COMPETING OBJECTIVES IN DOMESTIC DEMAND SIDE MANAGEMENT: LERANING FROM THE NORTHERN ISLES NEW ENERGY SOLUTIONS PROJECT

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ABSTRACT

Implementing the smart grid requires coordinating competing objectives and constraints from multiple engineering domains. This paper explores the challenges involved in scheduling flexible demand according to objectives in two: the power system and household heat domains. The context is the Northern Isles New Energy Solutions project on the Shetland Islands, UK, where Active Network Management is being used to schedule flexible electric storage and immersion heaters. The study highlights that simplifications and assumptions in both domains must be coordinated to understand the overall effectiveness of a scheme. In the case study, customer facing objectives such as home comfort levels are prioritised over the power system objective of reducing fossil fuel generation. Power system operation aggregates houses into a small number of groups to allow practical scheduling. Modelling results show that this prioritisation and aggregation achieves a reduction in fossil fuel generation of 0.71GWh; 65% of that achieved if customer facing objectives are not prioritised.

INTRODUCTION

The Northern Isles New Energy Solutions project (NINES) involves the roll out of a number of innovative grid management technologies on the Shetland Island distribution network in the UK. The objective is to reduce the reliance on fossil fuel generated electricity on Shetland. This will be achieved by the use of Active Network Management (ANM) to manage new wind connections, the use of battery energy storage and demand flexibility.

The power system on Shetland is electrically isolated and wind generation capacity has been severally limited due to grid stability issues, despite the fact that the only significant wind farm operates with an annual capacity factor that can exceed 0.5. The ANM scheme will allow new wind generation to connect, but will curtail that new capacity when required to maintain stability. A number of papers are available that review NINES and describe its limitations [1, 2].

A major flexible demand component of NINES is Domestic Demand Side Management (DDSM) which will allow central management of smart electric storage heaters and hot water tanks in domestic properties. The devices are currently being installed in an initial estate of 250 homes after a trial in 6 properties; DDSM is expected to further expand in the future.

The infrastructure required to implement DDSM includes the heaters themselves, a Local Interface Controller (LIC) in each house, an element manger which interfaces between the houses and the power-system wide ANM scheme. The ANM scheme includes a module to produce schedules for groups of DDSM devices based on forecasts of demand and wind generation over the coming 24 hours. The structure of DDSM is shown in figure 1.

DDSM provides a number of benefits to the power system: it can shift demand for electricity to periods with wind curtailment, therefore reducing that curtailment; secondly DDSM devices can act in frequency responsive mode to support the stability of the system in respect to frequency. Through these two processes it can reduce curtailment for a particular capacity of ANM controlled wind generation and can raise the level of wind capacity that is likely to be economically viable.

The effectiveness of schedules at meeting the power-system objectives can be reduced by two key factors: errors in the forecasts which feed the scheduling algorithm; and the prioritisation of customer comfort over power system benefit.

The first of these – forecast error – has been studied in a previous paper [3] that suggests that errors in wind forecasts can lead to a loss of 40% of the benefit achieved with a perfect forecast. The second issue – that of competing objectives for DDSM, is the focus of this paper.

OBJECTIVES FOR DOMESTIC DEMAND SIDE MANAGEMENT ON SHETLAND

The DDSM devices operate under a series of prioritized objectives, these are designed to ensure that customer comfort levels are maintained and that customers do not unknowingly use excess energy from handing over charging control. Under the current architecture these customer facing objectives take priority over the power system objectives of reducing reliance on fossil fuel generation. To understand the benefit that can be achieve from such a system requires that power-system and household modelling is combined.

The link between DDSM and ANM is managed by grouping houses together. If houses are grouped on a locational basis, power-system models can schedule aggregate group demand at particular power system busses. However, the diversity of house types and occupational patterns within a group means that a 'group profile' will not fit each house perfectly. The storage capacity in DDSM devices provides buffering between the individual heat-demand profiles and the power-system optimal schedule, but in cases where customer facing objectives require a divergence, DDSM devices will over-ride the power-system optimal schedule.

Ensuring that customer-facing objectives are prioritized is achieved by setting a number of conditions which must be met before the heater follows the schedule. Important conditions used in DDSM devices are, in order of priority:

1. If heater is at its maximum state of charge: no further charge;
2. if maximum daily energy requirement has been reached: no further charge for the rest of the day;
3. if minimum state of charge is reached: charge at full capacity;
4. else follow power-system optimal Schedule.

The first of these ensures the core-temperatures of devices do not exceed safe levels, the second manages the total electrical energy used and the third ensures that some heat is available to meet comfort levels.

METHODOLOGY

To investigate the effect of competing priorities on the power system objectives, this paper makes use of two models: (I) a Dynamic Optimal Power Flow (DOPF) [4] to produce schedules optimised for the power-system

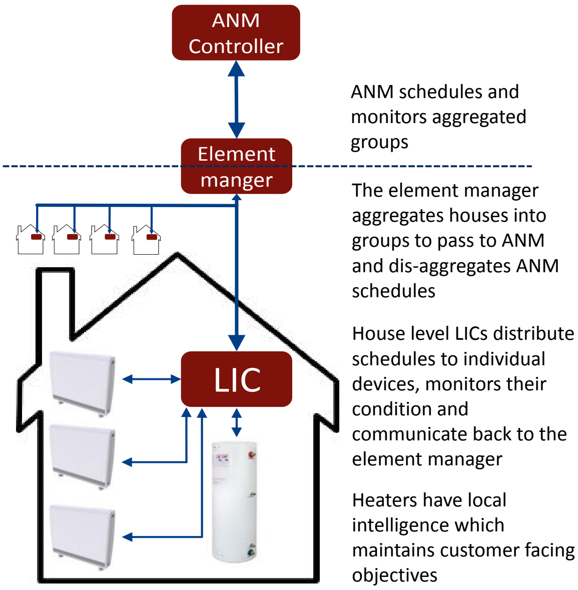

Figure 1: Schematic of the interacting control and communications levels within the DDSM scheme.

wide objectives of minimising fossil-fuel generated electricity; and (II) a finite-volume based thermodynamic model (ESP-r) of houses to simulate the heat transfer process within individual heaters and dwellings [5]. DOPF is an extension of Optimal Power Flow to cover multiple time-steps and model the intertemporal linkages created by flexible demand.

The modelling procedure makes use of historical time-series data for wind generation on Shetland, historical fixed electrical demand profiles, typical meteorological, structural and behavioural data to inform the thermodynamic simulations. The modelling procedure is as follows:

1. ESP-r simulations of representative houses taking account of variations in: house construction, occupancy patterns and comfort levels, to create time-series of underlying demand for heat in the full DDSM estate at 15 minutes resolution.
2. The underlying 96-point heat-demand profile for each day is modelled from a power system perspective using DOPF which includes full network characteristics and available wind generation time-series for that day. The DOPF objective is to minimise conventional generation. A solution includes the optimised schedule of delivery of energy to DDSM groups throughout the day making use of the heat-storage capacity to buffer this delivery of energy from the underlying demand for heat. This schedule is the 'power-system optimal' solution.
3. The power-system optimal schedules are disaggregated and applied to representative houses

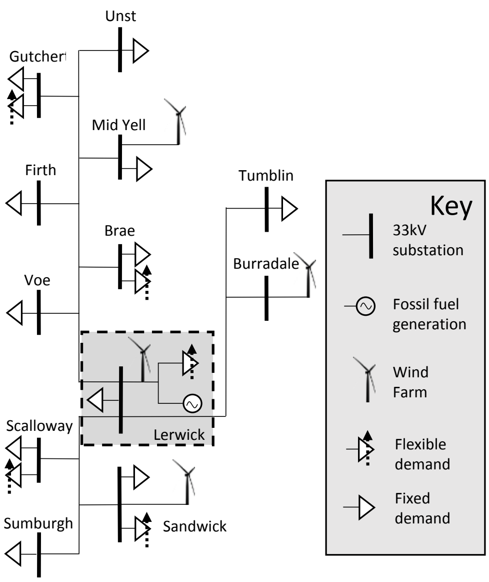

Figure 2: Electrical diagram of the Shetland power system showing locations of DDSM enables houses and generation.

Table 1:Locations of DDSM enabled houses.

LOCATION	NO OF HOUSES
Lerwick	1190
Scalloway	180
Sandwick	105
Brae	200
Gutcher	75

Table 2: Location of Firm and Non-Firm (NF) wind in the case study. Non-firm wind is connected with LIFO principle of access and the priority of each non-firm wind farm is given.

LOCATION	CAPACITY (MW)	CONNECTION TYPE / PRIORITY
Burradale	4	Firm
Lerwick	7.6	NF: Priority 1
Mid Yell	4.7	NF: Priority 2
Sandwick	2.7	NF: Priority 3

in ESP-r. The difference between the shape of an individual house demand for heat and that of the group leads to divergence from the group schedule so as to maintain customer facing objectives. The actual electricity drawn by the heater is then re-aggregated back to group level.

4. Finally, the actual demand for each DDSM group as calculated in step 3 is fed back into the power system model and a standard OPF is carried out for each 15 minute time-step.

Steps 2 – 4 are carried out separately for each day within the simulation period and results are summed. The differences between the results of steps 2 and 4 represent the loss of power-system optimality caused by the group aggregation process and prioritisation of customer facing objectives over power systems objectives.

CASE STUDY

As part of the modelling for the NINES project a wide range of scenarios have been simulated to cover multiple possible futures for Shetland. This study presents one such scenario which is specifically designed to highlight the issues related to DDSM priorities. The case study components are as follows:

- The existing Shetland power system (Figure 2) ;
- fossil fuel generation from Lerwick Power Station (LPS);
- firm wind generation connected at Burradale to represent the existing wind capacity on Shetland;
- 1750 DDSM enabled houses split between four locations around Shetland with the number of houses at each reflecting the size of the local population (Table 1); and
- three ANM controlled wind farms (NF1 – 3) located at Lerwick, Mid-Yell and Sandwick. These are curtailed according to a Last In First Off (LIFO) principle of access with Lerwick given highest priority, Mid-Yell has medium priority and Sandwick has lowest priority (Table 2).

Historical time-series of demand and wind generation for the period 1st January – 31st December 2010 are used with 6 days removed due to data errors. The results presented here therefore represent 359 days covering all seasons. Numerical results are summed across the simulation period, and an illustrative set for the first 7 days of April are displayed in Figure 3.

RESULTS

To allow the effect of optimal and achieved schedules to be benchmarked, a base-case study is run at the power system level with no DDSM enabled houses and wind generation distributed as described in Table 2. In the base case, no demand flexibility is provided and wind generation is curtailed when required to maintain network stability limits. The base case energy generation from LPS and the three non-firm wind farms is shown in Table 3.

A detailed presentation of the thermodynamic modelling in Stage 1 is given in [6]. This gives the profile of underlying heat demand. The 1750 houses consume 11.9GWh over the year, and the profile during the first 7 days of April is shown in the dotted line of Figure 3. The storage component of DDSM devices allows this profile to be buffered from the delivery of electrical energy to the devices through the power system.

The key objective of the NINES project is to reduce

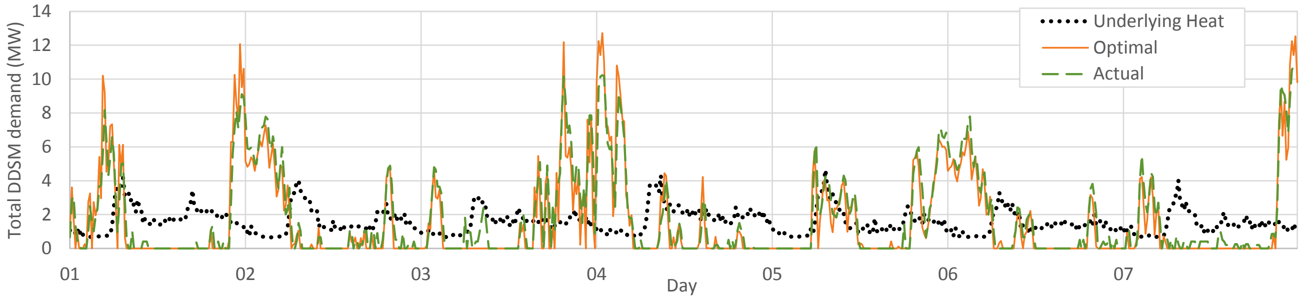

Figure 3: Underlying heat demand, optimal and actual draw of electricity for the total DDSM estate during the first 7 days of April.

Shetland's reliance on electricity from fossil fuel generation, represented in this study by the output of LPS. Stage 2 of the modelling process optimises the delivery of electricity to the DDSM estate based on the locational groups listed in Table 1. This means that for each day the DOPF model produces a schedule for delivery of electricity to each group based on that group's total power capacity, energy storage capacity and state of charge. The total power-system optimal schedule for DDSM is represented by the solid line in figure 3. The difference in LPS and wind generation between the base case and the case of DDSM following the power system optimal schedule is shown in Table 4.

Stage 3 disaggregates the group schedules delivered by the DOPF model and applies them to individual houses. The modelling also takes into account the customer focused objectives so it is possible to assess how closely individual houses are able to follow the group schedules. Results for a typical group containing three house types show that 83% of electrical energy delivered is in-line with the schedule, whilst the reaming 17% is taken outside the schedule. In addition, 14% of the optimal schedule is not drawn due to devices having reached a maximum level of charge.

Figure 4 shows the breakdown of schedule following for a group by time: 50% of the time the group operates in line with the schedule, the remainder the group deviates from the optimal schedule, although for many time-steps the deviations are small. The two main reasons for deviating are that the state of the charge within DDSM devices is at an extreme: either minimum or maximum states of charge have been reached; together these constraints account for a further 48% of time. The actual draw of electricity by DDSM is illustrated by the dashed line in Figure 3.

Table 3: Base case generation values for LPS and generation and curtailment at non-firm wind farms.

	(GWH)
LPS Generation	158
Wind Generation:	
NF1	27.9
NF2	14.6
NF3	5.84
Total	48.3
Wind Curtailment:	
NF1	0.27
NF2	2.81
NF3	4.17
Total	7.25

Finally the results of step 4 in the modelling process shows the effect of the actual DDSM charging on the power-system. The change in LPS and wind generation and curtailment compared with both the based case and the power-system optimal case is given in Table 4. The actual decrease in LPS generation is 0.71GWh or 65% of the optimal solution. The increase in wind generation is 0.72GWh or 69% of optimal showing that the actual schedule leads to an increase in electrical losses over the base case. The effect on individual wind farms differs depending on their LIFO priority number.

DISCUSSION

The implementation of DDSM creates an incremental improvement for the NINES project in terms of reducing fossil fuel generation and increasing wind generation. The results of the full modelling procedure suggests that LPS generation can be reduced by 0.71GWh compared with a base case of no flexible demand. This reduction in fossil fuel generation is achieved whilst prioritising

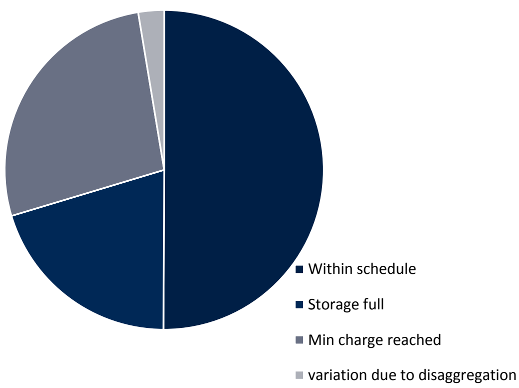

Figure 4: Breakdown of schedule-following for a representative DDSM group consisting of three house-types.

Table 4: Change in generation with 1750 DDSM enabled houses for the optimal (Step 2) and achieve (Step 4) draw of electricity by DDSM devices.

	Optimal (GWh)	Achieved (GWh)	Fraction of Optimal
LPS Generation decrease:	1.09	0.71	0.65
Wind Generation increase:			
NF1	0.17	0.09	0.52
NF2	0.45	0.34	0.76
NF3	0.44	0.30	0.69
Total	1.05	0.72	0.69

customer facing objectives. The power-system optimal schedule – the output of Stage 2 of the modelling process – would provide an even greater fossil fuel saving of 1.09GWh. However, achieving such a saving would require either greater complexity or a system in which it was accepted that customer facing objectives would not always be maintained. A more complex system is likely to be impractical to implement, and one in which customer facing objectives were not maintained is unlikely to be acceptable to customers, regulators or the industry as a whole. As the solutions being rolled out on NINES presents a balance between creating the greatest benefit in terms of overarching objectives, whilst at the same time protecting customers. The solution, and the trade-offs of complexity, priority and optimality may be improved in future iterations of the NINES solution.

The level of benefit that demand flexibility can provide is significant higher on small islanded power systems which rely on relatively expensive diesel generation. In this situation, every unit of fossil fuel generation displaced by wind generation leads to a significant financial benefit through fuel costs. In addition to the benefit discussed here created by the *flexibility* in demand. DDSM devices can act in a frequency responsive mode. On Shetland this benefit can support power system stability, a significant issue for islanded power systems. Connected to the UK grid it has the potential to allow aggregations of DDSM to provide frequency response service to the system operator

Both the roll out of DDSM on Shetland and the modelling presented here highlight the importance of considering the interaction of priorities, objectives and modelling methodologies for different domains. Here bottom-up house level thermodynamic modelling carried out by experts in mechanical engineering expertise is combined with top-down power system modelling using electrical engineering expertise. The two approaches need to interface effectively for the results to be useful; and when deployed the two systems must themselves interact effectively for the DDSM project to be a success. Modelling and deployment approaches in both domains make assumptions and simplifications regarding the other and an important learning point from is the need for clear communication and coordination between domains.

Aggregating demand across multiple houses allows the complexity of the ANM scheduling task to be reduced to a pragmatic level – only a small number of group schedules are needed. However the results show that the simplifications, inherent in disaggregating to the household level, lead to reductions in the effectiveness of DDSM in meeting its original objectives.

When designing and implementing energy projects across multiple domains (household, power system etc.) it is important that modelling and deployment in each domain takes appropriate account of other domains: trading off the simplifications and assumptions needed to produce feasible systems against loss of performance.

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