generation export that can be accommodated on Shetland.

This rule is defined as

$$CTR3 = 0.6 \text{ x Total Demand} – P(SVT) – P(BUR) – Margin3 \quad (4)$$

where

- *P(SVT)* is the output from SVT
- *P(BUR)* is the output of Burradale wind farm
- *P(ACG)* is the sum of outputs of other ANM controlled generators, i.e.,

$$PACG = P(Garth) + P(Luggie's\ Knowe) \\ + P(Shetland\ Tidal) + P(North\ Hoo)$$

- *Margin3* is a parameter configurable via the ANM HMI

The limit of energy export from ANM controlled generators must be the minimum of the limits defined by the three constraints rules CTR1, CTR2 and CTR3 stated above if SVT is online; otherwise, the ACG limit is zero.

In SGS Balance which issues the scheduled set-point to ACG and calculates the schedule of controllable demand, the value of *P(SVT)* is a constant from SVT Export Manual Override; *PBUR* and *PACG* are forecasts of wind generation outputs from Burradale and ACG respectively; and *Total Demand* in *CTR3* is the forecast of uncontrollable demand. In contrast, real-time power outputs of LPS, SVT, Burradale and ACG are used in SGS Power Flow to estimate the active set-point of ACG which replaces the scheduled set-point. Note that *Total Demand* in *CTR3* is calculated as the sum of real-time power outputs of all generating plants on the network in SGS Power Flow.

3.2 Original assumptions regarding controllable devices

Based on the initial ANM constraint rules, the SGS Balance included in the ANM system was implemented to manage other NINES controllable devices, i.e. the controllable demand, with a primary objective of avoiding the potential generator curtailment actions. This was done to mitigate the curtailment of renewable energy export and maximise renewable output on Shetland. These requirements considered the following parameters of the controllable devices to maintain the constraint limits:

Level of the Domestic Demand Side Management (DDSM): 4.2 MWh

An estimated 750 houses would be provided with new electrical space and water heaters, releasing controllable electrical demand and providing sub-second frequency response. In addition to alleviating generator curtailment, this DDSM capability can be scheduled at times of low demand to smooth the overall demand curve. Both capabilities present potential to support the constraint rules and mitigate generator curtailment.

Level of the Large-scale Demand Side Management: 135 MWh

Large scale DSM comprising a 4MW electric boiler connected to a 135MWh thermal storage tank providing DSM to the grid while supplying a district heating scheme. Similarly to DDSM, managing overall system demand can adapt the loading curve to provide periods of high demand during periods of increased renewable export capability. Both large-scale DSM and DDSM must be managed within bounds that ensure customer's heating needs are met and not adversely affected.

Size of the battery: 6MWh

Use of the grid-scale battery to import power during forecast constraint periods, and export power at peak demand times. During the initial requirements specification, it was not proposed that the battery provide fast-acting frequency response.

Prior to the connection of additional renewable generation, no steady-state power-flow (i.e. thermal) constraints occurred on the Shetland system, and existing conventional generation was used to manage voltage constraints, as reflected in CTR3 *Network Operation Constraint*. However, the connection of additional renewable generation could cause thermal or voltage constraints, depending on the generator connection location.

3.3 Revision of the original constraint rules

Since the initial design the original assumptions are no longer valid for all constraint cases. This led to the development of new rules or modification of the initial constraint rules to reflect operational experience.

The rule CTR3 was put in place to make sure LPS provided a minimum of 40% of total generation output (TGO). However, CTR3 was primarily the binding constraint, and the ANM system cannot directly influence LPS engine outputs therefore when LPS is operating higher than 40%. ANM will not seek to curtail ACG, and SVT is displaced as a result. In addition, the CTR3 balances on a knife edge, experience found an "all or nothing" outcome for ACG. Either the ACG was released completely and would result in no curtailment. Or, the ACG was curtailed completely and would not be released. This led to an additional constraint rule, CTR4 Asset Protection Constraint rule, being introduced on 1st September 2015.

CTR4 – Asset Protection Constraint

The objective of this new rule CTR4 was to ensure that renewable generation exports did not cause excessive displacement of SVT export by limiting the production from ACG:

$$CTR4 = P(SVT) + P(ACG) - P(SVTc) - \text{Margin4} \quad (5)$$

where

- *P(SVTc)* is the minimum-take export limit of SVT, which is a configurable parameter to specify the minimum SVT value
- *P(SVT)* is the output from SVT
- *P(ACG)* is the sum of outputs of other ANM controlled generators, as defined for equation (4)
- Margin4, a configurable parameter via the ANM HMI

3.4 Binding Constraint

The limit on ACG export is usually determined by a Binding Constraint:

$$BC = CTR0 \times \min(CTR1, R2, CTR3, CTR4) \quad (6)$$

In real-time operation, an increase in system demand from charging the battery or DDSM would be taken by the fast-acting SVT export. Then the increase in SVT export reduces the ACG limit if the binding constraint is determined by *CTR2* or *CTR3*, this may aggravate ACG curtailment. Due to operational experience CTR2 and CTR3 are not used in ANM any longer –but are still part of other system operation tools. To achieve this, these two constraint rules have been made inactive by adjusting values of Margin2 and Margin3 parameters (e.g. setting them to large negative values). This prevents CTR2 or CTR3 from being the binding constraint. Therefore, the constraint on ACG export is generally dominated by *CTR4* in real-time control.

3.5 Effects of Constraint Management Rules

3.5.1 Effects of the Binding Constraint

As detailed in the Battery Operational Effectiveness report[5], the Binding Constraint is currently dominated by CTR4 due to the fact that the minimum value of CTR1 is always greater than the total capacity of connected ACG, and CTR2 and CTR3 have been negated by negative margins. As an illustration, Figure 4 shows the values of each constraint rule over a day from 07:00 on 31/05/2016 to 07:00 on 01/06/2016 during which negative margins of -13 and -10 were used to negate both CTR2 and CTR3, and CTR4 determined the Binding Constraint.

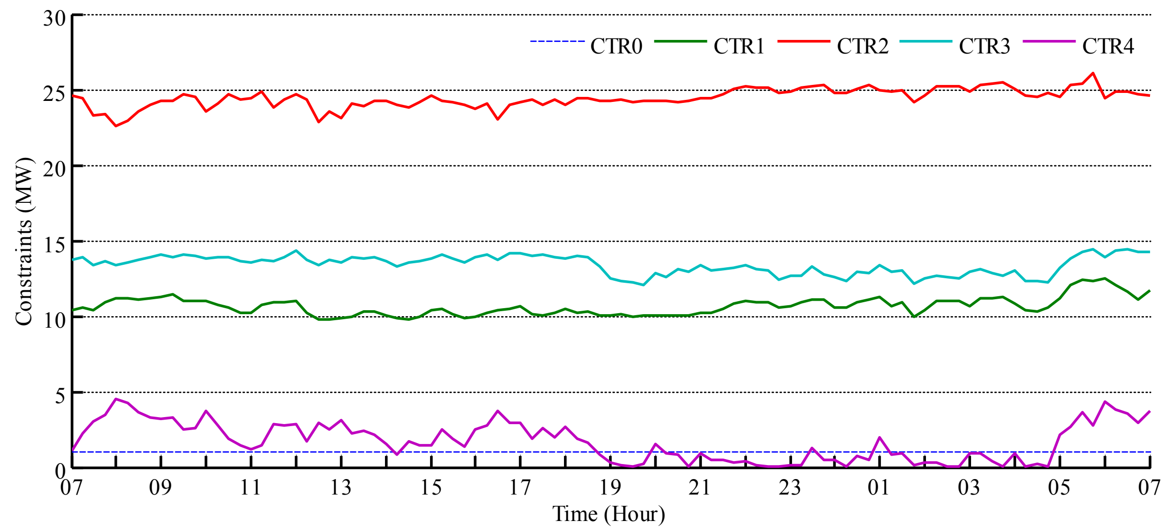

Figure 3: Values (MW) of constraint rules from 07:00 on 31/05/2016 to 07:00 on 01/06/2016

In practice, the fast-acting governors at SVT 'grab' or release the load to accommodate the ACG export. Without CTR4, the fast-acting governors at SVT would reduce output. As SVT output reduces the calculated ACG limit from CTR2 and CTR3 increases. The increasing ACG output would first breach the minimum-take export limit of SVT. Left unchecked and with enough ACG available the reverse power flow protection at SVT would then be triggered and lead to CTR0=0, i.e. BC=0, which curtails all ACG export. It is likely an unacceptable under frequency event would follow. The implementation of CTR4 has therefore been critical to preventing the operation of reverse power flow protection at SVT and operating the network securely.

3.5.2 Illustration of ANM effectiveness to manage trip event and curtailment release

One of the main requirements of the applied ANM solution was to ensure that non-firm distributed generation (i.e. ACG) will be curtailed when necessary. Figure 5 illustrates this capability of ANM based on active set-points and real-time outputs of 3MW Luggie's Knowe (LK) and 0.5MW North Hoo (NH) on 14/10/2016. In this particular day, NH was completely curtailed for majority (60%) of the time (e.g. during 00:00 – 06:00 and 10:00 – 16:00), while LK, which is higher in the Last-In-First-Out (LIFO) stack order, was allowed to produce at reduced levels to maintain network stability. When there was sufficient headroom for LK to generate, a set-point of 3MW was issued to LK and then NH was permitted to access the network subject to the remaining headroom. NH would receive a set-point of 0.5MW and its export would not be curtailed when the remaining headroom was found to be greater than the available power output of NH.

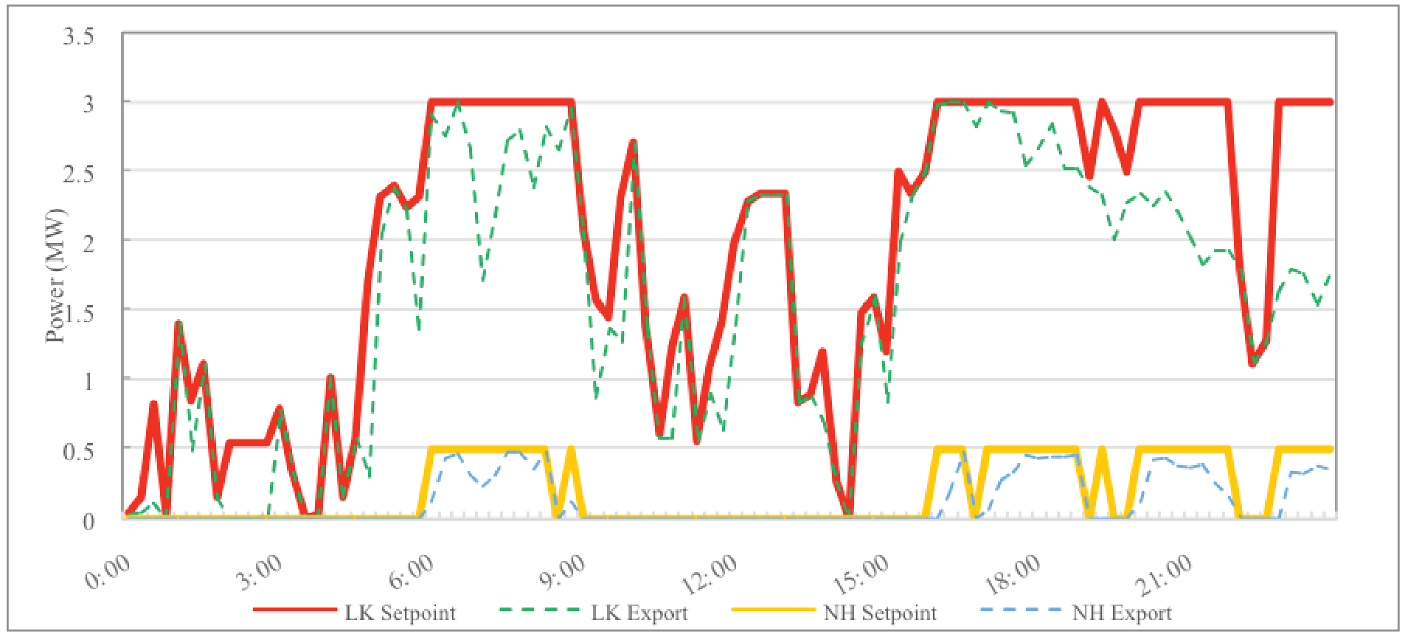

Figure 4: Setpoints (MW) and outputs (MW) of non-firm distributed generators on 14/10/2016

3.5.3 Illustration of ANM effectiveness to maintain generators' output levels below AGC export limits

Total output of ANM Controlled Generation (ACG) cannot exceed the ACG limits defined by constraint rules, and ANM is responsible for maintaining their total generation outputs below such limitation. Figure 6, provided for the period 01/10/2016 – 07/10/2016 illustrates that ANM was effective in achieving this goal.

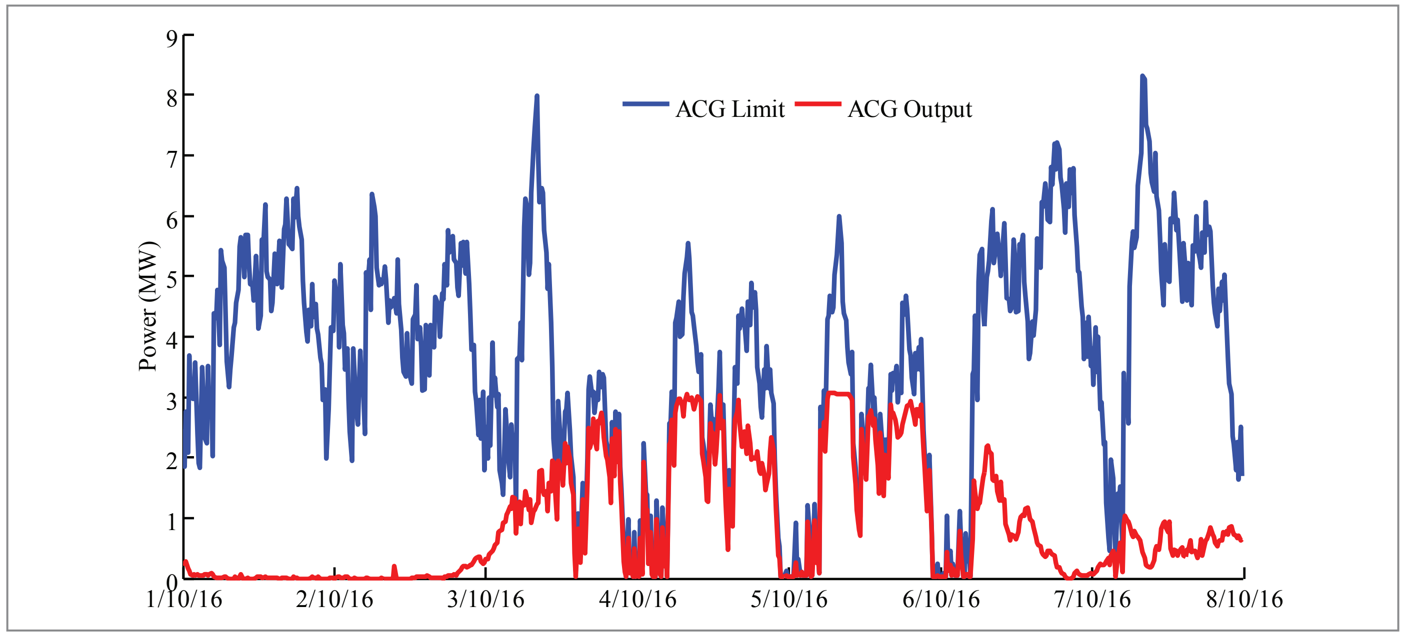

Figure 5: Export limits (MW) and corresponding outputs of ACG from 1/10/2016 to 7/10/2016

4

Integration of Battery Energy Storage System

4. Integration of Battery Energy Storage System

The devices on the Shetland network inclusive of the BESS and DDSM groups were integrated with the ANM system. The objectives were to smooth the demand curve by filling troughs and lopping peaks, and to promote the utilisation of ACG on the Shetland network.

Following this decision SHEPD continued to work with S&C Electric (S&C) to identify a suitable replacement battery. Proposals were presented to Ofgem for a replacement option in the form of change requests which were subsequently agreed by Ofgem on 17th September 2013. The replacement 1MW/3MWh lead-acid battery was completed to plan and initially commissioned during February 2014. MW values were recorded at the 11kV circuit breaker and therefore included all incurred energy losses at battery bank, PCS, transformer, etc. In the main, the BESS was scheduled to discharge at peak times and charge during the off-peak. More specifically, the daily discharge was limited to 3MWh in addition to a minimum 45% state of charge (SOC). Twelve 15-minute discharge periods of 1MW were specified to coincide with peak demand each day. More detailed analysis of BESS operation is provided in the Battery Operational Effectiveness Report[5].

4.1 ANM system calculated schedule

The devices on the Shetland network inclusive of the BESS and DDSM groups were integrated with the ANM system. The BESS was operated under the ANM calculated schedules over four months from February to late May 2015. The objectives were to smooth the demand curve by filling troughs and lopping peaks, and to promote the utilisation of ACG on the Shetland network subject to constraint rules described above. The expectation was that, by charging, the BESS may increase the constraint limit and lead to a higher level of maximum allowable ACG export.

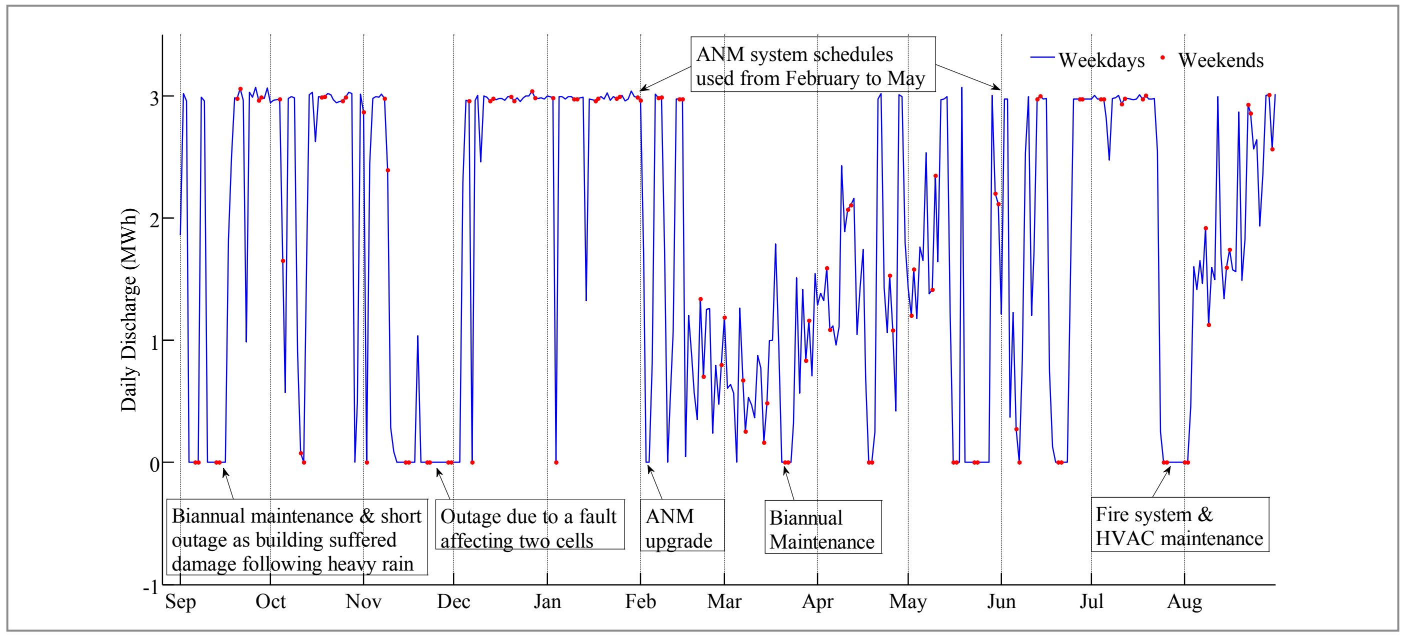

Figure 6: Volumes (MWh) of daily discharged energy of the 1MW, 3MWh BESS in the first full year from September 2014 to August 2015

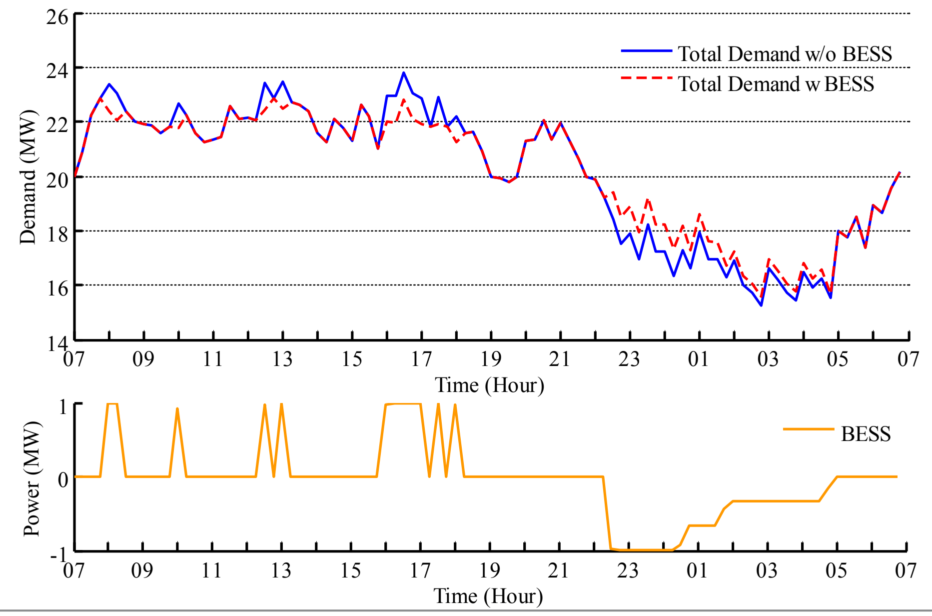

Figure 7: Variations in total demand (MW) to be met by generators following the operation of the BESS from 07:00 on 03/09/2014 to 07:00 on 04/09/2014

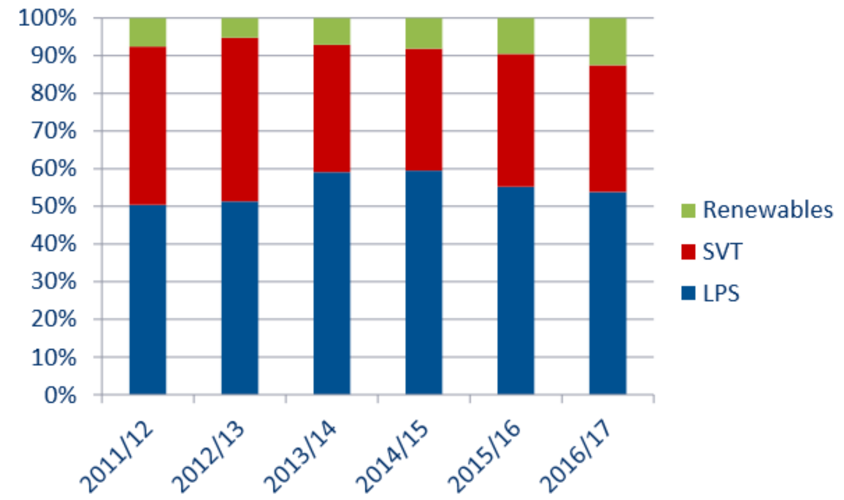

Figure 8: Percentages of outputs of renewable generation and conventional generation, i.e. Lerwick Power Station (LPS) and Sullom Voe Terminal (SVT) against total generation outputs in each year

Operating the BESS under ANM calculated schedules revealed a number of deficiencies in the ANM algorithm. From operational data, and as shown in Figure 7, the schedules did not fully utilise the 3MWh available from the battery.

By not fully discharging the battery, less energy was required to recharge thus reducing the controllable demand available to alleviate constraints. Second, the algorithm utilised a single energy requirement rather than the two energy requirements that were expected. This was set to 3MWh, and the schedule did not provide the 4MWh – or equivalent thereof – necessary to fully charge the battery to 100% SOC. Therefore, manual schedule intervention was required to ensure that the battery was fully charged. Based on measurements, the BESS completed 98 cycles under the ANM calculated schedules and discharged approximately 138.7MWh in total. Exclusive of the outages made for operational reasons, the utilisation of the BESS was only about 47.2% in this time period.

4.2 Manually derived schedule

To temporarily remedy the above described issues, the BESS was manually scheduled beyond June 2015. The objective of the manual schedule was to smooth the demand curve through discharging the battery at peak times and charging the battery at times of low demand. As shown in Figure 8, the maximum demand provided by generators was reduced from 23.86MW to 22.86MW by discharging the battery at a rate of 1MW. Furthermore, the standard deviation of total export from generators decreased from 2.5MW to 2.1MW on that day, indicating that the demand curve was largely smoothed.

Based on recorded outputs of BESS, 190 cycles were completed under manual scheduling and 491MWh were injected into the grid in the first full year. When the battery was scheduled to cycle (i.e. excluding the outages that have been labelled in Figure 7), the utilisation of the BESS during the periods prior to February 2015 and beyond June 2015 was around 86%.

4.3 Impact of BESS Operation on ACG connection

Shetland has rich and various renewable energy resources. A key objective of the NINES project is to increase levels of renewable generation subject to network stability. Figure 9 shows NINES has increased penetration of renewable generation and reduced conventional generation that relies on fossil fuels. The renewable generation supplied approximately 10% of total system demand in the year 2015/16, which is expected to increase to around 12% in 2016/17. Although the renewable penetration has increased under NINES, a smaller, but considerable amount of renewable generation was curtailed. Including the commissioning period at the start of the year 2016 , LK exported approximately 7.5GWh to the network throughout the year 2016, while 1.94GWh energy was curtailed due to the constraint on export. The annual export of renewable generation is expected to increase in the future now that all the distributed generators under NINES management have been connected and are able to generate onto the Shetland network. In addition, a further reduction in renewable generation curtailment could be achieved through further optimisation of the scheduling of the controllable demand.

As analysed in the Battery Operational Effectiveness Report[5], the 1MW growth in TGO from charging the battery would lead to 1MW increase in the limit on ACG export when *CTR4* was implemented on 01/09/2015. Therefore, charging the battery could provide additional headroom for ACG to generate and thus may allow additional ACG on the network which would otherwise be curtailed if the battery had not been available. The stored energy in the BESS provided by additional ACG could then be injected into the grid at peak times with a rate of 75% round-trip efficiency, which reduced the demands to be met by conventional generation and achieved corresponding cost savings.

4.3.1 Volume of additional ACG export

The ACG export was limited by different representations of constraint rules over the period from February 2015 to November 2016. Prior to the implementation of *CTR4* on September 2015, charging the battery reduced the ACG limit and therefore would not alleviate ACG curtailment due to operational issues with *CTR2* and *CTR3*.

When the CTR4 was implemented on 01/09/2015, the increase in the limit of ACG export from charging the battery had enabled ACG to put additional energy onto the network which would otherwise be curtailed. In the evaluation period of 15 months from September 2015 to November 2016, this totalled 597.25 hours. The volumes of additional export of NH and LK absorbed by the battery were calculated through comparing the outputs of NH and LK with the limit on ACG export and the limits if the battery had not been charged.

An example in Figure 10 shows the ACG export (i.e., the sum of export of NH and LK) comparing the ACG limit without the BESS, *Limit w/o BESS*, and that with the BESS, *Limit w BESS*, over a consecutive time period from 21:00 on 31/03/2016 to 05:00 on 01/04/2016. During that time around 3.9MWh electricity was used to charge the BESS. Charging the battery at off-peak times had allowed NH and LK to additionally generate 0.15MWh and 0.66MWh which would otherwise be curtailed.

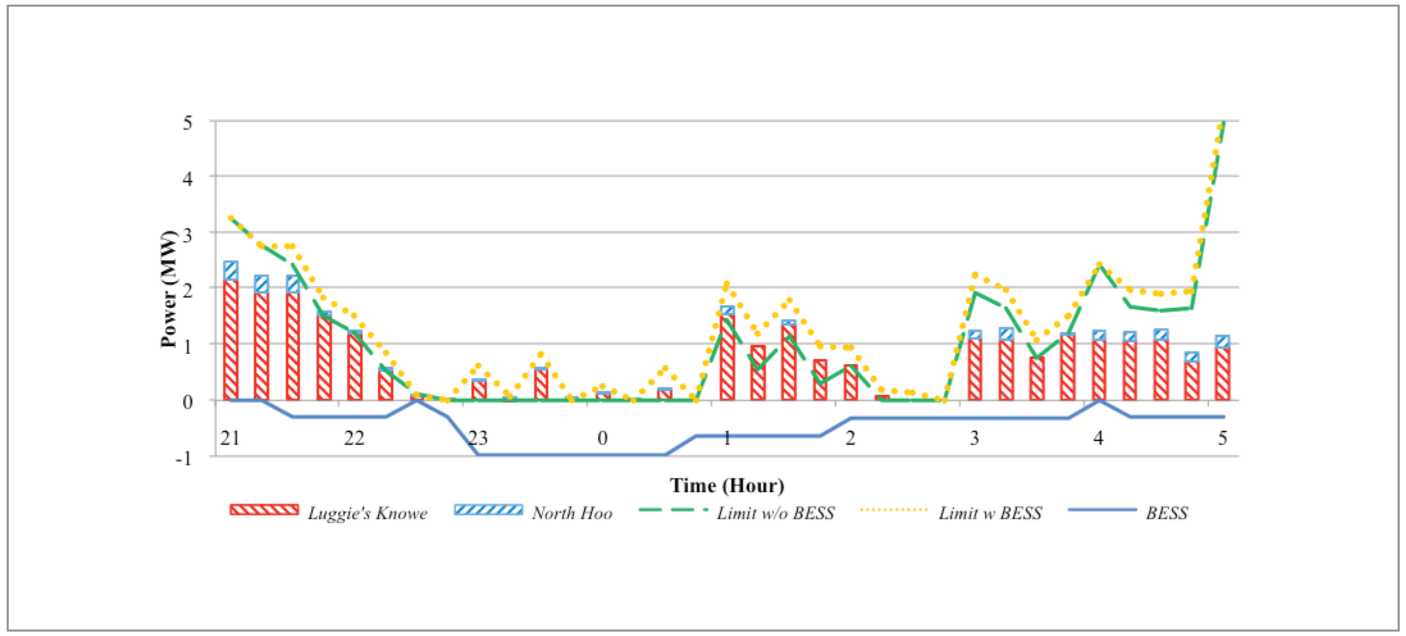

Figure 9: ACG export, *Limit w/o BESS* and *Limit w BESS* from 21:00 on 31/03/2016 to 05:00 on 01/04/2016.

The volumes of additional export of NH and LK enabled by charging the BESS were estimated to be about 18.1MWh and 34.6MWh respectively over the period from September 2015 to November 2016. Compared with the total amount of energy used to charge the battery (0.94 GWh during the period under review), the volume of additional ACG export enabled by the battery which would otherwise be curtailed was relatively small. This was in part due to only 0.5MW ACG connected to the network until February 2016 when LK was fully commissioned. The 0.5MW ACG was rarely curtailed which affected the battery's ability to reduce the ACG curtailment for most of the operational period. Furthermore, the battery was not directly scheduled to alleviate the real-time constraints on ACG. To resolve this issue, a new real-time algorithm has been developed by SSEN to charge the battery in direct response to the ACG curtailment and will be included in an upgraded ANM platform in 2017.

4.4 New real-time control algorithm for BESS

To maximise the benefit of the battery and further increase the penetration of renewable generation, the new real-time control algorithm would charge the BESS at the times the ACG is curtailed. Under the existing control architecture, the charge rate *(Pcha)* of the BESS would be determined as the lower value between the ACG curtailment *(ACGurtail)* and the maximum limit *(PchamaxSOC)* on the charge rate which depends on the SOC of the battery:

$$P_{cha} = \min\{AC_{Gurtail,} P^{max}_{cha}(SOC)\} \quad (7)$$

$$P^{max}_{cha}(SOC) = \begin{cases} 1MW & 45\% \leq SOC < 80\% \\ 0.66MW & 80\% \leq SOC < 90\% \\ 0.33MW & 90\% \leq SOC < 100\% \end{cases} \quad (8)$$

As evaluated in Battery Operational Effectiveness report, under the real-time algorithm, the battery would be charged at the times ACG was being curtailed subject to the maximum allowable charge rates; when the ACG export experienced a high level of curtailment, 4MWh of electricity used to charge the BESS to 100% SOC was all supplied by the ACG export which would otherwise be curtailed.

Prior to the commissioning of 4.5MW Garth wind farm, the 3.5MW ACG was not curtailed at times when the system demand was still at a high level during the off-peak times. In these particular cases, the real-time control algorithm may not work to charge the battery when it is implemented to schedule the BESS. Following Garth's commissioning, the total capacity of ACG has now reached 8.545MW under NINES, which will preserve the advantage of the real-time algorithm in alleviating ACG curtailment at almost all times of the year. Based on the battery completing the expected 300 full cycles per annum, 1.2GWh of reduction in ACG curtailment may be achieved by charging the BESS in a year.

5

Scheduling of Flexible Demand via ANM

5. Scheduling of Flexible Demand via ANM

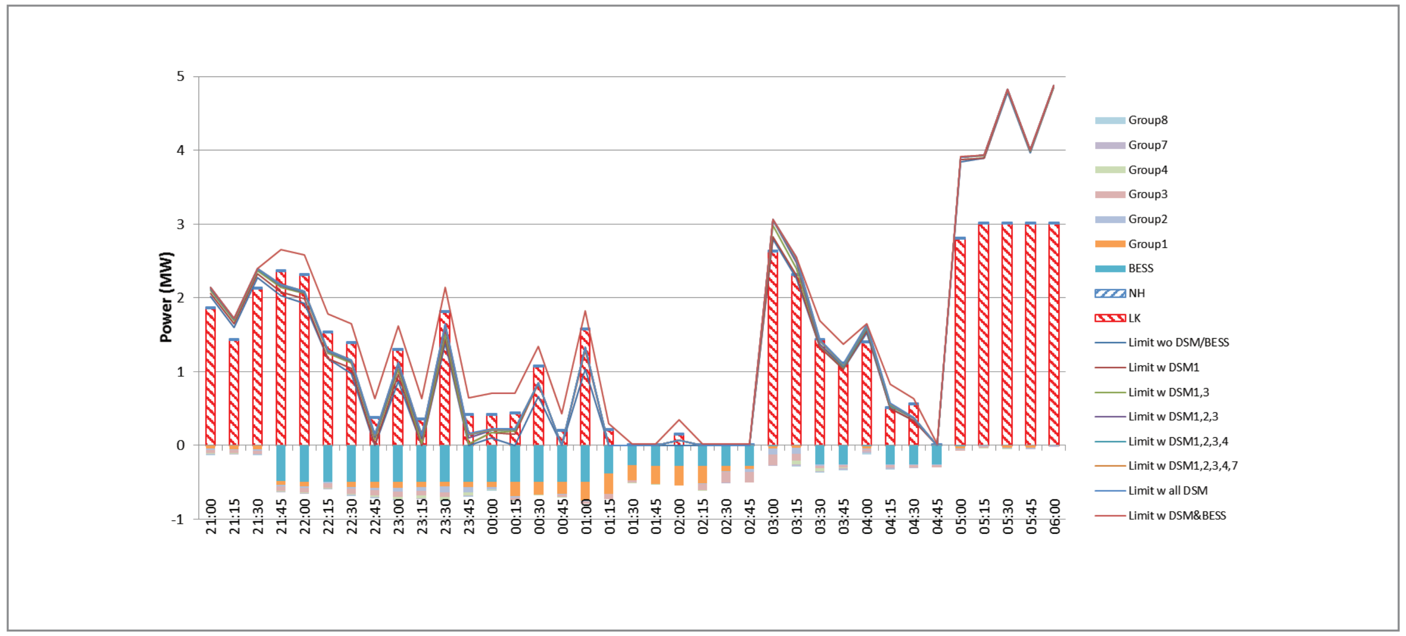

Figure 10: Contribution of DDSM on the increase in the limit on ACG exports for the period from 21:00 on 6/12/2016 to 06:00 on 7/12/2016

It is important to note that for a number of reasons outside of SSEN control, the planned volume of flexible demand was significantly reduced to:

- 234 DDSM Homes
- 3MWh BESS

In addition, the large thermal store planned for district heating was not integrated into the ANM system,. However, the reduction in availability of flexible demand resources did not trigger updates or alterations to NINES ANM system.

While the reduction in the volumes of available flexible demand had an impact on the bounds of the network support services, the reduction in the DDSM volumes had not directly impacted the total additional capacity of renewable generation accommodated on Shetland via the NINES Project.

5.1 ANM system calculated schedule for DDSM

5.1.1 Impact of DDSM Operation on ACG connection

The ANM schedules for Domestic Demand Side Management (DDSM) are calculated based on the forecasts of generation outputs. Where ANM Controlled Generation (ACG) is forecast to be constrained, the groups of DSM devices are allocated in order of DER (highest to lowest) to alleviate the curtailment. Any remaining energy to be allocated is achieved in the next step of the algorithm (fill troughs).

Initially, only DDSM groups 1 and 2 were providing flexible demand. Beyond 26th September 2016, DDSM groups 3, 4, 7, and 8 were moved from their fixed schedules which replicated their previous tariff schedules to flexible demand schedules. The contribution of all DDSM groups and BESS to increase the limit of AGC exports over the period from 21:00 on 6/12/2016 to 06:00 on 7/12/2016 is shown in Figure 11. Note that the order in which DDSM groups are applied to alleviate ACG curtailment is the following: Group 1, Group 3, Group 2, Group 4, Group 7 and Group 8, followed by the BESS. For the same data Figure 12 provides a detailed DDSM and BESS order for the particular instant at time (at 23:00 on 6/12/2016).

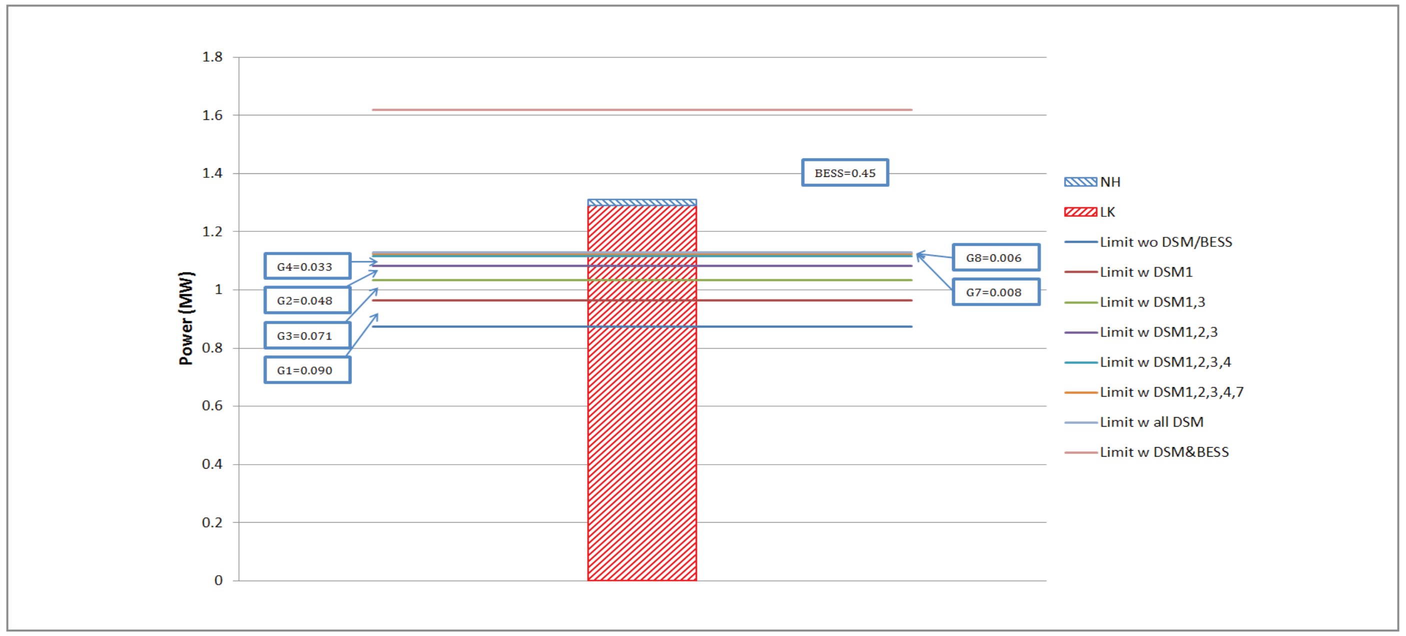

Figure 11: ACG Curtailment alleviated by DDSM and BESS at 23:00 on 6/12/2016

The increase in the real-time constraint limit on ACG was equal to the charge rate of the controllable demand under the present set of constraint rules.

Over the period from 2nd February 2016 to 31st January 2017, during which North Hoo and Luggie's Knowe were connected on the network, the reduction in ACG curtailment provided by each flexible demand is evaluated to be around 77MWh. Reduction of curtailment (in MWh) provided by each of the DDSM flexible groups is shown in Figure 13 for the total amount in 2016/17, while Figure 14 shows this given as a daily average for the same period. The reduction of ACG curtailment and the total DER for each flexible group will be compared later in Figure 16.

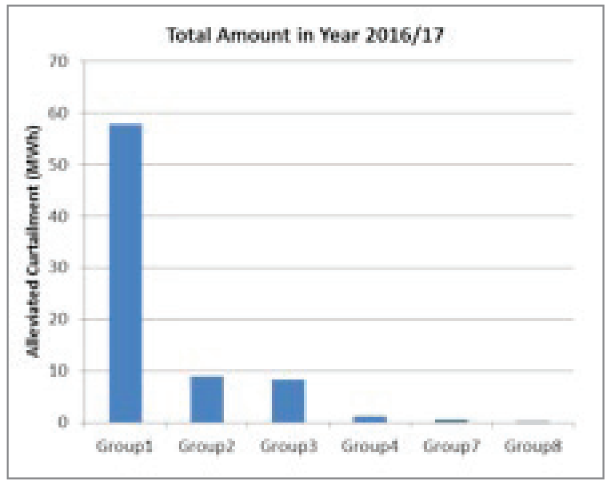

Figure 12: ACG curtailment (MWh) alleviated by each DDSM group in the year 2016/17

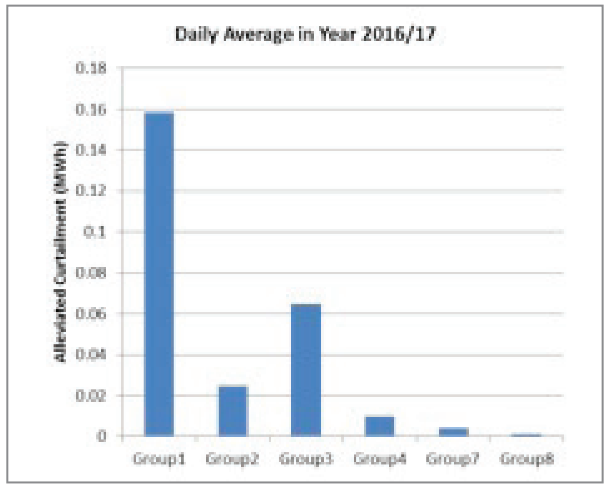

Figure 13: Daily average ACG curtailment (MWh) alleviated by each DDSM Group in the year 2016/17

Reduction of curtailment (in MWh) provided by each of the DDSM flexible groups per month is shown in Figure 15 for the total amount for 2016/17, while in Figure 16 this is shown as a daily average for the same period.

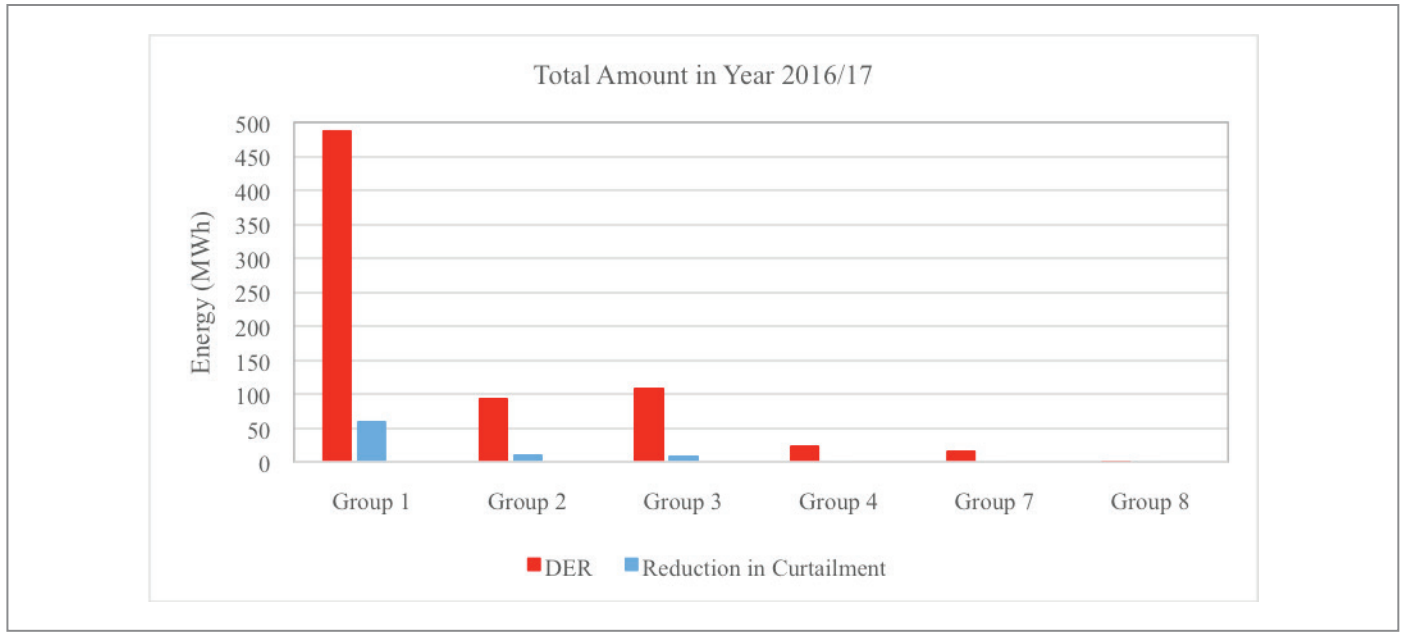

Figure 14: Total amount (MWh) of reduced curtailment provided by each group in each month

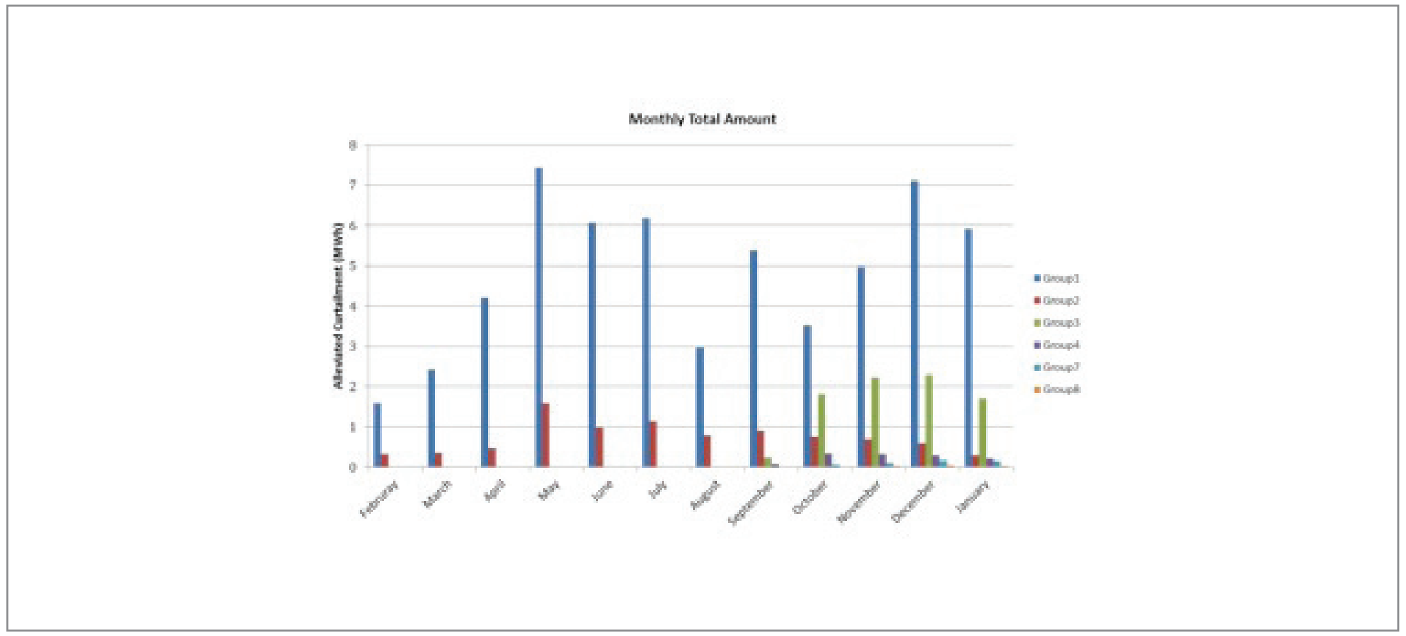

Figure 15: Daily average amount (MWh) of reduced curtailment provided by each group in each month

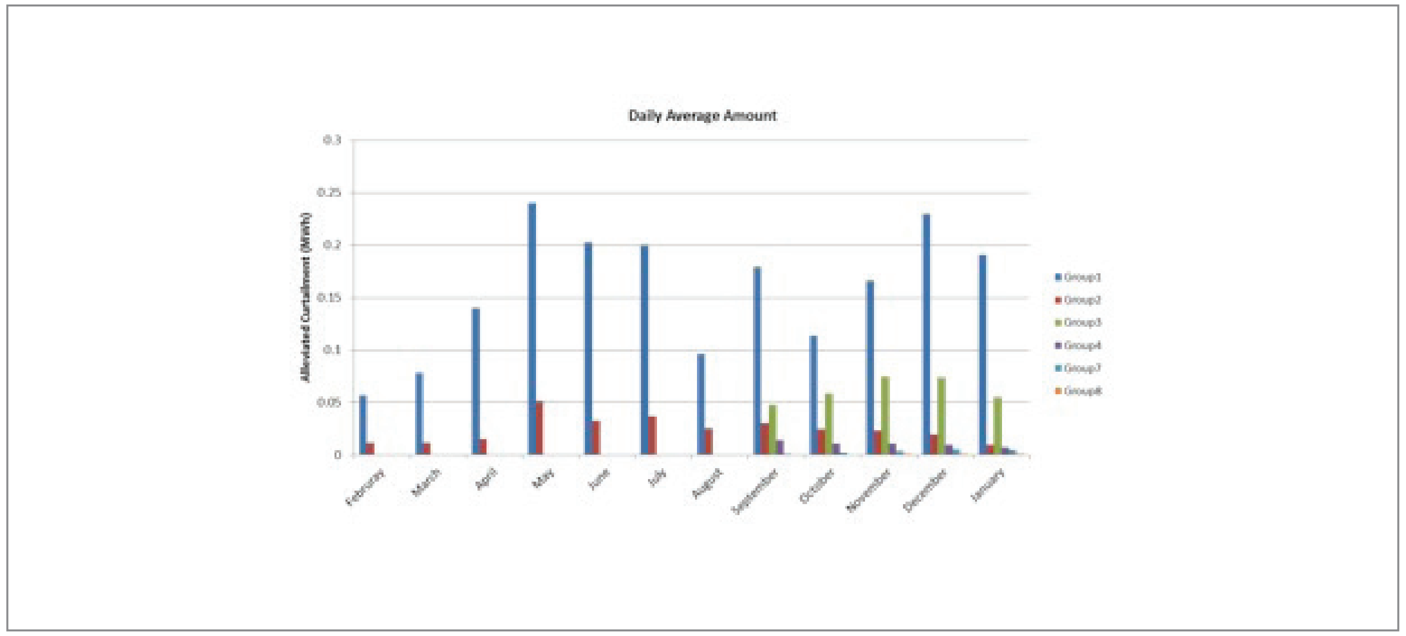

Figure 16: Comparison between total annual amount of DER and reduction in ACG curtailment for each group in the year 2016/17

Figure 17 compares the total annual volumes of DER and reduction in ACG curtailment for each flexible DDSM group in the year 2016/17. The annual DER of all DDSM groups totalled approximately 0.73GWh during the period under review, around 10.6% of which was from the ACG export which would otherwise be curtailed. Approximately 11.9% of total annual DER of Group 1 was from additional ACG export. This was higher than that for other groups due to that Group 1 usually had a larger DER and was the first group applied to alleviating ACG curtailment.

The primary objective of scheduling flexible DDSM groups is to alleviate ACG curtailment. It has been evaluated that 10.6% of total annual DER of DDSM groups was from additional ACG export which would otherwise be curtailed. In SGS Balance, DDSM groups were scheduled to absorb energy when the ACG was forecast to be curtailed. The unavoidable forecast errors of available power of renewable generation and uncontrollable demand could result in the limited controllable demand being allocated at the wrong times in real-time operation. In addition, the relatively small percentage of total reduction in curtailment against annual DER may be in part due to SGS Balance using a constant value for SVT export as described in section 3.1. The constant SVT export could not reflect actual system operation which may therefore lead to an incorrect calculation of the forecast constraints on ACG export. However, the DDSM could not be controlled in real time to charge in response to curtailment of renewable generation like the battery does. The day-ahead scheduling of DDSM groups should be improved in the further development of the NINES ANM system, e.g. using data of previous days demand to schedule the operation of flexible DDSM groups.

In addition, utilisation of the BESS should contribute to the reduction of curtailment. However, in the examined period, and as discussed in the Battery Operational Effectiveness report[5], there was an issue when the battery was scheduled by ANM, which lead to switching to manual scheduling where the battery was mainly used to reduce a peak demand. Although manual scheduling of the BESS could target only peak/off-peak operation, reduction in the renewable generation curtailment has still been achieved. It is expected that implementation of new scheduling algorithm will significantly remedy this issue so that BESS can help reduce curtailment of renewable generators.

As mentioned above, over the period of around 12 months (from 2nd February 2016 to 31st January 2017), alleviation of the curtailment was in the range of 77MWh.

5.1.2 Load levelling by DDSM

The second role of the flexible DDSM groups was to smooth the demand curve through using the remaining DER to fill demand troughs. As shown in Figure 18, the flexible DDSM groups were usually scheduled by the ANM to absorb energy during the night where system demand was at a low level. This would help increase the level of system demand during the off-peaks, smoothing the demand curve. Figure 18 shows the average measured charge rate of each flexible DDSM group per day, which was approximately half of the scheduled charge rate during the night. This may be because due to a variety of reasons, some of which by their nature we are unable to confirm around 60% of devices in each flexible DDSM group provided feedback on average. More information on this can be found in *NINES DDSM Infrastructure Report*[6].

The non-firm ACG was more likely to be curtailed at the times of low demand. Though the controllable demand might be allocated at the wrong times to alleviate ACG curtailment due to the forecast accuracy and the use of constant SVT export, these controllable demands would contribute to load levelling even if the 'wrong' times were determined as the moments of low system demand.

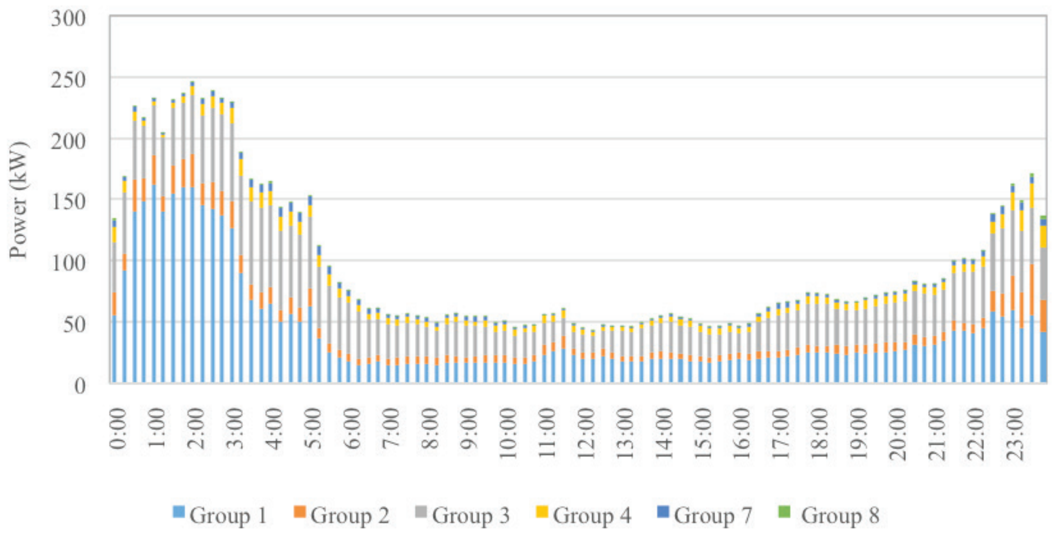

Figure 17: Average scheduled import (kW) of each flexible DDSM group per day over the year 2016/17.

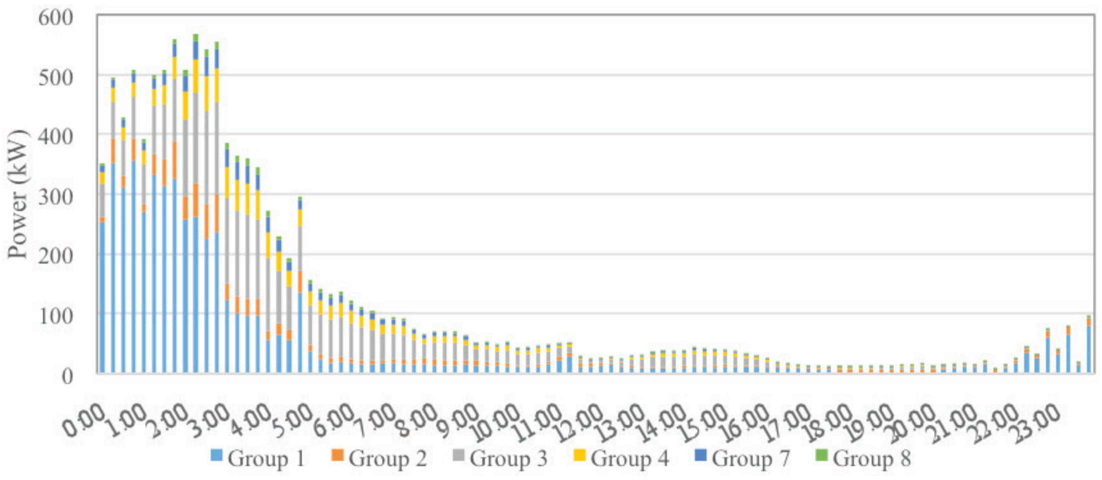

Figure 18: Average measured import (kW) of each flexible DDSM group per day over the year 2016/17

6

Configuration and Interface

6. Configuration and Interface

Scottish & Southern Electricity Networks

Complementing the functional requirements directly associated with the real-time management of constraints and scheduling of controlled devices, requirements were specified relating to the user interface and configuration features of the ANM system. The user interface must provide the capability for SSEN engineers to observe, intervene and re-configure elements of the ANM system and its actions.

A requirement was specified that the ANM Operations Team, consisting of SSEN engineers, could send manual control signals to ANM controlled devices. These signals will either:

- Synchronise date or time;
- Specify active set-points; or
- Specify device operational settings, such as frequency response characteristics for responsive loads.

In terms of the calculation of schedules, the operators must have visibility of the schedules, with the capability to define the resolution of schedule updates. This includes operator visibility of forecasts with the capability to update forecasts manually, allowing user experience to inform the forecasting process. The operator must be able to apply a manual reference schedule, or specify when the reference schedule is applied to devices.

Any manual schedule is not necessarily derived with reference to the limitations of devices and constraints. As a result, all manual schedule alterations must be validated by the ANM system to ensure that device constraints and energy requirements are met, and that all network and system stability constraints are met. If a manual operator intervention results in significant deviation from the active schedule, the ANM system must re-calculate new schedules for all devices.

The ANM system is also required to store all forecasts, schedules, active set-points, ANM system status, and configuration data in the PI Shetland historian. This allows for the review of specific ANM control decisions and analysis of long-term trends.

7

Conclusions and Next Steps

7. Conclusions and Next Steps

The Shetland ANM system represented a significant step forward in the development of ANM systems. Building on the success and experience of the Orkney ANM system, the Shetland ANM managed both Generation and Demand sources for the first time, while maintaining system stability on a closed electrical system.

A fundamental requirement of the ANM system was to effectively schedule ANM devices to smooth the demand curve. The requirements for scheduling were based upon two elements: the frequent day-ahead forecasting of network behaviour, and the ongoing calculation and issue of schedules to ANM devices.

The objective of the ANM-calculated schedules is to improve network performance and this must be performed within the constraints of both the network and controlled devices. For example, DSM must deliver a daily energy requirement to customers to meet a basic heating need, and the battery is limited by the energy storage capacity, power rating and round-trip efficiency. ANM must take account of the capability of all ANM controlled devices when calculating schedules.

Integration of DSM into ANM allows the network operator to balance demand with intermittent generation by controlling the charging of smart domestic space heaters and hot water tanks. The heaters can be switched on and off at varying power levels according to a target schedule transmitted from the network control centre; they also estimate their next day's energy requirement and transmit this back to the centre for next day scheduling. This is the first operational smart grid in the UK using this technology.

The ANM calculated BESS schedules were employed over four months from February to May 2015 to schedule the battery to lop peaks and fill troughs in the demand curve, and to alleviate the constraints on non-firm intermittent generation. From June 2015 the BESS was manually scheduled to discharge at peak times and charge at times of low demand. Manual intervention was required due to issues with the ANM calculated schedules which resulted in an unsatisfactory utilisation of the battery (47.2% evaluated exclusive of outages). Based on outputs of the BESS in the first full year, the manual schedules were evaluated and found to achieve a higher utilisation of the battery (86.1%) than the ANM calculated schedules.

In addition, the user interface was improved and adapted to provide the capability for SSEN engineers to observe, intervene and re-configure elements of the ANM system, schedule and actions. This included operator visibility of forecasts with the capability to update forecasts manually, allowing user experience to inform the forecasting process. Also, the interface enabled SSEN engineers to send manual control signals to ANM controlled devices. These signals include: synchronisation of date or time; specifying active set-points; and specifying device operational settings, such as frequency response characteristics for responsive loads.

Therefore, the NINES project has provided a significant amount of learning to those that operate the Shetland electrical system on a daily basis. SSEN, with support from the developers of the ANM system SGS, distilled the experience gained from the operation and evaluation phase of the project to develop a list of enhancements in order to provide further benefit from its ongoing operation beyond the end of the NINES project and into the business as usual life of the system. The main outcomes of this work were in the following areas:

- Understanding inherent limitations in day ahead scheduling prompting a revision of the optimization algorithm.
- Understanding the value of real-time control and the ability to schedule controllable demands via existing control functionality.
- Updated requirements for the ANM User Interface.
- Building a level of confidence in the ANM platform to deliver further ANM systems under BAU.

It is anticipated that the upgrade to the existing ANM system will be completed in 2017. Following the introduction of these enhancements, the NINES ANM will operate in a more effective way providing even more benefit to the connected assets than have already been provided via the NINES Project and will allow the NINES ANM to more easily meet the potential requirements following the completion of the current Shetland competitive process.

Appendix 1

Acronyms and Footnotes

ACG	Controlled Generation
ANM	Active Network Management
BESS	Battery Energy Storage System
CMZ	Constrained Managed Zones
CTRs	Constraint Rules
DDSM	Domestic Demand Side Management
DGs	Distributed Generators
DNO	Distribution Network Operator
(D)DSM	(domestic) Demand Side Management
ERDF	European Regional Development Fund
FAI	Fraser of Allander Institute
HHA	Hjaltland Housing Association
HVAC	Heating, Ventilating, and Air-Conditioning
LIC	Local Interface Controller
LIFO	Last In First Off
LO	Learning Outcomes
LPS	Lerwick Power Station
NINES	Northern Isles New Energy Solution
PCS	Power Conversion System
RPZ	Registered Power Zone
SGS	Smarter Grid Solutions
SSEN	Scottish and Southern Electricity Networks
SOC	State of Charge
SVT	Sullom Voe Terminal
TGO	Total Generation Output
UoS	University of Strathclyde
VRLA	Valve-Regulated Lead-Acid

1	**https://www.ninessmartgrid.co.uk/**	**5**
2	**https://www.ssepd.co.uk/ShetlandEnergy/**	**5**
3	Project Report: USM 1b – Report on Proposal of Rules for the NINES Shetland Active Network Management scheme: Stability and Scheduling Rules, November 2012, University of Strathclyde	**16**
4	A detailed breakdown of the NINES connected flexible distributed generators (ACGs) can be found in project report: 6A NINES Commercial Arrangements & Economics Report, 2017, University of Strathclyde	**16**
5	Project report, NINES Battery: operational effectiveness report, 2017, University of Strathclyde	**25**
6	Project Report, NINES DDSM: Infrastructure report, 2017, University of Strathclyde	**32**

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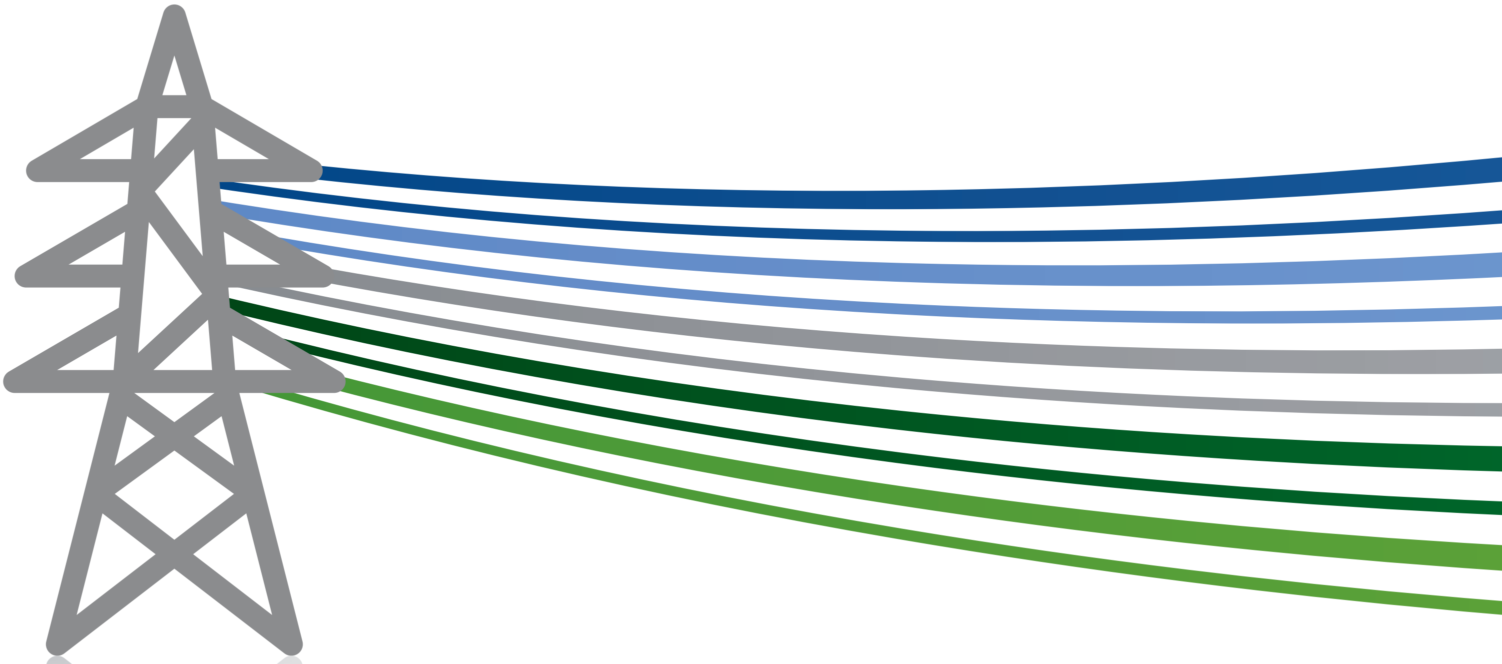

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