A MULTI-OBJECTIVE ASSESSMENT OF THE FUTURE POTENTIAL OF THE SHETLAND ISLES ACTIVE NETWORK MANAGEMENT SCHEME

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ABSTRACT

The Active Network Management (ANM) scheme to be employed on Shetland is a key component of the Northern Isles New Energy Solutions (NINES) concept. The NINES project integrates energy storage, Domestic Demand Side Management (DDSM) and renewable generation onto an islanded grid. Previous work has presented the design of the ANM scheme to manage the various components within constraints and to maintain system stability. This paper focuses on defining the future potential of Shetland's ANM scheme to improve network access for onshore wind generation and reduce the island's reliance on fossil fuel generation. A Multi-Objective System Development Optimisation (MOSDO) model has been developed to carry out this study. The model creates future system configurations with varying penetrations and locations of DDSM, energy storage and onshore wind generation. The most desirable system configurations, according to a multi-objective analysis, are investigated to identify the potential operational and economic impacts of the ANM scheme and the individual components.

INTRODUCTION

Shetland, located off the north coast of the United Kingdom (UK), has a high onshore wind resource. Burradale onshore wind farm – currently the islands only significant renewable generator – is able to achieve an annual capacity factor of around 49%; nearly double the average of mainland UK (26% for 2012 [1]). This wind resource needs to be fully harnessed to reduce the islands reliance on fossil fuel generation. The Northern Isles New Energy Solutions (NINES) project will allow more wind generation onto Shetland's islanded network through the use of an Active Network Management (ANM) scheme, launched by the network owner and operator; Scottish and Southern Energy Power Distribution (SSEPD). This ANM scheme will direct multiple components including flexible frequency responsive demand, through Domestic Demand Side Management (DDSM); new renewable generation; and energy storage through lead acid batteries. Currently a lead acid battery, capable of storing 3MWh of electrical energy, is to be installed at the diesel fuelled Lerwick Power Station (LPS) – the islands main power plant – as part of the NINES project. Depending upon the success of the battery for facilitating additional renewable generation connection and for improving the management of network voltage constraints, increased energy storage at new locations could be a possibility.

For the proposed DDSM scheme, the Hjaltland Housing Association (HHA) is committed to providing 234 domestic homes for the installation of new controllable storage heaters and hot water tanks. SSEPD's future goal is to extend this rollout beyond the social housing market, with a plan to recruit a further 500 privately owned homes. Whereas the locations of the HHA homes have now been defined, the locations of the rollout to private homes are unknown. If DDSM proves successful in increasing renewable penetration on the island and provides a competitive option for domestic heating, further rollout of storage heating could be likely.

As future system developments in DDSM, energy storage and renewable generation are unclear in Shetland, a model has been developed to analyse a pre-defined search space of these developments. The Multi-Objective System Development Optimisation (MOSDO) model explores varying penetrations and locations of these ANM components creating many system configurations, before using a Genetic Algorithm (GA) to determine the most desirable configurations for the following conflicting objectives:

- Minimise conventional energy usage (GWh)
- Reduce conventional generation peak output (MW)
- Maximise onshore wind energy usage (GWh)
- Maximise capacity factor of lowest priority wind farm (priority based on Last-In-First-Out order)
- Minimise network line losses (GWh)

This paper presents the model and analyses the outcomes of the multi-objective analysis to identify the future operational and economic impacts of the ANM components (specifically DDSM and energy storage), and the overall ANM scheme in reducing the reliance on LPS and improving network access for onshore wind generation. This will be of interest to other network operators who are planning to implement similar schemes. Further, as LPS is coming to the end of its operating life, this paper goes on to investigate whether the ANM scheme can have an effect on reducing the required size of a replacement power station.

THE MOSDO MODEL

Previous work presented the design of the ANM scheme, including rule formats and ANM parameters to manage the various components that are to be connected [2]. Power system dynamic simulations were carried out to determine system stability rules, defining constraints due to frequency, network operation and spinning reserve. The format and parameters of these rules are flexible enough to allow the analysis of a wide range of potential future system developments.

A Unit Scheduling (US) model was utilized to inform the design of the ANM scheme scheduling engine. The US model finds the optimal schedule across a 24-hour period for flexible demand and energy storage to minimize renewable generation curtailment and the variability of conventional generation output [2]. The US model accounts for network constraints and inter-temporal constraints (applied to each flexible demand group and energy storage unit) on a 15-minute time step through the use of the Dynamic Optimal Power Flow (DOPF) concept [3]. The network stability rules for Shetland are included in the US model as linear constraints on the combinational output of conventional and renewable generators [4].

The MOSDO model has been designed to wrap around the US model, producing the required inputs for each generated system configuration and using the outputted optimal 24-hour schedules of all generation units and flexible devices on the network to evaluate the model objectives. Inputs to the US model include: the network (with thermal and voltage constraints); forecast profiles (day-ahead 15-minute time step) of fixed demand, flexible demand and renewable generation; network stability rules (for both frequency stability and network operation [2]) and device characteristics.

The MOSDO model generates diverse good quality system development solutions using an advanced GA known as the Strength Pareto Evolutionary Algorithm 2 (SPEA2). The SPEA2 has been found to outperform a number of state-of-the-art multi-objective algorithms [5] and has been used in multiple power system problems [6], [7]. The SPEA2 method involves population evolution (using the survival of the fittest hypothesis) through many generations until a final set of unique non-dominated solutions is obtained for the multi-objective problem. In multi-objective problems, the concept of "dominance" is used to determine if one solution is better than another. A solution x is said to dominate a solution y if x is no worse than y in all objectives and x is better than y in at least one objective. The SPEA2 procedure, with a maximum generation limit T, is carried out as follows:

Step 1: **Initialization:** Generate an initial population of system development solutions P_t, and create an empty external archive A_t of size N. Set generation count t to zero.

Step 2: **Fitness assignment:** Calculate fitness (using the operator in [5]) of each solution in P_t for the multi-objective problem.

Step 3: **Environmental selection:** Copy non-dominated solutions of P_t and A_t to A_{t+1}. If size of A_{t+1} exceeds N then reduce A_{t+1} using the truncation operator [5]. If size of A_{t+1} is less than N then fill A_{t+1} with the fittest dominated solutions in P_t and A_t.

Step 4: **Termination:** If $t \geq T$ then the final solution is the non-dominated set $A_F = A_{t+1}$. Stop SPEA2 process.

Step 5: **Mating Selection:** Fill mating pool through performing binary tournament selection on A_{t+1}.

Step 6: **Variation:** Create the new population P_{t+1} by applying crossover and mutation operators to the mating pool. Increment generation counter $(t = t + 1)$ and go to Step 2.

The SPEA2 creates a new population of solutions by swapping genes of fit solutions (called "parents"), paired together in the mating pool, to create new individuals (called "offspring"). This is achieved in Step 6 using the crossover operator. For this study an example of a gene is the quantity of renewable generation at a particular network location. Each parent is split at multiple points using a crossover mask which has been created using a uniform probability distribution. Figure 1 shows an example of this process. Quantity in this context refers to either the MW capacity for onshore wind generation, the number of homes in each flexible demand group for DDSM, or the number of batteries connected. The mutation operator is applied to the offspring after crossover. Here the mutation of a gene involves assigning a random value within the search space region for location (i.e. network bus) and penetration of the type of gene. The MOSDO model has been designed to ensure that the system development solutions that result from the crossover and mutation operator adhere to the user defined search space created for each gene type.

Due to the computational effort required for the iterative nature of the SPEA2 process, annual fixed demand is estimated by creating demand blocks (of demand level and time) to fit, as accurately as possible, the Load Duration Curve (LDC) for winter and summer. For each

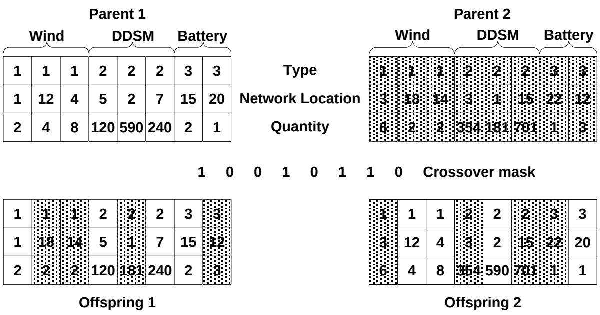

Figure 1: An illustration of the method employed for this case study to carry out the uniform crossover operator.

demand block, a representative 24-hour 15-minute time step profile is obtained from an annual fixed demand profile. To estimate annual onshore wind generation, a mean 24-hour 15-minute time step profile is used from a full year profile. The US model also requires a day-ahead 15-minute profile for underlying heat demand for each flexible demand group. This is obtained by scaling up a seasonal per-household profile of total domestic demand (i.e. both water and heat). The MOSDO model assesses the objectives for each system configuration by sequentially running the US model for each demand block under the onshore wind profile. The annual objectives chosen for the analysis are then derived from these simulations, taking into account the varying demand block time lengths.

Following the SPEA2 process, the model runs a full year, full time-series simulation of each non-dominated system development solution. Hence here the US model is run sequentially for each 96-value profile of the annual demand and onshore wind profile used. This is to take into account changes in energy output from onshore wind and conventional generation that may result, on an annual basis, from the network stability rules. The model outputs the solutions and objective results from both the SPEA2 process and the full year analysis that follows for comparison.

THE SHETLAND CASE STUDY

The MOSDO model is applied here to Shetland's islanded 33kV network. A total wind power capacity of 17.8MW is assumed to be connected as a base case. This includes 3.68MW of non-curtailable wind at Burradale. Excluding Burradale, all onshore wind farms are assumed to be curtailable and provide reactive power support to the network. The annual normalised output profile of Burradale wind farm is currently used as a basis for all output profiles of onshore wind. For fixed demand, a normalised profile of Shetland's electrical demand during the year 2011 is used and scaled up to represent the level of demand expected in 2025 – the chosen year for this future case study – creating an annual profile that has a peak of 61.55MW and a total energy requirement of 278.82GWh. To estimate the annual profile for the SPEA2 process, 10 demand blocks for winter and summer were used to fit the LDC for 2025.

For flexible demand, the per-household day-ahead profiles used estimate weekday and weekend behaviour in both the winter and summer seasons. These profiles are detailed in Figure 2. Currently domestic heat and water demand for the majority of Shetland's homes (amounting to 38MW) is provided through storage heaters using a teleswitching scheme. The teleswitching schedule remains constant throughout the year and brings a basic level of control to domestic demand. The new frequency responsive storage heaters will replace these heaters and be controlled through a new schedule

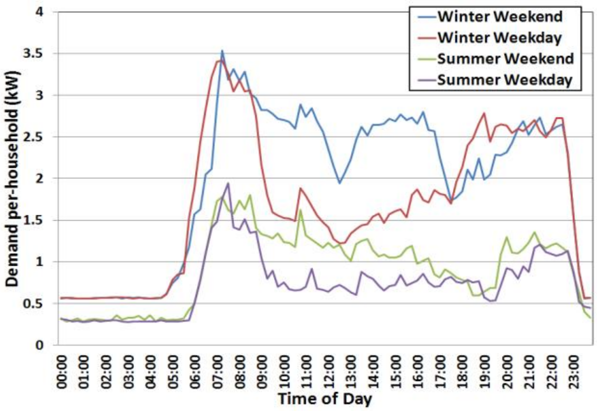

Figure 2: Per-household storage heater demand for water and space heating. For a winter weekend, winter weekday, summer weekend and summer weekday the total demand is estimated to be 47.48kWh, 40.92kWh, 22.06kWh and 17.49kWh respectively.

from the ANM scheme. As each system development solution created by the MOSDO model will involve a different number of households connecting to the ANM scheme from the teleswitch format, the MOSDO model adjusts the energy delivered by teleswitching so that the total energy demand (fixed plus flexible) across a particular day is the same for all solutions. This ensures that analysis into the effect of DDSM on Shetland's system is restricted only to a change in scheduling.

For each flexible demand group within the DDSM scheme of the solution, the energy storage potential of space heating is derived using the characteristics detailed in Table 1. These were obtained from detailed thermodynamic modelling of the Shetland housing stock. The average heating capacities were calculated based on the type, location and number of heaters used for each household. During the summer season a reduction of 57.43% in overall DDSM space heating capacity is assumed to account for users switching off their boilers. A maximum daily charging time of 8.5 hours is assumed for space heaters to match the off-peak electricity tariff of the current teleswitch scheme. For water heating, the energy storage potential was derived using the assumption that all water tanks have a capacity of 2.625kW and can be charged daily for up to 5.75 hours (again to match the teleswitch scheme).

The search space of the MOSDO model is defined as follows:

- New onshore wind – 0MW to 30MW capacity with each unit sized at 2MW. Eleven possible locations in Shetland's 26 node network.
- Overall DDSM scheme size – 0 to 2000 homes.

Table 1: Housing type distribution and average household heating capacities of a flexible demand group.

	Bedsit	1 Bed	2 Bed	3 Bed	4 Bed	5 Bed
% of Type	2.2	32.8	35.4	27.5	2.0	0.1
Capacity (kW)	4.41	4.69	6.17	7.63	8.55	7.16

Twelve possible locations for sighting a flexible demand group. Geographical penetration is constrained by a nodal household limit determined from the 2001 Scottish census.

- Lead acid battery addition – 0 to 5 batteries each rated at 1MW, 3MWh, with a round trip efficiency of 75% (determined from [8]). Same location possibilities as with onshore wind.

THE ASSESSED FUTURE IMPACT OF SHETLAND'S ANM SCHEME

The multi-objective results of the non-dominated solutions generated by the MOSDO model, for the year 2025, are detailed in Figure 3. It is clear that the effect of the required network stability rules on restricting renewable generation is more significant when analysed across the whole year. The average contribution of conventional generation (i.e. LPS) as a percentage of total generation, across all solutions, increases from 55% to 59.5% when assessed across a whole year as opposed to using the LDC estimation (an average fall of 14GWh in renewable energy usage is also experienced). Further, the peak output of LPS, when simulating across the whole year, struggles to fall below 55MW in contrast with a peak output of 42.5MW achieved from the LDC estimation. This highlights the importance of carrying out the full year analysis and taking into account the network stability rules. The following conclusions are derived from the full year simulations.

To encourage connection, Shetland's network needs to accommodate new onshore wind generation and ensure that a capacity factor of at least 26% can be achieved. For the year 2025, when adding 6MW additional wind capacity (to the 17.8MW of the base case) the capacity factor of the lowest priority (LP) wind farm falls below this lower limit. From analysing the solutions, the capacity factor of the lowest priority 2MW wind farm varies from 23.2% to 32.97%. This is due partly to small changes in annual network line losses (through varying locations of wind and DDSM), but mainly due to the increasing penetration of DDSM; from 144 households to 1400 in this case. Hence as a result of this increase in flexible demand, at least an extra 2MW of new wind generation can be accommodated by the network. In general when curtailment becomes significant (around 17% in this instance) an increment of 500 homes to the ANM scheme can achieve an increase in capacity factor of 3% for the lowest priority wind farm. Further to this is a potential increase in annual renewable output of 2.16GWh and a resulting decrease of 2.22GWh in annual LPS output (the difference between the two is due to reduced electrical network losses). If the replacement power station is to be fuelled by natural gas then this decrease in output could result in an annual fuel cost saving of around £149k; a lifetime saving for SSEPD of nearly £4million (assuming a constant fuel price).

Adding battery energy storage to the system can also affect wind generation. From analysing the solutions the

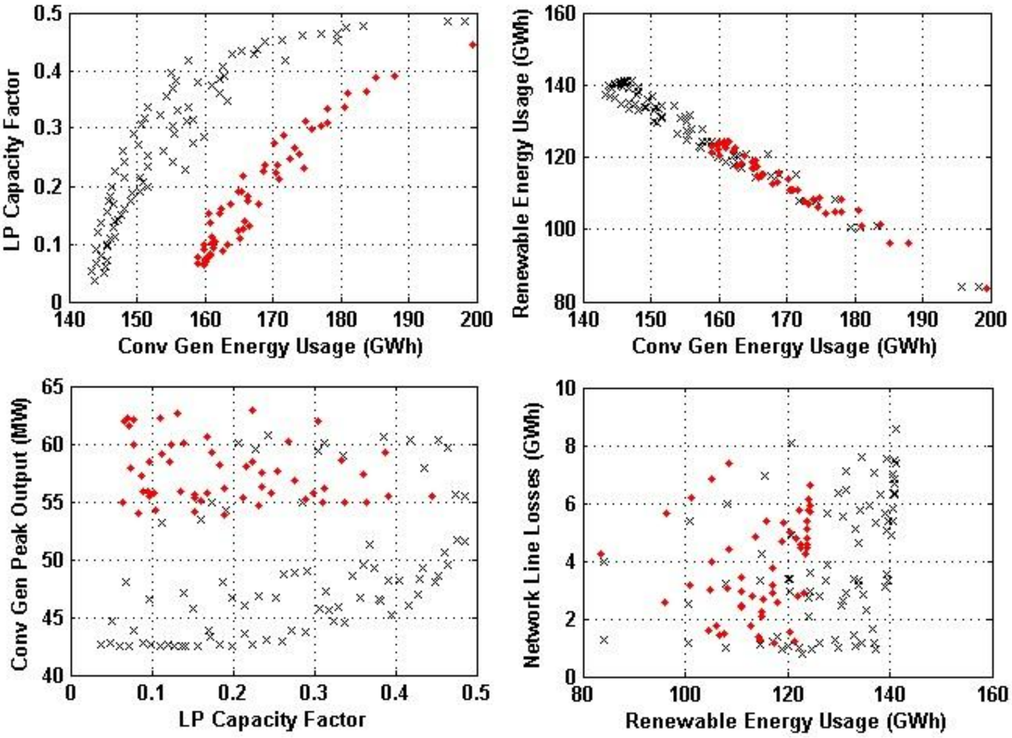

Figure 1: Key multi-objective results of the MOSDO model. Results from the SPEA2 LDC analysis and annual simulations are marked with a black cross and red dot respectively. The SPEA2 solutions were generated after 300 generations with a population size of 120 and archive size of 80. A crossover and mutation rate of 0.9 and 0.02 was used.

largest improvement in annual renewable energy generation, achieved purely by the addition of energy storage, was found to be 1.15GWh from the addition of 5 1MW batteries; nearly half the effect of adding 500 homes to the DDSM scheme. However, the impact of additional energy storage is more significant on the peak requirement of LPS. Wind generation cannot realistically reduce peak demand as there is always the possibility that there will be a lack of wind at any given time. Hence the new power station will have to be sized solely for future predictions in peak demand (including backup units for security).

However, energy storage, having been charged previously, can ensure a reduced peak energy requirement from conventional generation. It is found that the peak output requirement of the replacement power station at Lerwick could be reduced by 2.6MW as a result of energy storage alone. This solution includes 22MW capacity of wind generation and two batteries; one of which is located at Lerwick, providing needed voltage support to the area. Neither battery had an average depth of discharge (DoD) that exceeded 47% under this solution; hence each battery would have a life span that exceeds 1000 cycles – the minimum lifespan (at 70% DoD) of a lead acid battery according to [8]. Despite this demonstrating that the per-battery effect of energy storage for peak demand reduction can be greater than the capacity of the battery itself, the capital expenditure (CAPEX) of a lead acid battery is currently too high to justify replacing conventional generation. For a single duel fuel full duty generating unit, of 9MW size, with heat recovery and emission abatement equipment (the likely unit to be used in the replacement power station), the CAPEX is estimated to be equivalent to three 1MW batteries, which, according to the simulations, can only achieve a potential peak demand reduction of around 3.9MW. However, energy storage can still allow for extra demand on Shetland without the need to add another unit to the LPS replacement for supply security.

Overall in 2025, without DDSM and energy storage the potential output requirement of the LPS replacement is in the range 173.5GWh – 200GWh (renewable energy usage from 107.9GWh – 80.4GWh) with a peak of around 57MW, for 30 – 2MW of additional wind generation to the base case. With the use of DDSM and energy storage, the potential output requirement of the LPS replacement is in the range 159GWh – 199.4GWh (renewable energy usage from 124.3GWh – 83.6GWh) with a peak that falls to 53.8MW, for the search space region analysed. Hence, with the use of DDSM and energy storage in the ANM scheme, a maximum reduction (at the highest renewable penetration) of 14.5GWh in the annual requirement of conventional generation can be achieved. This could result in a potential annual fuel cost saving of £971.5k for the LPS replacement and a lifetime fuel cost saving to SSEPD of around £24million (again assuming a constant fuel price), if the replacement is to be fuelled by natural gas.

CONCLUSION

Before investing in an ANM scheme for a system, the benefits of the managed individual components, and therefore the overall scheme itself, need to be identified. This is a challenging problem in an uncertain future. This paper presents a model to define the potential effects of DDSM, battery energy storage and an ANM scheme itself on the energy usage of conventional and renewable generation, when constrained by system stability rules. When applied to Shetland's system under estimated 2025 demand levels, the model results indicate potentially good financial savings in fuel costs to SSEPD from the application of DDSM through the ANM scheme. Whereas the effect of battery energy storage in reducing fuel costs appears less significant, it still has the potential, according to the model results, to reduce the peak output of conventional generation beyond the total storage capacity; securely allowing extra demand onto the system. However, currently the CAPEX of a battery is too high to justify replacing a duel fuel full duty conventional generating unit of equal size on Shetland, despite the improved peak demand reduction able to be achieved when directed by the ANM scheme.

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