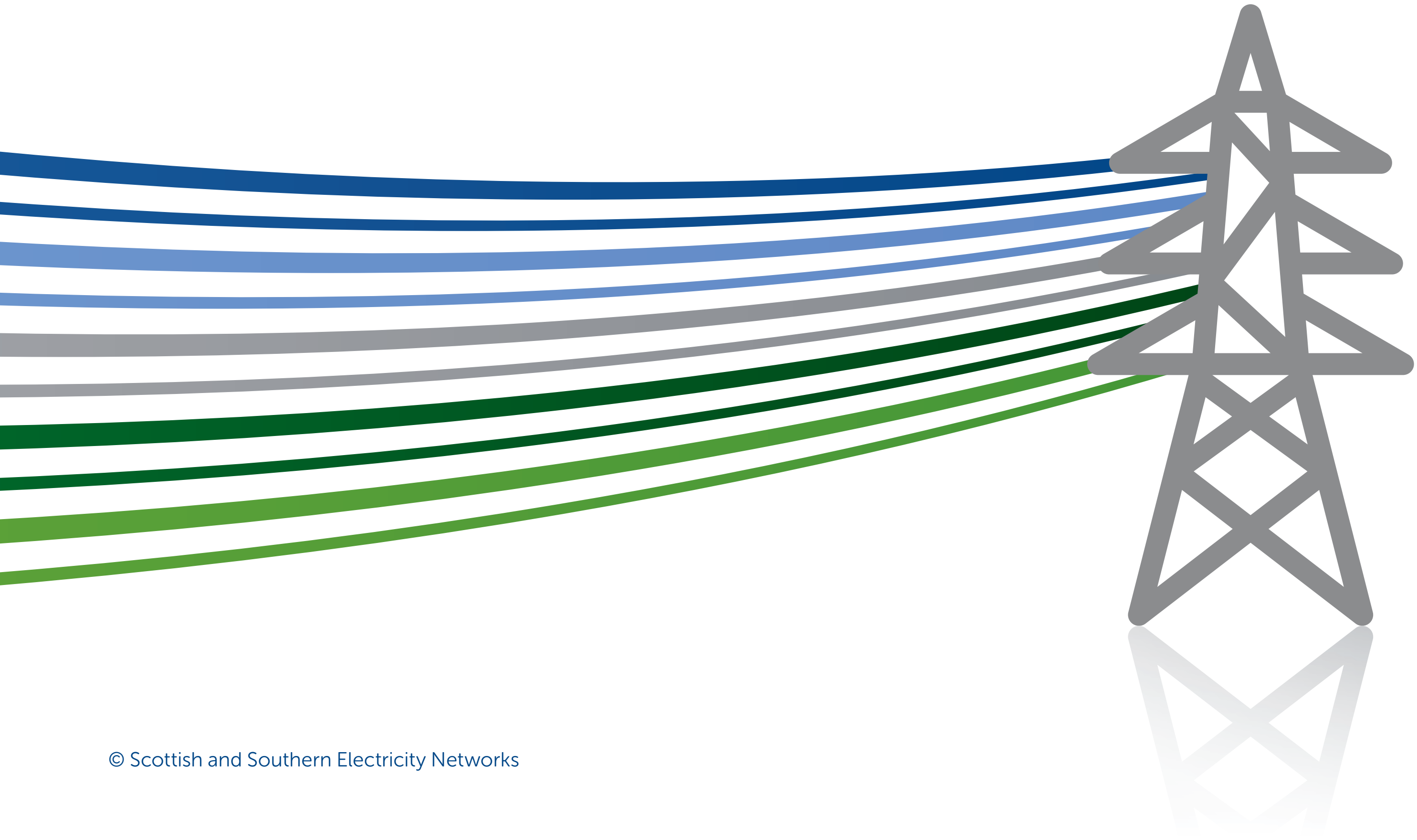
Scottish & Southern
Electricity Networks

University of
Strathclyde
Engineering

NINES

1C DSM Network Benefits Report



Prepared by

Document Owner	Project / Organisation Role
Joe Clarke	University of Strathclyde
Andrew Cowie	University of Strathclyde
Kati Svelha	University of Strathclyde
Raheal McGhee	University of Strathclyde
Stevie Adams	SSEN Senior Project Manager
Casey Bauchope	SSEN DSM Project Manager

Summary

A Demand Side Management system has been successfully implemented in Shetland within the SSEN NINES project. DSM 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 every 15 minutes, 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 devices are currently installed in 234 socially-owned houses, which together provide 1.6 MW of connected capacity. 199 houses with 1.44 MW are currently on flexible charging; the rest are on fixed schedules, either because customers are unwilling to share data or because they are on tariffs where a fixed time clock will not allow a 24 hour low rate supply. This report gives an overview of the impact of DSM on the Shetland network, and the issues that need to be resolved in order to deploy DSM at scale.

The conclusions are based on field data collected by the network from the heaters and hot water tanks themselves as well as aggregated data used by the network scheduling system. Independent monitoring of customer comfort (room temperatures and hot water consumption) in a representative sample of 35 homes was also available, and field data has been supplemented by modelling where appropriate.

Key learning outcomes:

- Moving houses to DSM from teleswitching reduced their maximum possible load at peak times by 0.5 MW as long as the devices follow the imposed schedule. This results from altering fixed schedule times as much as from flexible scheduling. However, unlike teleswitching, DSM heaters can charge outside schedule. As the current wind capacity is below the 14 MW threshold no fossil fuel has been displaced, but with 19 MW wind the current deployment could displace 385 MWh of fossil fuel each year

- Only around 50-60% of installed capacity was reliably available to the network on any given day because of poor communications with houses. A solution has been developed but this should be installed and tested well before any further DSM deployments. With only 50-60% of devices available the fossil fuel that could be displaced by wind reduces from 385 to 230 MWh.

- Peak loads were less than scheduled and a consistent 5% charging took place outside schedule. This is significantly better than the prototype trials: some devices will always become full or empty and stop or start charging at the wrong time because occupant behaviour cannot be predicted. Modelling indicates that out-of-schedule behaviour means that 30% more houses must be deployed for the same benefit.

- The ANM generally schedules flexible groups to charge between midnight and 5 am when other demand is low. This uses up the controllable storage so that little remains after midday.

- DSM has had little impact on control room operations but has caused a fundamental change in the network's relationship with customers as it provides heat and hot water rather than electricity.

- Future rollouts should target larger, hard to insulate houses to maximise the controllable capacity available to each set of DSM enabling equipment. Such houses will also have a longer heating season and heaters are less likely to be turned off in summer than in the current deployment. Heaters should be placed in living areas and halls where heating demand is high and controllable capacity is available more of the time.

- A number of functionality enhancements to the LIC and EM should be made to improve controllability and resolve some of the current problems. A real-time data analysis package should be added to EM to provide easy diagnostics for problems.

- Around 2,500 houses would need to be deployed with DSM to provide 15.8 MW of frequency responsive DSM reliably and support the optimal amount of wind generation. This represents a quarter of all the houses in Shetland, but is feasible.

- The maximum net value of each house to the DSM supply chain is slightly less than £200 per year, plus the value to the network operator of 1-5 kW of flexible load and up to 8.2 kW of frequency responsive load. The net cost of each house is £330-£380 per year in communications and support services. In order to be financially viable an order of magnitude reduction is needed in communications costs, together with subsidy payments.

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Introduction

1. Introduction

1.1 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 environmental obligations.

As part of the Integrated Plan submission, consideration was given to, amongst other things, the upgrading or replacement of Lerwick Power Station, 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 Lerwick Power Station by SSEN, taking into account the learning acquired during Phase 1 and, where appropriate, extending the Phase 1 technology.

1.2 NINES Elements

NINES was originally designed and developed to operate in conjunction, and integrated with, Lerwick Power Station 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 as part of, or alongside, the new energy solution. 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; and
- commercial model.

Facilitated by modelling and practical learning, the aims of NINES were 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. 1 MW battery at Lerwick Power Station
A 1 MW 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 a significant amount of new renewable generation that would otherwise not have been viable.

2. Domestic demand side management with frequency response
As part of the wider NINES benefits, Hjaltland Housing Association contracted with Glen Dimplex to install advanced storage heating and water heating in 234 existing homes. These appliances were provided through HHA and ERDF funding and have been specifically designed to use a more flexible electrical charging arrangement. This new charging arrangement is determined based upon the predicted demand, weather forecasts, availability of renewables and any network constraints. This initial roll out was intended to help gauge the

effectiveness of energy 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 better control of temperature and operating times when compared with conventional space 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 45 kW up to 4.5 MW. 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 issue, NINES has trialled an Active Network Management regime, which has offered new 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. Active Network Management (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 that are being 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 of 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 delivered by the University of Strathclyde research partner and focuses on the benefits of Demand Side Management (DSM) to the electricity network on Shetland.

The DSM element of NINES uses innovative smart heaters remotely controlled by an Active Network Management (ANM) system to store energy in homes during periods of excess electricity supply. Prototypes of these smart storage heaters and hot water tanks were developed by Glen Dimplex under the name 'Quantum', and were trialled in 6 houses in Lerwick from 2011 to 2013. Glen Dimplex incorporated lessons learned from the trial into the design of the production versions, which were installed between July 2013 and October 2014 in 234 electrically heated properties owned by the HHA.

This report gives an overview of how DSM has impacted the Shetland network and contributed to the benefits anticipated at the end of the prototype trials. Its scope is limited to DSM functionality alone; interaction with other components of NINES in network operations is covered elsewhere[1]. Other parallel reports cover the impact of DSM on customers[2], the infrastructure required[3], the operational effectiveness of DSM in frequency response mode[4], and the operational effectiveness of the Active Network Management system[5].

The report contributes to the following NINES learning objectives:

'How can a distribution system be securely operated with a high penetration of renewable generation?'

'What is the relationship between intermittent generation and responsive demand, including storage?

a) Effectiveness of frequency response demand side management
b) Maintaining network stability in an operational environment
c) Interaction of numerous variables on a closed electrical system'

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

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DSM concept overview

2. DSM concept overview

2.1 Background

As part of Phase 1 of the Integrated Plan for Shetland, submitted to Ofgem in 2011[6], SSEN were required to provide the infrastructure necessary to actively manage demand, generation, reactive compensation and energy storage assets, including water and space heaters, to store energy in the form of heat. Heater charging is controlled by the DNO using an Active Network management (ANM) system. The ANM system schedules generation from the wind farms, and uses a 1 MW battery as well as DSM to balance peaks and troughs in electricity demand and generation dynamically. The system is intended to allow more intermittent renewable generation to be connected to the network. Figure 2.1 shows the main components of NINES in Shetland.

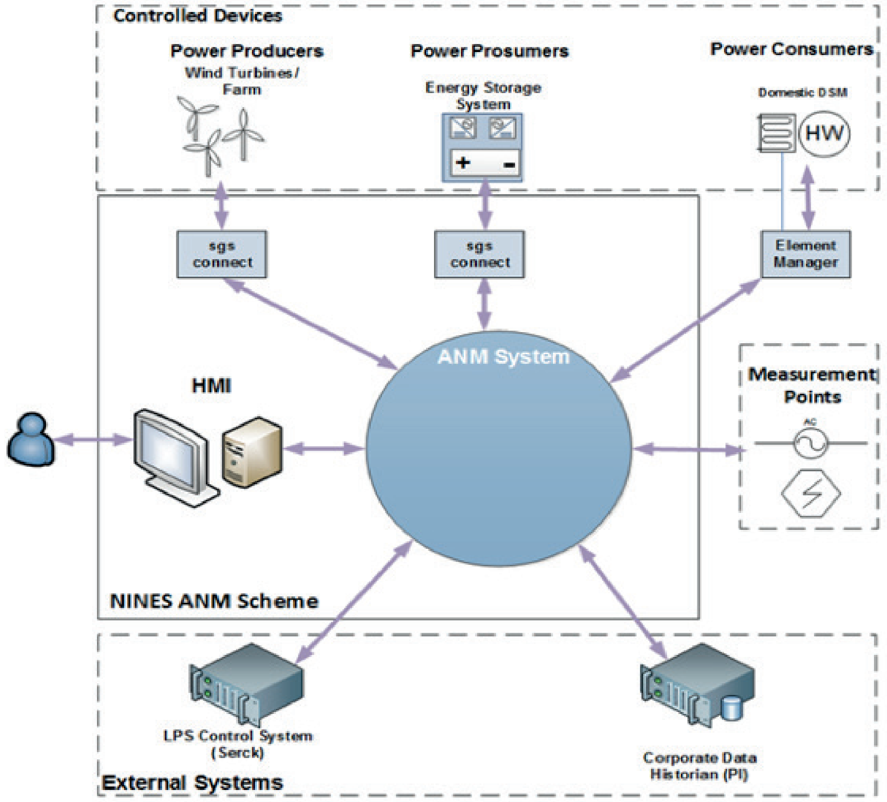


Figure 2.1 NINES ANM with DSM components and communications at top right.

At the end of the prototype trial it was concluded that every DSM house where the heating elements are fully charging allows an additional 2.37 kW of wind generation online as well as contributing to network stability[7].

Originally DSM was intended to operate at an industrial scale as well as domestic, through a 4MW/130 MWh hot water tank to be installed by the district heating provider, Shetland Heat, Energy and Power Ltd. (SHEAP). In early 2015 SHEAP advised SSEN they would no longer be taking part in NINES due to funding and commercial issues.

	2011 proposal to Ofgem	2013 plan	June 2016 live
Houses	750-1000	250	288
Appliances	–	922	708
Flexible power kW/house	15.0	8.2	7.2
Physical storage capacity kWh/house	–	46.8	42.4

Table 1 Evolution of SSEN's domestic DSM scope.

Included in the original NINES submission was the installation of DSM within 750 homes provided by HHA and Shetland Islands Council (SIC). However due to internal financial constraints, SIC announced in October 2012 that they would be withdrawing from the project leaving only the HHA dwellings (Table 2.1). To limit the impact of this change on the project, and provide new learning around domestic DSM, SSEN proposed to recruit private domestic customers to provide DSM and customer engagement events were held in 2014[8].

In April 2014 SSEN's initial Integrated Plan for a replacement power station was rejected by Ofgem in favour of a competitive process to identify a new energy solution for Shetland. This new obligation to invite tenders for network services of the kind offered by DSM caused SSEN to decide that it would be more appropriate to allow the market to take on the development of DSM to a larger scale, so the rollout to the private market was put on hold.

Production versions of the DSM equipment were installed in 234 houses owned by HHA by October 2014: this represents 2% of all homes in Shetland and 9% of social rented dwellings. Most of these houses are newer stock, and smaller properties than the typical Council home, demanding fewer heaters. In addition, only two-thirds of the NINES houses received new hot water tanks: the Quantum tanks were larger than those they replaced, and could not be installed in the constrained space available in some of the houses. A variety of issues led to the removal of the DSM equipment from 6 houses, and another 4 were disconnected although the kit is still installed within those homes. In June 2016, 228 DSM-enabled homes were operational, with a total power demand of 1.6 MW (Table 2.1).

SSEN introduced the flexible charging regime in March 2015, making Shetland the first operational smart grid in the UK that incorporates domestic DSM. The system started to operate in its final mode in early February 2016.

2.2 The DSM system

The Quantum heaters at the core of DSM were developed and are marketed by Glen Dimplex[9]. For NINES, Glen Dimplex developed customised device controllers: the devices in Shetland can accept instructions for altering input power every 15 minutes, and relay back status information to the centre. They also contribute to network stability, automatically shutting down charging when the network frequency drops below an acceptable, configurable level and increasing charging when the frequency rises.

The heaters are well insulated, allowing fan-assisted regulation of active output by a user-controlled temperature set point

(USP) within user-set heating hours. They contain three separate heating coils to allow them to be charged at varying power levels. They also incorporate a maximum temperature cut-off for safety and a minimum temperature switch-on to ensure occupant comfort. The hot water tanks have three heater coils of different sizes to allow variable level charging and were built specifically for NINES. The NINES-specific device controllers in both space and water heaters operate in the same way.

The device controllers employ an automatic charge control algorithm to predict the energy required for the next day (Daily Energy Requirement, DER), based on a number of factors. For space heaters these include the predicted outdoor temperature for the next day, user settings for room temperature, and heating hours. For hot water tanks, the DER is the average of the energy used in the previous three days. Embedded in the control rules is a requirement to prioritise customer comfort over the needs of the network in order to maximise customer satisfaction.

DSM-specific equipment supplied by HHA (the owner of the properties) consists of a transceiver on each heater and hot water tank, which communicates by RF with a Glen Dimplex Home Hub. The Hub in turn is connected serially to a Local Interface Controller (LIC) supplied by SSEN.

Figure 2.2 shows a logical view of DSM communications. The LIC collects status data from the devices and forwards it from the house to a central Element Manager (EM) via a Wide Area Network (WAN) supplied by Airwave Solutions. The EM can poll each LIC at configurable intervals, currently set to 4 times per hour. It aggregates the data into groups for ease of handling, before transmitting it on to the ANM system at Lerwick Power Station. The key data sent are the energy required for the next day (DER) as calculated by the device controllers at midnight GMT, plus the number of devices in communication within the group and their overall rated power and storage capacity.

These data are used by the ANM system to generate 15-minutely target schedules for all the controllable generators and controllable storage on the network. The system was designed to be capable of re-computing and re-transmitting schedules every 15 minutes if necessary, although for operational reasons currently this is done once a day just after midnight. The target schedule for each group is sent back to the EM together with a forecast for the outdoor temperature for the next day. EM passes this information down to the LICs; it also sends out heater configuration instructions, such as the minimum core temperature or frequency control parameters. The daily charging schedule for each group consists of a target power profile expressed as a percentage of the total power available at 15 minute intervals. This target power can vary continuously from 0 to 100%. The LIC translates the continuous profile into a set of instructions that each device is physically capable of following, with its individual fixed charging levels, at the same time as delivering the DER. Figure 2.3 illustrates how a group schedule works at an individual device level.

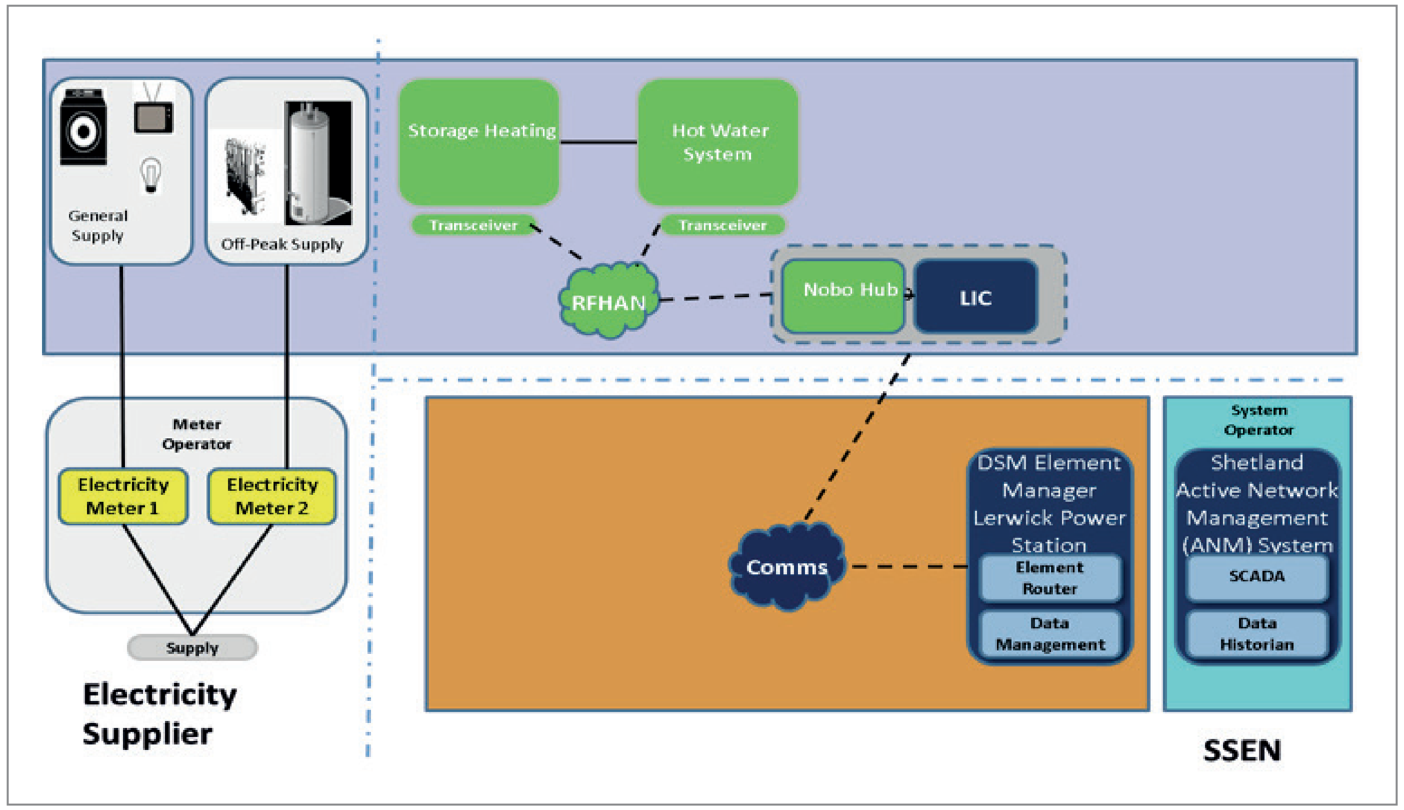


Figure 2.2 Logical view of DSM equipment and communications.

Each device is assigned to one of 18 groups, depending on:

- the type of device (space or water heater) as these have different demand profiles;
- the type of tariff, as customers were not asked to change commercial arrangements with their energy supplier;
- whether the customer's metering arrangement allows DSM to be operated – where a fixed time clock does not allow a 24-hour low-rate supply, DSM is set to allow charging at all times, and the actual charging is controlled by the time clock at full power as before;
- whether occupants are vulnerable – priority service customers and those on prepayment were initially put onto fixed timing DSM where the charging level could be varied but the times were fixed;
- whether the customers have opted out of allowing their devices to transmit status data, in which case the communications network cannot be used – these homes receive the same fixed-timing target schedule as the equivalent opted-in vulnerable group.

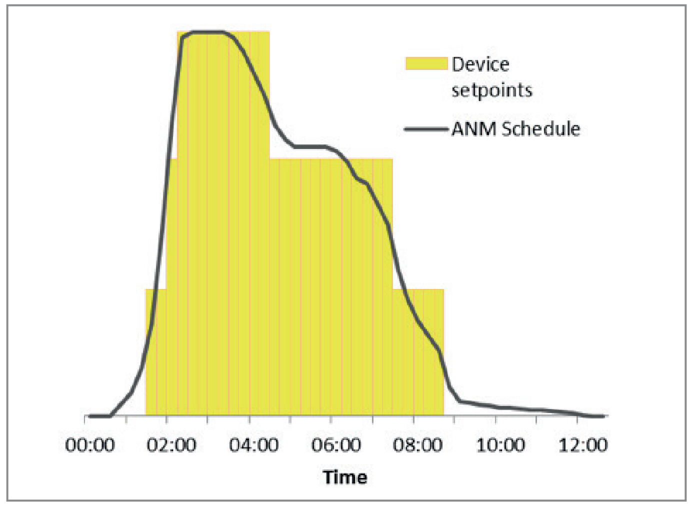


Figure 2.3 ANM generated schedule and its translation to device level.

At the completion of the NINES Project, 199 houses with 1.44 MW of controllable power were in groups with fully flexible charging; 88 of these houses (0.59 MW) are prepayment customers who were transferred to flexible charging at the end of September 2016 after research had shown that the change to flexible charging would not lead to the customer's credit being used at unexpected times. Only 24 houses (0.17 MW) are currently either opted out or have meters and tariffs that do not allow flexible charging.

2.3 Data collection

The system was designed to have no adverse impact on customer comfort or cost while giving the DNO flexibility to run the network in the most effective way. Throughout the project, close contact was maintained with customers via a dedicated Housing Officer at HHA, and associated with the NINES Project team within SSEN, who recorded customer queries, practical issues and conducted customer satisfaction surveys.

The performance of all devices could be monitored centrally from data from built-in sensors transmitted by the LIC. Device data collected by EM over an 18 week period from 15 February to 19 June 2016 was analysed, as was 12 weeks of group level data from 29 February to 22 May 2016. In addition, customer comfort was monitored independently in a sample of houses selected to be representative of the rollout estate: room temperatures were monitored in 35 houses and hot water consumption in 19, from the time the devices were installed until April 2016. The 8 million lines of data collected, with over 90 million individual data points, were analysed by the University of Strathclyde's Energy Systems Research Unit (ESRU). ESRU also carried out modelling studies to supplement the field data. Analysis did not cover the behaviour of devices in frequency response mode as the data collection frequency was too low to permit this: this topic is covered in the Frequency Response Operational Effectiveness Report[10].

3

Value proposition to the network - theoretical

3. Value proposition to the network - theoretical

This section examines the benefits envisaged from DSM at the end of the prototype trial, and the extent to which the scale of the rollout impacts these in theory.

The Shetland Islands are located 130 miles from northern Scotland, and are isolated from the mainland grid. With a population of 23,200, electricity demand varies between 11 and 47 MW. Although the islands have some of the best renewable energy resources in Europe – in wind, tidal and wave power – the ability to connect intermittent generation conventionally is restricted to less than 4 MW. The NINES project aim was stated as[11]:

"Implementation of the infrastructure necessary to actively manage demand, generation, reactive compensation and energy storage assets. These elements will be 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."

Figure 3.1 shows the NINES project components and the linkages with existing generation. Energy storage from 20 MW of flexible demand was envisaged in SSEN's original 2011 proposal to Ofgem[12], 15 MW of which was to come from domestic DSM. This was revised to a maximum of 8-9 MW in after early project studies[13].

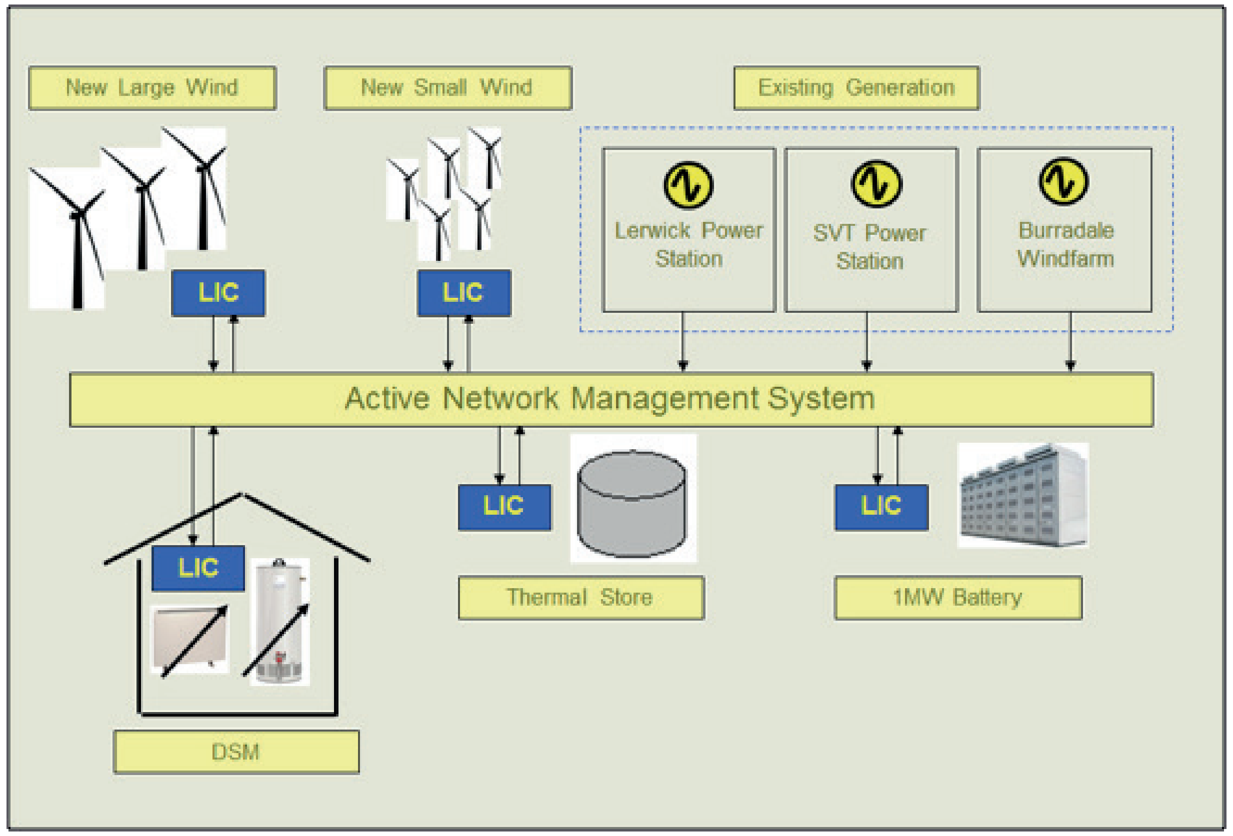


Figure 3.1 Overview of original NINES concept.

Simulations of network scheduling carried out by UoS during field trials of the prototype devices[14] concluded that, if the devices followed the schedules generated by ANM.

- A maximum peak load reduction of 2.0 kW per house could have been achieved in 2010/2011 if up to 1,500 houses had been on DSM, or 1.2 kW per house with more than 1,500 houses. The actual reduction available depended on the timing of the system peak relative to the timing of the removed teleswitching demand.
- With 19 MW installed wind capacity, every house with frequency responsive DSM could replace 2.4 MWh of fossil fuel based generation by wind power over a year. Without frequency response the value is reduced to 1.2 MWh. This holds up to 1,750 DSM houses.
- Each house with frequency responsive DSM would allow an additional 2.37 kW of wind generation online when the heaters are charging.

Field data from the prototype heaters and hot water tanks showed that the device controllers were overriding central instructions much of the time. Several factors affected schedule following, the most important of which was the rules built in to the heater controllers, which would over-ride central instructions. The heater control algorithm was modified significantly in the production versions of the Quantum devices[15], and the main cause of the problems – an algorithm which applied an adaptive cap to the maximum level of fill – designed out.

3.1 Installed controllable capacity

The ratio of controllable power to controllable storage is a measure of the effectiveness and therefore the value of energy storage to the network. The smaller this ratio, the greater the flexibility for storing excess generation.

The controllable power installed in the 223 live houses is 1.6 MW, and only 90% is currently in groups that can be charged flexibly. Not only is the number of houses smaller, but the capacity per house at 7.2 kW is less than envisaged. This is partly because only two-thirds of the houses received new hot water tanks, and partly because the HHA houses are among the smaller and better insulated properties in Shetland so they need less heating. For comparison, the SIC houses in the plan were also fairly small but older, and their planned space heating would have been approximately 1 kW/house higher than for the HHA houses.

The physical storage capacity of the heaters is less than the nominal capacity reported by the devices because the control algorithm defines 'empty' at a core or water temperature that is never allowed to be reached. This issue is described in detail in the DSM Infrastructure Report[17]. For space heaters this maximum real capacity is 95% of nominal value, while for water tanks the available capacity is further constrained and in effect the tank level can never fall below one-third full. Therefore the rules-based maximum ratio of controllable power to controllable storage is greater (worse) than the device could physically provide.

	Total installed	Space heating	Hot water[16]	Live flexible
Houses	223	223	151	199
Flexible power kW	7.2	5.4	1.8	7.3
Physical storage capacity kWh/hse	42.4	36.0	6.4	43.2
Rules constrained storage kWh/hse	41.3	36.0	5.4	40.3
Total flexible power MW	1.6	1.2	0.4	1.4
Physical storage capacity MWh	9.5	8.1	1.4	8.1
Rules constrained storage MWh	9.3	8.1	1.2	7.9
Apparent kW / kWh storage (phys)	0.17	0.15	0.28	0.17
Apparent kW / kWh storage (rules)	0.17	0.15	0.33	0.18

Table 3.1 Flexibly charging DSM capacity as of September 2016.

Within DSM, space heating is more effective because in theory it can offer 0.15 kW controllable power per kWh storage, while hot water is less so at 0.33 – when this value is higher it means there is less storage flexibility. This is the limiting case when the device is drawing full power and the store is empty according to the control rules. This maximum level of effectiveness is limited to days when the energy required (DER) is greater than or equal to the storage capacity.

For most devices and most days, the effective storage capacity available at midnight each day is the DER. As the heaters draw charge through the day, the storage fills up and the control effectiveness falls at a rate that depends on schedule timing. DER varies with temperature, day of week, and season, as well as with the random actions of occupants. The seasons also drive the number of storage heaters that are switched on and available; water tanks are less likely to be turned off. So the controllable capacity/controllable storage is a variable parameter, starts at a minimum level fixed by the DER at midnight, increases through the day as power is drawn, and approaches infinitely large as the remaining undelivered DER approaches zero.

3.2 Peak load reduction

Peak loading in Shetland occurs at three well defined periods in the day as depicted in Figure 3.2, and the highest peaks, when demand is over 40 MW, historically occur in January between 13:00-13:45 and 16:45-17.30[18].

Shetland has over 38 MW of restricted timing demand controlled by 14 different teleswitching schedules with fixed daily timing. The time periods are staggered to spread the load. However, one or more fixed schedule allows power to be drawn at every point in the day. Typically, all the devices on that schedule switch on at the same time and draw power until they are full, when they stop; so the teleswitching load for each schedule reduces over each time period. Although it is not possible to know how much is actually being drawn by teleswitching at any point, an envelope of the maximum load at each point through the day can be made based on the total capacity in each schedule provided by Lerwick Power Station[19].

The majority (77%) of the current DSM houses were on either Shetland specific Domestic Economy and Heating Load Tariff, or Total Heating, Total Control tariff, both of which allow a low rate supply at any time of the day defined by the System Operator. Using the same method of calculation as the earlier UoS study[20], the maximum load envelope of the 1.6 MW DSM houses in Table 3.2 shows that the DSM houses could have been drawing up to 1.4 MW at the beginning of the morning peak, but only 0.7 MW in the maximum peak times in January. These estimates are the theoretical maximum load that could occur if all the devices were charging at full power during the scheduled periods.

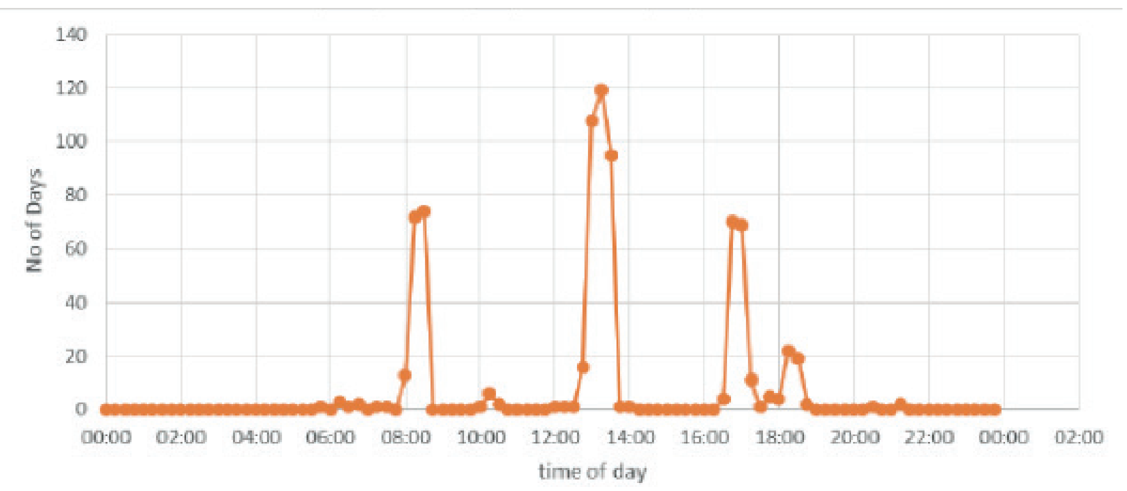


Figure 3.2 Timing of daily peak demand in Shetland, 2010-2011 (from USM05 Unit Scheduling Simulations Report, 2013).

	DSM houses		07.30	07.45	08.00	08.15	08.30	12.30	12.45	13.00	13.15	13.30	16.30	16.45	17.00	17.15	17.30	17.45	18.00	18.15	18.30	18.45
THTC H	MW	% total																				
THTC H	0.92	6%	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.0	0.0
THTC HW	0.31	6%	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Others	0.37	2%	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1
TOTAL			**1.4**	**1.2**	**1.0**	**1.0**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.6**	**0.8**	**0.7**	**0.7**	**0.7**	**0.5**	**0.6**	**0.6**	**0.6**	**0.1**	**0.1**

Table 3.2 Estimate of maximum load envelope during teleswitching from DSM houses before installation.

DSM houses			07.30	07.45	08.00	08.15	08.30	12.30	12.45	13.00	13.15	13.30	16.30	16.45	17.00	17.15	17.30	17.45	18.00	18.15	18.30	18.45
Live	Default	MW																				
3	1&3	0.50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	100%
4	2&4	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	100%
5	5	0.08	100%	100%	100%	100%	0	100%	100%	100%	100%	100%	100%	100%	100%	100%	0	0	0	0	0	0
6	6	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7–10	7–10	0.12	0	0	0	0	100%	0	0	0	0	0	0	0	0	0	0	0	0	0	100%	100%
11–14	11–14	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15–18	15–18	0.05	0	0	0	0	0	0	0	0	0	100%	0	0	0	0	0	0	0	0	0	0
TOTAL	**0.31**		**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.7**	**0.7**
kW bebefit per house			5.7	5.2	4.2	4.2	2.3	2.2	2.2	2.4	2.1	1.9	3.2	2.7	2.7	2.6	2.4	2.5	2.5	2.5	-2.6	-2.5

Table 3.3 Maximum load envelope from fixed timing DSM schedules.

The controllable devices are on charging patterns that vary from day to day, with the space heaters following one schedule and the water tanks a different one. The ANM scheduling algorithm should ensure that both these groups are scheduled away from peak load. Controllable devices that are out of communication with either the LIC or the EM follow a default, fixed charging pattern which overlaps the end of the afternoon peak period. Since the number of out of communication devices averaged around 50% of the total (see Section 4.1), the maximum possible load at the tail end of the afternoon peak period was 0.6 MW higher than before. This could however be resolved by shifting the default schedule for Groups 1-4.

All Quantum heaters within one group that are not permanently switched off will come on at the same time when a charging period begins, but will switch off at different times thereafter depending on whether they have reached their DER or are full – in this they are no different to conventional storage heaters. However, the Quantum heater controllers prioritise customer comfort rather than network convenience, so they can turn on at unscheduled times if the energy stored falls below a minimum reserve level. All DSM capable heaters may charge during unscheduled periods except in the groups where the metering arrangement kept the time switch. This is a disadvantage compared to the teleswitching regime, where although it was never known how long the heaters stayed on when the time switch was open, it could be guaranteed that they were not charging during the periods when the switch was off.

3.3 Replacing fossil fuel generation by wind

NINES DSM in its current configuration was not expected to contribute to replacing fossil fuel generation by wind. Currently only 7.5 MW of wind generation is installed, and previous simulation studies showed that increased wind generation enabled by flexible storage start to be visible only when the connected wind capacity is at least 14 MW[21]. With 19 MW wind, the 199 houses with 1.44 MW controllable capacity could in theory allow 385 MWh of fossil fuel generation to be replaced; but if, as at present, 50-60% of devices are out of communication (Section 4.1.1) this reduces to 230 MWh.

		2013 plan[22]	Installed	Sept 2016 flexible
Houses		250	224	199
Flexible power	kW	8.2	7.2	7.3
Total installed flexible power	MW	2.1	1.6	1.4
Additional wind enabled	kW/house	2.21	1.94	1.97
Total additional wind	kW	550	430	390

Table 3.4 Theoretical additional wind generation enabled by frequency responsive storage.

3.4 Additional wind supported by frequency response

All the devices have frequency response capability, whether they are in flexibly charging groups or not, provided that they are in communication with the LIC. They are however currently configured to disable frequency response when in stand-alone mode; although Glen Dimplex advise that this could be altered if SSEN wished. The 223 live houses should in theory be able to support 430 kW of additional wind through frequency response (Table 3.4), but with only 50-60% of the devices in communication at any time the available capacity is 220-250 kW at best.

DSM frequency response overrides both the schedule and the requirement to maintain a minimum reserve, but it is disabled if the device is full or the DER has been delivered[23]. DSM frequency response is valuable to the network because the devices can drop load quickly if the wind drops, but this is available only when the devices are on – typically 8-8.5 hours or a third of a day for fixed schedule groups in winter, less in summer. This issue is discussed in detail in the Frequency Response Operational Effectiveness Report[24].

4

Impact of performance issues

4. Impact of performance issues

The DSM system does not always perform in the expected manner. This section outlines the performance issues seen with individual components and the way they interact, and estimates the impact on available controllable power and storage capacity. Conclusions are largely based on field data collected from devices and at Group level in the period 29 February to 22 May 2016. At that time, only 0.84 MW was connected in flexibly charging groups (Groups 1 &2), and another 0.59 MW, which was subsequently moved, was in groups with fixed timing charging (Groups 3,4,7,8).

The EM collects data from the LICs every 15 minutes and aggregates it for each group before passing to the ANM. The Group data shows, for each time period:

a) the number of devices in the group, and the percentage seen;

b) the sum of the rated power and storage capacity of the devices in the group, and the percentage of each available, calculated based on a); and

c) the total energy required next day by the group, estimated by adding up the DER from the devices seen, and pro-rating for the missing ones by the average DER/rated power of those seen.

4.1 Installed and available power

4.1.1 Impact of communications outages

The actual capacity available at any one time is typically around 50-60% of that connected as the rest is out of communication. This is the case for all groups.

During the 12 weeks of data analysed, the total power of individual devices seen by EM in the flexible charging groups was between 0.43-0.49 MW. The persistent communications problems are believed to be caused mainly by outages in the RF network within the houses as discussed in detail in the DSM Infrastructure Report[25]. The occupants were not affected because devices not seen centrally continued to deliver DER to a fixed time schedule in standalone mode (if the device could not see the Hub) or in default mode (if the LIC could see the device but had temporarily lost communication with EM). The controllable capacity available to the network was however significantly reduced.

The number and capacity of the devices seen by EM varied over time. On any day around half of the installed space heater capacity was typically in communication (Figure 4.1) and 60-70% of the hot water tank capacity (Figure 4.2).

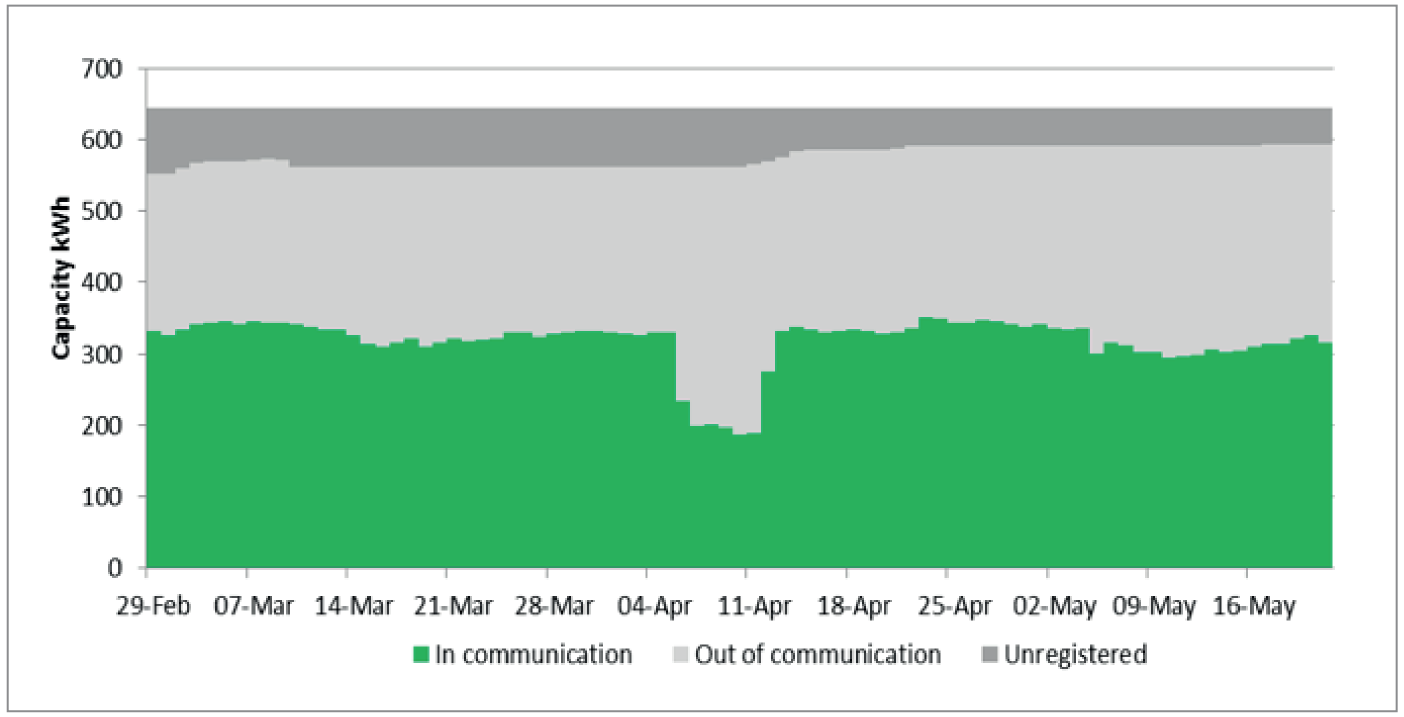


Figure 4.1 Space heaters (Group 1) controllable capacity over 12 weeks.

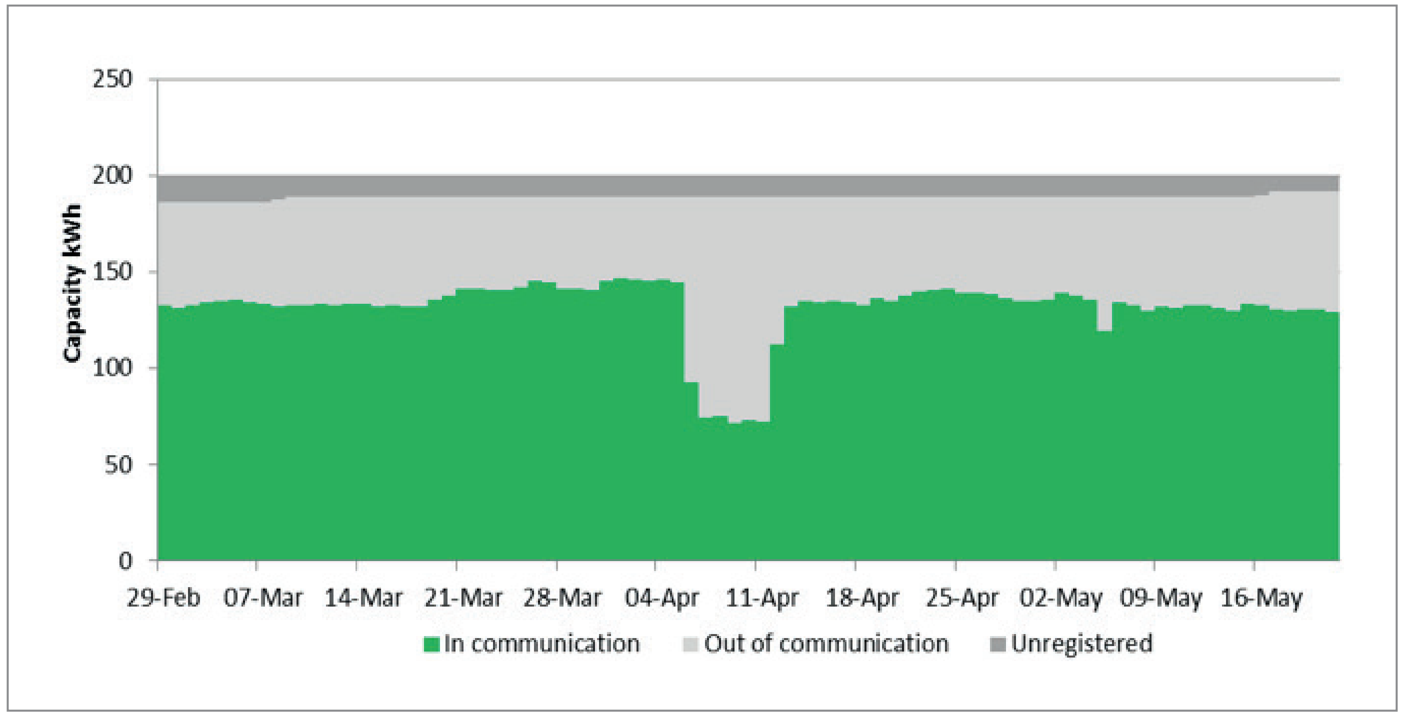


Figure 4.2 Hot water tanks (Group 2) controllable capacity over 12 weeks.

The EM compensated for devices recognised as missing by assuming that they were collectively following the same average pattern of energy demand and storage as those devices it saw. The big drop in the available capacity in the period 7-13 April was because the EM developed a fault where it was cutting off before it had interrogated all LICs. SSEN report that the fault was fixed and has not recurred.

The number of devices recognised as being in a group also varied from day to day, so some of the installed capacity did not register at all. This occurred either because the device had been switched off or was completely out of communication. These 'invisible' devices are represented by the dark bands at the top of Figures 4.1 and 4.2; their number went down over time. All these devices were operating in stand-alone mode all the time, and their demand was not included in the calculation of DER for the group.

Data collected from the individual devices offers a more detailed insight. Figure 4.3 shows all the devices in the flexible charging groups plus those in fixed charging groups that were subsequently moved to flexible charging. Individual devices with high data, which responded to EM at least 75% of the time over a day, were in practice available and are shown in dark colours: on any particular day around 50-55% of all devices were available by this definition. A slight decline to 46-48% set in after 6 May, when the outside temperature started to rise and some space heaters were turned off.

Low data devices, responding to EM on less than 75% of occasions, accounted for 5-9% of the capacity on any day. The largest contribution to the missing capacity came from devices that were not visible at all that day, although they did appear at some point in the period under analysis. Many followed an erratic pattern, appearing and disappearing again multiple times – it is unlikely that these devices were being switched on and off.

Some devices were never seen during the whole data collection period. For space heaters in Group 1, unregistered capacity was around 8-13% of the total while for hot water tanks in Group 2 it was slightly less at 4-7% (Figure 4.3). It is unlikely that hot water tanks were either permanently off or else being regularly switched off and on, so this difference indicates that at most only half of the missing space heaters were switched off. It is likely that devices in bedrooms and halls that never registered have never actually been turned on.

Few devices were available all the time. Figure 4.4 shows, for all groups, the number of days each device was available over the 12 week period from 29 February to 22 May 2016, leaving out the 5 days where the EM was known to be faulty. In this period only 11% of the devices were visible and available every day, and 36% were visible for less than 28 days out of the 79.

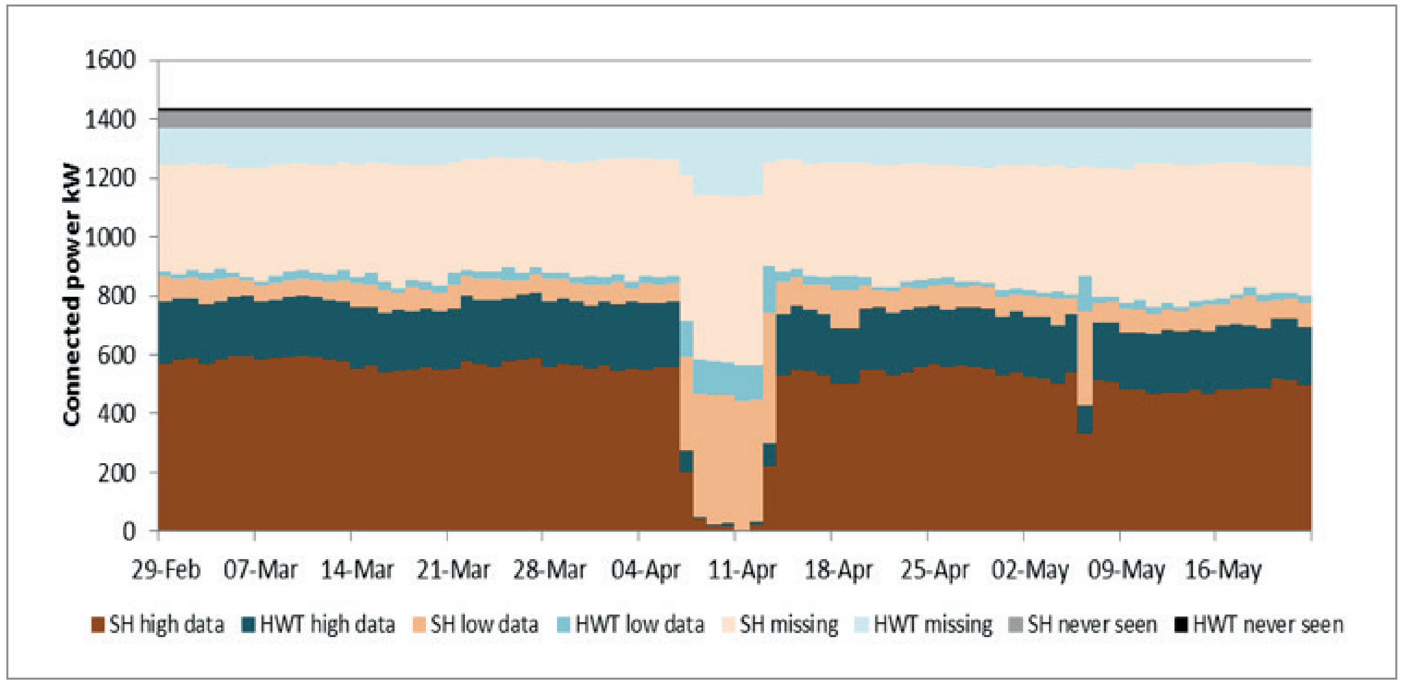


Figure 4.3 Connected power in flexible or potentially flexible groups (G 1&2, 3&4, 7&8).

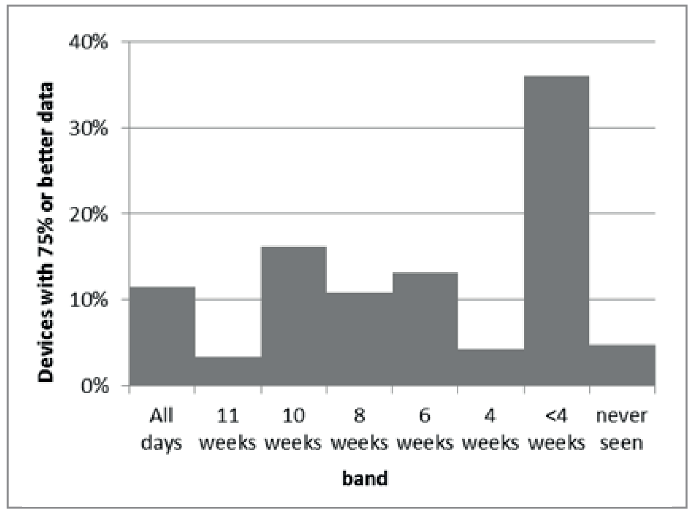


Figure 4.4 Frequency distribution of devices returning >75% data per day, all groups.

SSEN's investigations concluded that the root cause of data outages lay with the RF network within the houses. Most (although not all) LICs responded when 'pinged' directly, showing that the WAN is working adequately. Within the houses, the interference from neighbouring RF networks could corrupt the pairing of a device with its Home Hub. Glen Dimplex subsequently upgraded the code for the Hub to controller interface but this has not yet been rolled out.

However, it is possible that there are some functionality problems with the LICs themselves. According to the specification, if they do not have recent data for a device they ought to transmit the last known data, with the device communications status flag set to zero[26]. In practice however not a single data line recorded by EM shows zero comms status, but devices appear and then disappear from period to period.

The 199 houses therefore provided only 0.84 MW of controllable capacity in practice rather than the 1.44 MW installed. This will not have affected peak load shifting as this occurs even if the devices are in stand-alone mode (Section 3.1). The frequency response capability was also reduced. Fossil fuel replacement was not taking place as not enough wind was connected, but if this level of communications outages were occurring with high installed wind, 70% more houses would be needed to achieve the expected benefit[27].

4.1.2 Devices switched off in the summer

Around 35% of storage heater capacity appears to have been switched off by the early summer. This trend is visible in the Group data (Figure 4.1) but is even clearer from the device data which covered a longer period. In the week 20-19 February when the weather was coldest, the available space heating power was 598 kW in the groups that were in or subsequently moved to flexible charging (Groups 1,3, and 7), while in the week 10-19 June this was 386 kW. For comparison, the available capacity in the equivalent hot water tank groups was 207 and 208 kW for the two periods.

4.1.3 Total demand

It was not possible to see the actual energy delivered because of the variation in the number of missing devices. However, an estimate has been made of the total flexible demand (Table 4.1) for all the groups that were on flexible scheduling or were shortly to be transferred by:

- calculating the actual energy taken by the devices with 90% or more clean data each day;
- comparing that to reported DER; and
- applying the ratio of actual to DER for that day to those devices seen in that day but with lower clean data.

Estimate of total energy delivered by month, MWh				
	March	April	May	Total
Flexible space heat Group 1	36.9	28.4	20.2	85.4
Flexible hot water Group 2	8.6	7.1	7.0	22.7
Actual Flexible Total	45.5	35.4	27.2	108.1
Potential space heat Grps 3+7	24.9	19.9	14.3	59.1
Potential hot water Grps 4+8	5.5	4.6	5.0	15.1
Actual & later Flexible total	75.8	59.9	46.5	182.3

Table 4.1 Estimated energy delivered to flexible and potentially flexible groups.

Overall demand for space heating reduced by 55% between March and May, both because outside temperature increased, and because with longer days there was an increasing contribution from passive solar heating. There was also a small diminution in hot water demand because mains water temperature increases from around 5 C in the winter to 15 C in summer.

The proportion of demand taken by hot water increased from 13% in February to 38% in May, roughly in parallel with the rise in outside temperature (Figure 4.5).

4.2 Inaccuracies resulting from device performance

4.2.1 Overestimation of daily energy demand

The Group DER calculated by EM for scheduling purposes overestimated the real demand from space heaters by 10% in the winter and up to 50% in the summer. This was due to two quirks of the way heaters report status and is discussed in detail in the DSM Infrastructure Report[28]. Both problems can be corrected by changing the calculation method in the EM.

4.2.1a Spurious DER in space heater groups

The aggregate DER seen by the EM over the winter contained 10-15% of spurious demand from storage heaters whose heating circuits were switched off but whose control circuit had been left on. These calculated extremely high DERs and transmitted plausible data, but showed core temperatures as flat at 50 C so were not actually drawing any power. This affected the ratio of Average DER/Rated Power that EM uses to pro-rate for missing devices. The impact of spurious DER on the apparent energy demand over 18 weeks can be seen in Figure 4.6.

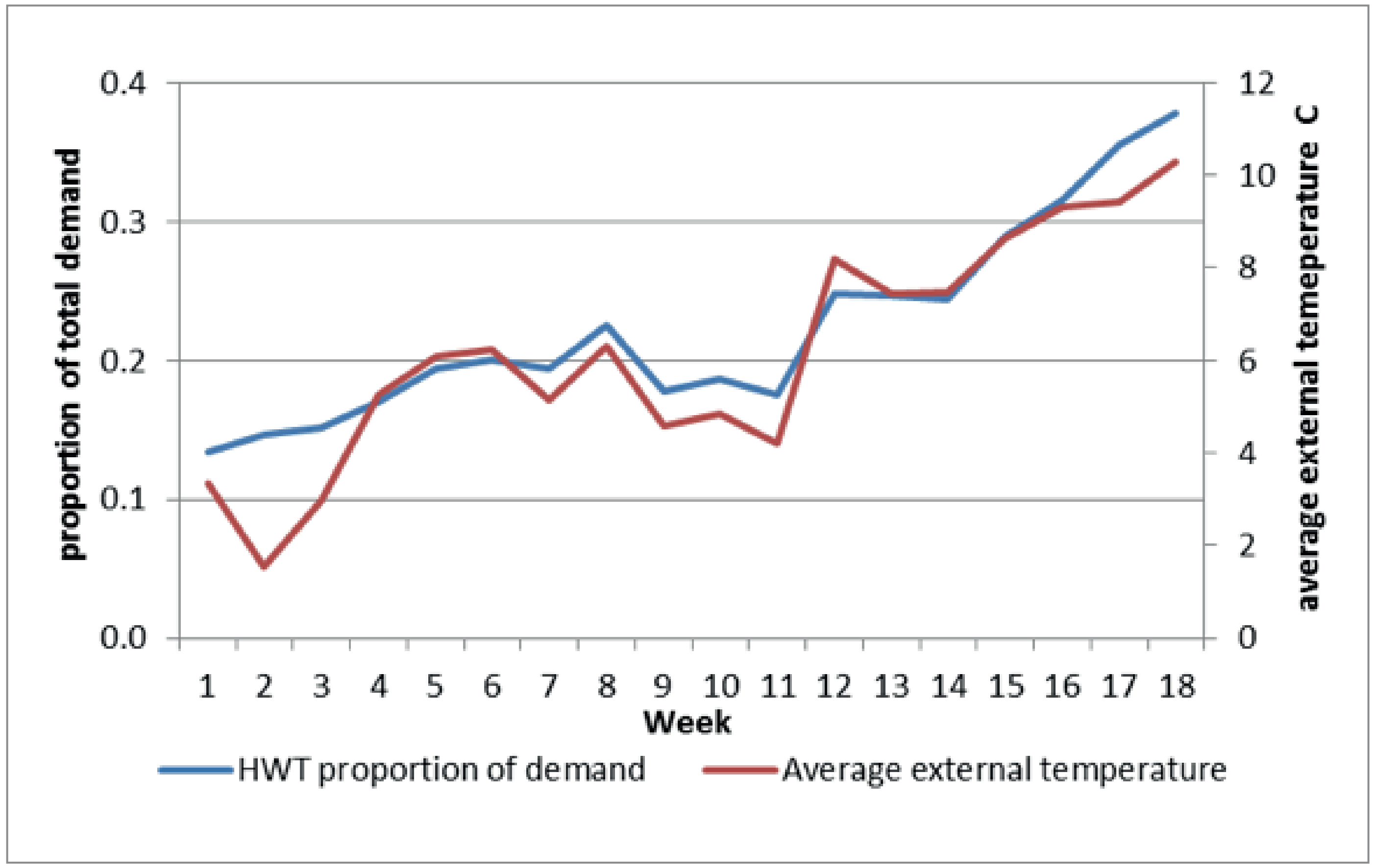


Figure 4.5 Proportion of total energy demand for hot water.

Figure 4.6 Impact of spurious device DER on calculated Group DER.

4.2.1b Zero rated power devices

Some space heaters had periods when they reported perfectly plausible data except that they showed a zero rated power and maximum storage capacity: 8% of space heaters exhibited this behaviour for at least one week and 6 devices reported zero rated power for the whole period. This undervalued the visible controllable power by up to 10% and so resulted in the Group DER being over-estimated by up to 5%, in addition to the spurious DER described in 4.2.1. It is not clear why this was happening and the problem should be investigated by Glen Dimplex. However, it should be possible to correct for this in the EM calculation even if there is no change in the device controllers.

4.2.2 Devices in communication but with unchanged data

In some cases the LICs appear to be resending exactly the same data for a device over several reporting periods, but still reporting the device to be in communication. An example of this 'stuck' behaviour is illustrated in Figure 4.7, which shows the appliance setpoint, instantaneous power, and core temperature over 4 days. The Group target setpoint is also shown for comparison as a black line. The LIC appears to be correctly transmitting the last reported value, but without marking that it has lost communication with the device.

This behaviour is hard to spot except by detailed examination at this level, unless it goes on for a long time, because many parameters are fixed for a day (DER) or vary very slowly (room temperature, core temperature when close to empty). However, if there is no change in core or average water temperature over an hour (5 or more consecutive periods) then this can indicate that the device data is stuck. Over the 18 weeks, 3% of devices classified as available were regularly stuck for periods of 4 or more hours per day, and all devices occasionally. Hot water tanks were less prone to this, except for one which transmitted the same data for the whole period.

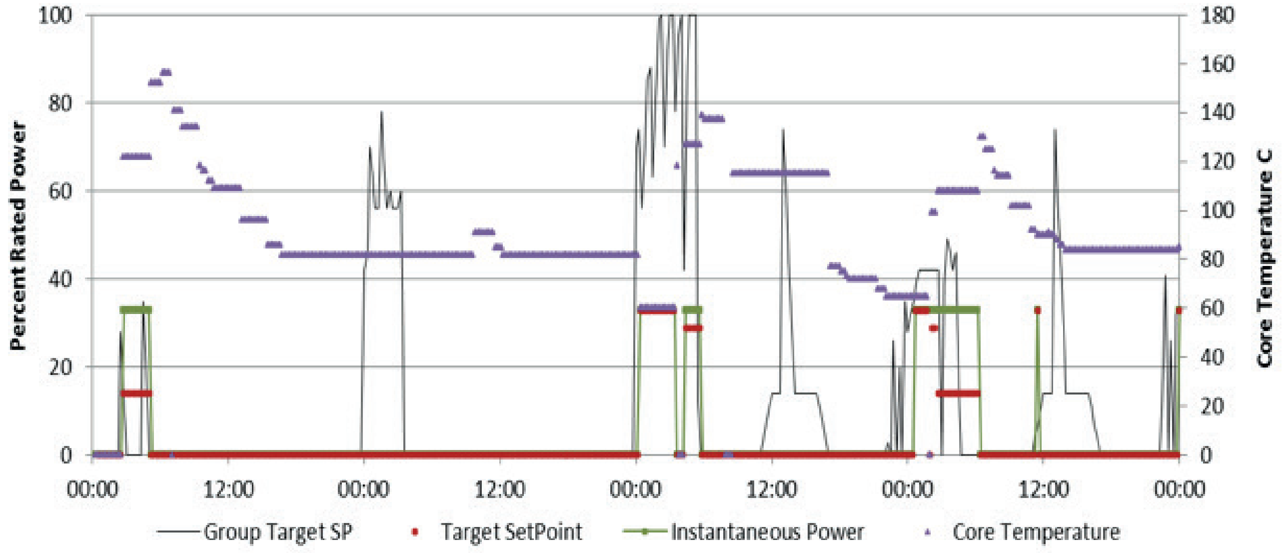


Figure 4.7 Example of 'stuck' behaviour on one device.

Devices in this state are switching back and forth from stand-alone mode to LIC control. This matters only for the devices that are following a flexible schedule, as the live and stand-alone schedules are identical for all fixed timing groups. However, because the device is not flagged as out of communication, it introduces errors into the Group aggregation.

4.2.3 Polling period

The 15-minute polling period followed by the EM is longer than the 5 minutes initially specified and much longer than the 1 minute implemented in the prototype houses. The heating circuits are able to switch on or off at 1-minute intervals or less, and in the prototype trials they were observed to be doing just that[29]. Energy consumption can therefore be monitored accurately only if device charging level data is collected once every minute or more often.

The reasons for moving to 15-minute data collection are outlined in the DSM Infrastructure Report[30]. In the current Version 2 of the system, the control function has been devolved to the LIC and the EM is now merely a messaging and data storage system, so external communication every 15 minutes does not compromise functionality for the customer.

However, the network operator has little insight into how well energy is being delivered against schedule, as the data now being sent to ANM about energy consumption and storage capacity represent less than 7% of the time the devices are operating. The only point when the ANM system has an accurate picture of how much energy is still required is at midnight when new DER targets are received; as the day progresses, a central estimate of how much energy has already been delivered during the day becomes progressively less reliable. This will restrict the ability of the ANM to fine-tune load shifting if in future it is decided to re-schedule more than once a day. This could however be resolved if the LIC were programmed to calculate and transmit energy delivered as well as instantaneous power. This should be straightforward to implement: the basic functionality to integrate under a load curve already exists because that is also used for schedule translation.

5

Scheduling and schedule following

5. Scheduling and schedule following

5.1 Schedule timing and peak load

The timing of the flexible schedules is set by ANM taking into account forecast demand and wind availability. The typical demand profile has a minimum between midnight and 03:00 (Figure 5.1), so on most days the ANM schedules the bulk of energy delivery for that time.

Figure 5.2 shows a typical sequence of 10 days in the water heater group (Group 2) where almost all the charging took place overnight when demand elsewhere is at a minimum.

Over the 12 weeks, 60% of the space heating and two-thirds of the water heating demand was scheduled between 00:00-03:00 (Figure 5.3) and there were only 3 days of space heating and 9 days of water heating when there was no scheduled charging in that period. 75% of the total average daily charge was scheduled before 05:00.

This could reduce the usefulness of frequency response, because the heaters are charging within narrow time bands, although the most likely reason for demand exceeding supply is the loss of a generation set which could occur any time.

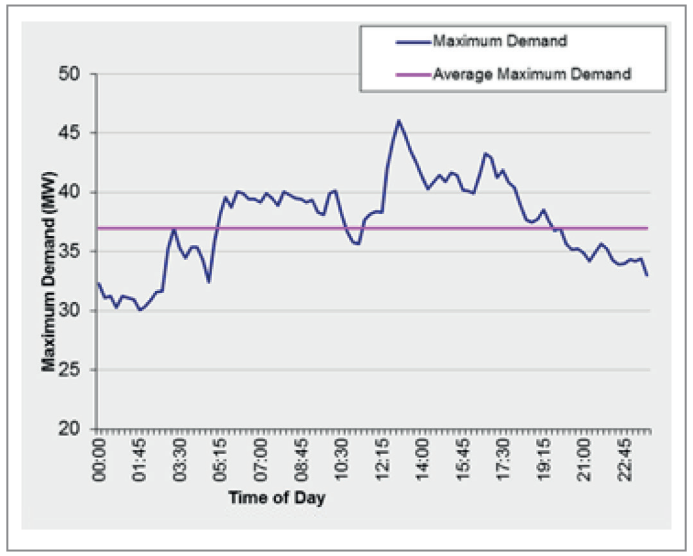


Figure 5.1 Shetland demand profile on a maximum demand day (SSEN).

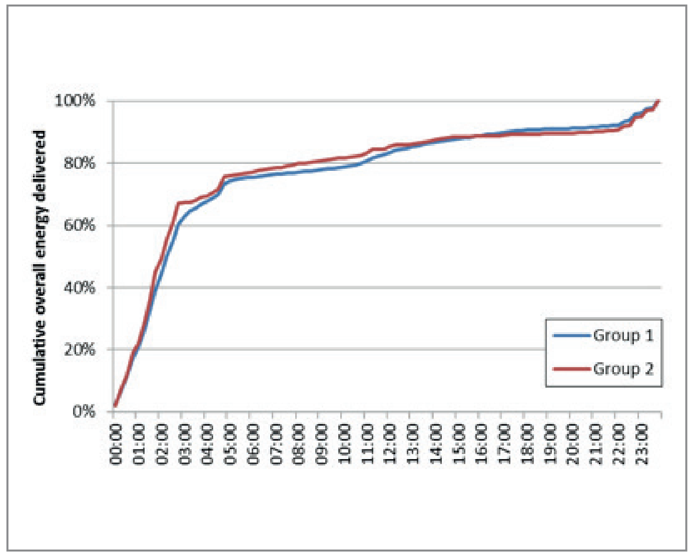


Figure 5.3 Cumulative daily scheduled charge averaged over 12 weeks.

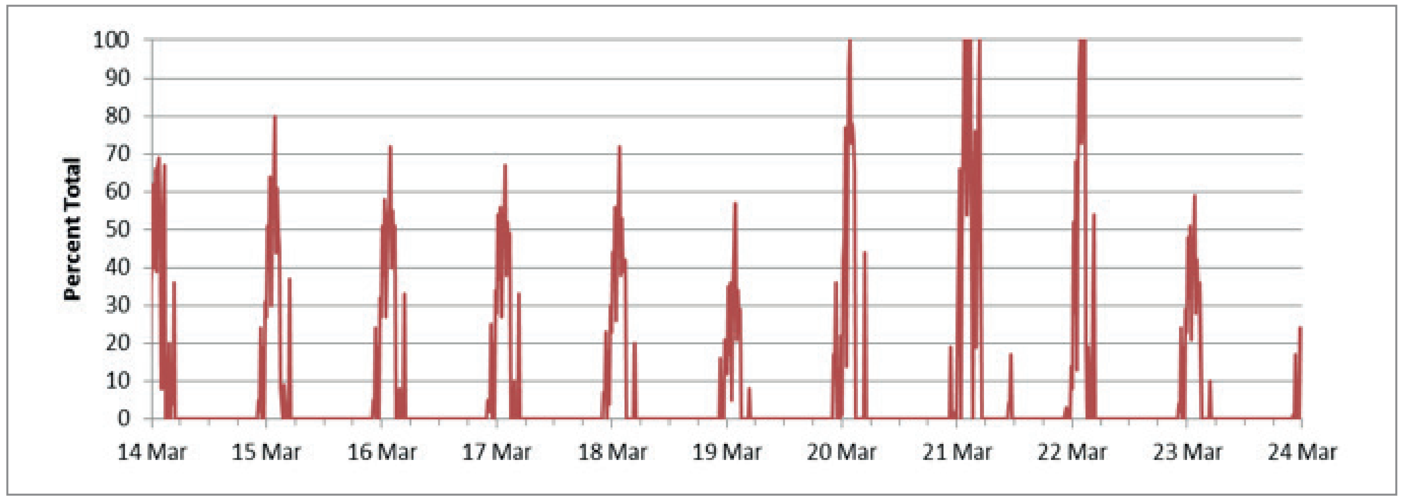


Figure 5.2 Connected power in flexible or potentially flexible groups (G 1&2, 3&4, 7&8).

Scheduling was normally outside the expected peak periods shown in Table 3.3. However, between 21 April and 5 May 2016, the space heater groups were scheduled to be on during the day on a number of occasions, and these included significant charging over the periods of historical maximum peak from 13:00-13:45, and 16:45-17.30 (Figure 5.4). Presumably this was to make best use of wind availability; the effectiveness of ANM scheduling is discussed in the ANM Operational Effectiveness Report[31].

During the period analysed, the highest actual peak load on the station occurred on 7 March at 06:00. No flexible load was scheduled at that time, and fixed timing Groups 3-10 were not scheduled to charge either. However, fixed timing Groups 5, 6 and 11-18 were all due to charge at 100%. Table 5.1 shows the scheduled and actual demand for each group at that time. The actuals for the invisible devices and for the opted-out groups were estimated based on the nearest similar group. Spurious data from switched off devices were eliminated.

The unscheduled groups were collectively charging at 5%. On the other hand, groups scheduled to be charging were drawing less power than expected: only 17% in the case of the space heater group 15. So the actual contribution to peak load from the NINES groups was only around 20% of the potential maximum envelope.

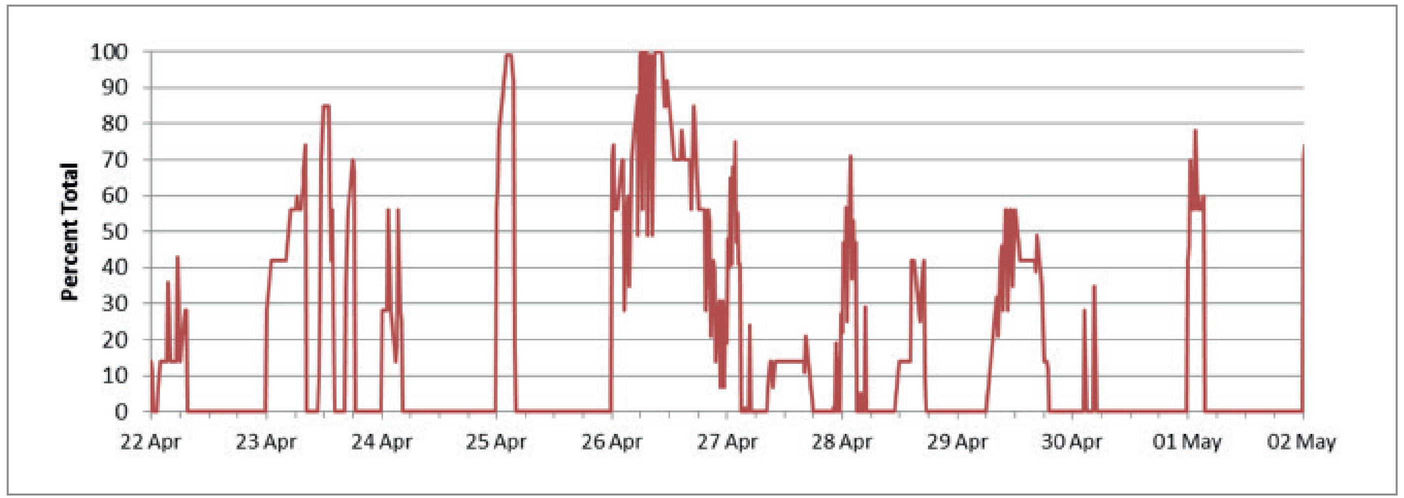


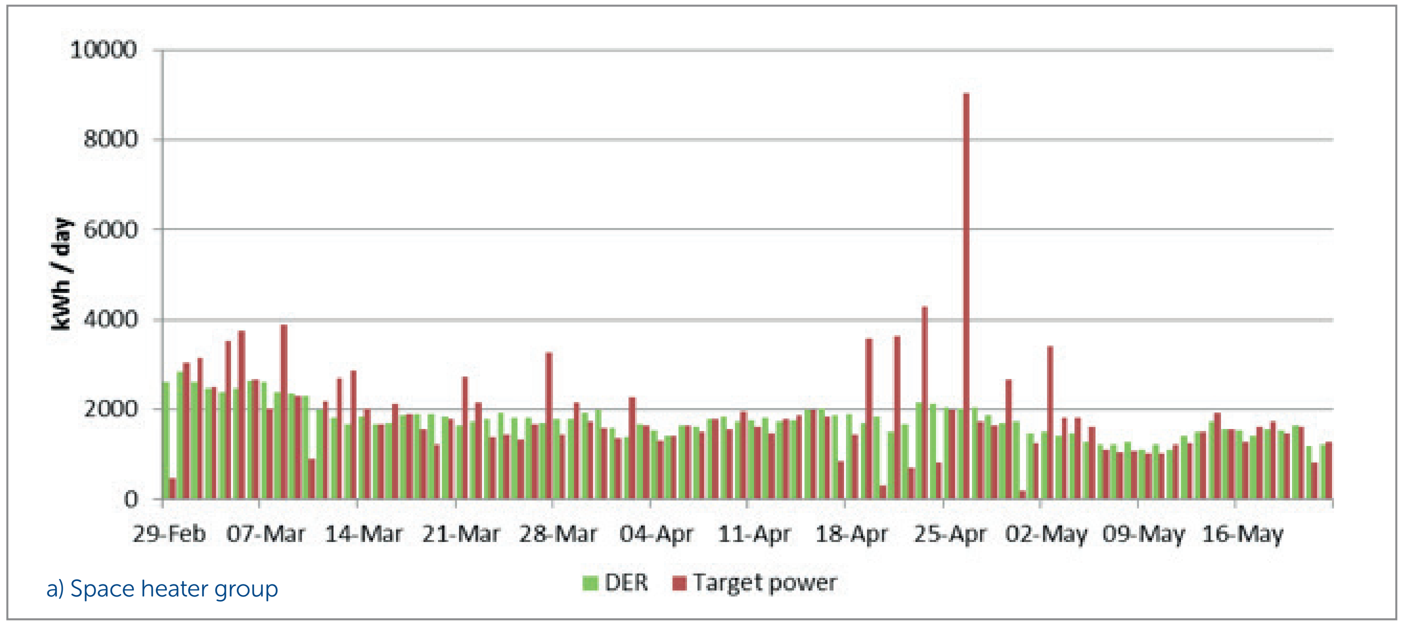
Figure 5.4 Target schedule over 10 days, with significant scheduling at peak load times – Group 1.

Group	Rated power kW	Scheduled kW	Actual or Estimated kW
Flexible 1 (visible)	335	0	23
Flexible 2 (visible)	136	0	2
Fixed 3 + Default 1	360+299	0	55
Fixed 4 + Default 3	123+64	0	4
Fixed 5	82	82	14
Fixed 6	21	21	4
Fixed 7–10	122	0	7
Fixed 11–14	7	7	0
Fixed 15–18	48	48	6
TOTAL	**1612**	**151**	**117**

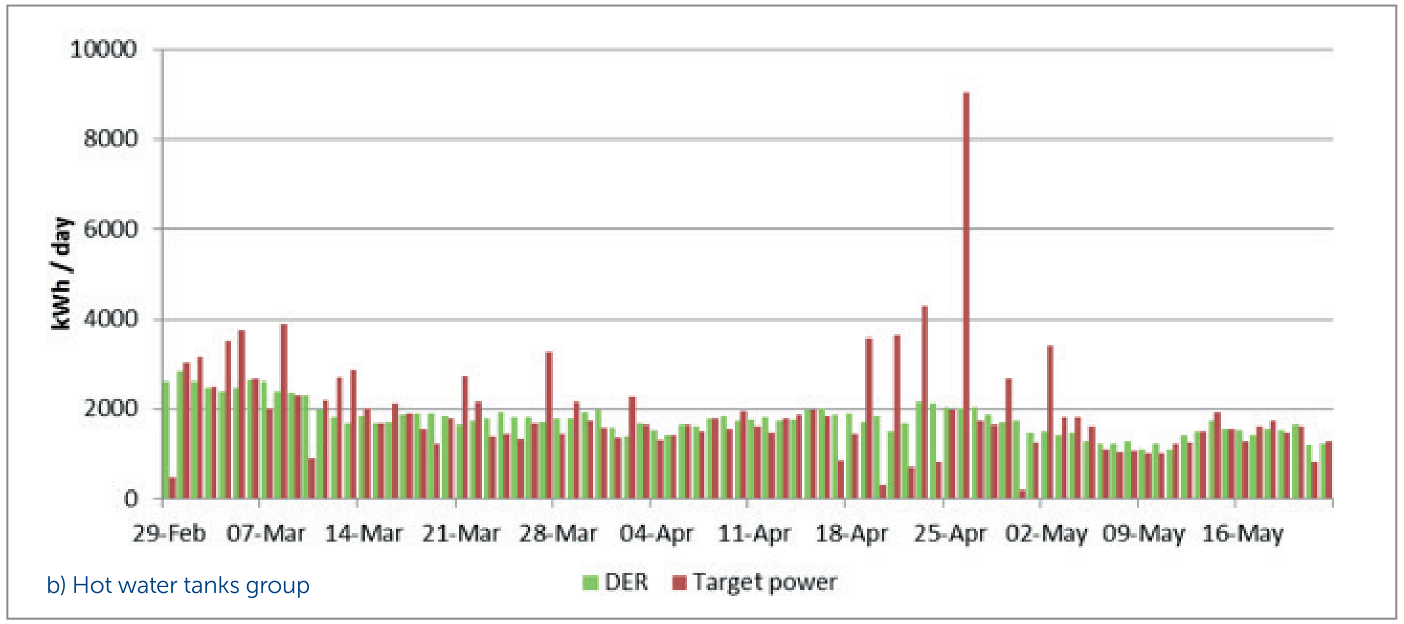
Table 5.1 Scheduled and actual charging by group during the peak at 06:00 on 7 March 2016.

5.2 Target schedule and Daily Energy Requirement

The target schedule calculated by ANM varies from day to day, and can deliver much higher or lower energy than the daily energy requirement. Figure 5.5 compares the DER reported at 00:15 each day with the energy that would be delivered by the target schedule, by the devices seen.



a) Space heater group



b) Hot water tanks group

Figure 5.5 Flexibly charged groups – target schedule vs daily energy required.

Small differences between DER and target energy could be due to timing. In this analysis the DER, Group rated power, and number of devices visible are taken from the first data available each day, on the assumption that scheduling was done just after midnight. If however data from a different time slot was used for scheduling, the target would have been based on different values as reported DER does vary within each day depending on the number of devices seen at any point (Figure 5.6).

This would not however account for the very large differences seen at certain times; in particular, the unusual scheduling pattern from 21 April to 5 May seems to have resulted in large differences between scheduled energy and DER (Figure 5.5). The pattern is consistent with an attempt to schedule over more than one day in a period of high wind around 21-26 April. The total energy delivered by the schedules over the 12 weeks was within ±1% of DER for the water tank groups, and 8% higher than total DER for the space heater groups. This is further evidence of spurious DER effect, but as discussed in Section 4.2.1 it should be possible to correct this in the EM calculation of Group DER.

5.3 Target schedule and delivered energy

Actual energy delivery appears to be close to schedules on most days: Figure 5.7 compares the target and actual power each day for both groups.

Once again the unusual scheduling pattern for space heaters from 21 April to 5 May resulted in too much scheduled energy on some days and not enough on others. If there was in fact an attempt to schedule over more than one day – something that modelling studies show would be possible without affecting occupant comfort[32] – then the new control algorithm in the production heaters was overriding their instructions from the LIC. In contrast to the prototype heaters, the production versions will not accept more than the DER that they calculated for that day, unless the fill level falls below the minimum reserve.

Where the delivered energy is much higher than in the schedule, this is in periods where the reported Instantaneous Power (IP) remained constant for more than 24 hours. The space heater group reported an unvarying 44% of rated power drawn between 02:45 on 13 March and 09:45 on 14 March; both the space and water heater groups showed constant power draw at 39% of rated for more than 24 hours on 20-21 March. It is not clear why this should happen, because the device data varies as normal, and so do the other aggregated values calculated by EM (target point, number of devices seen). It may be possible that the EM was overwriting the same value at times.

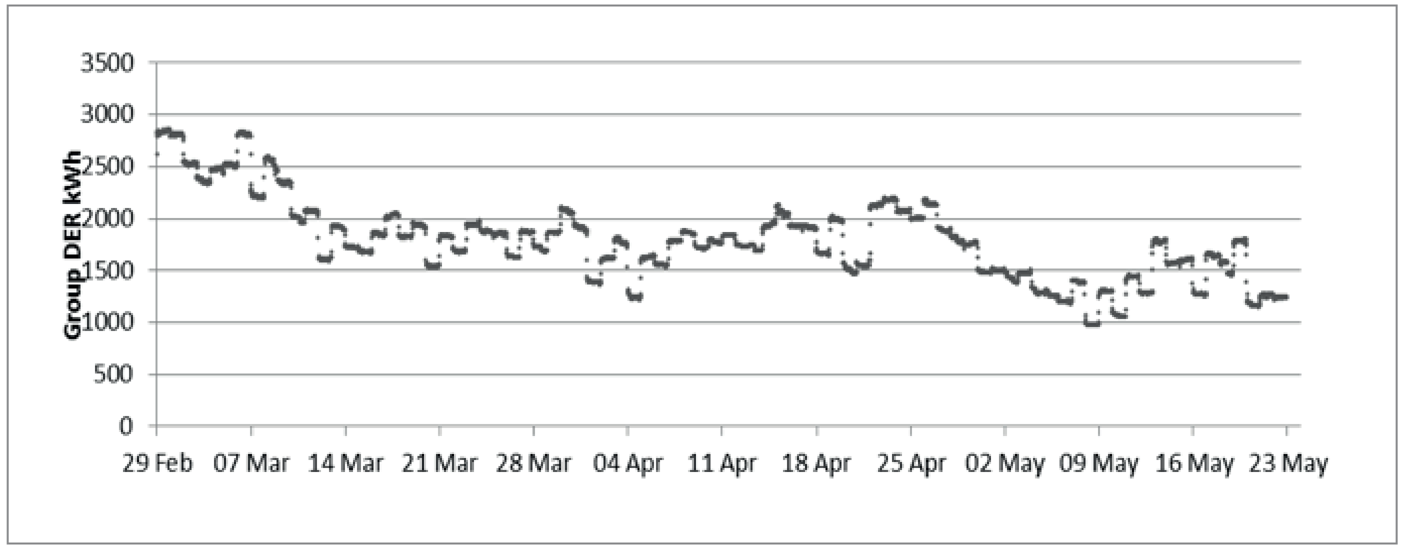
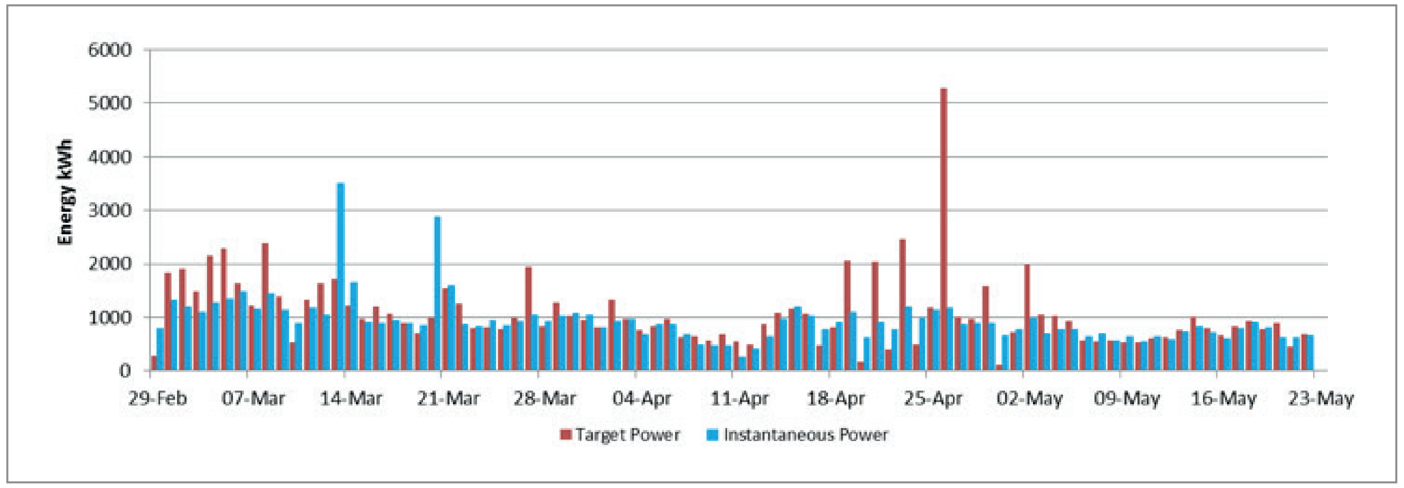


Figure 5.6 Flexibly charged space heater group – reported DER varying within a day.

a) Space heaters



b) Hot water tanks

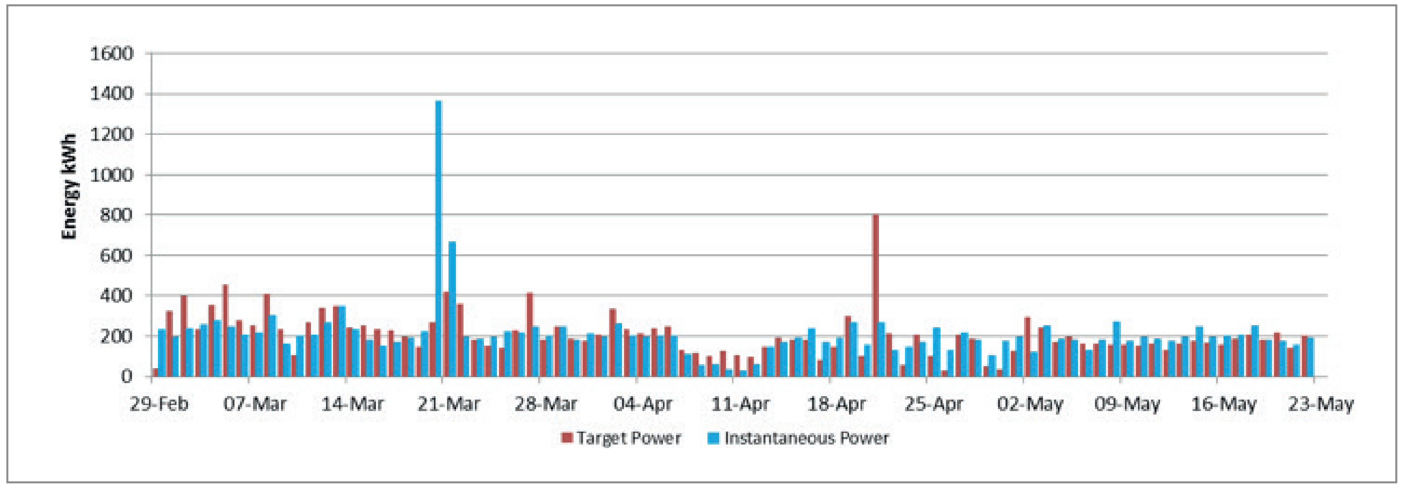
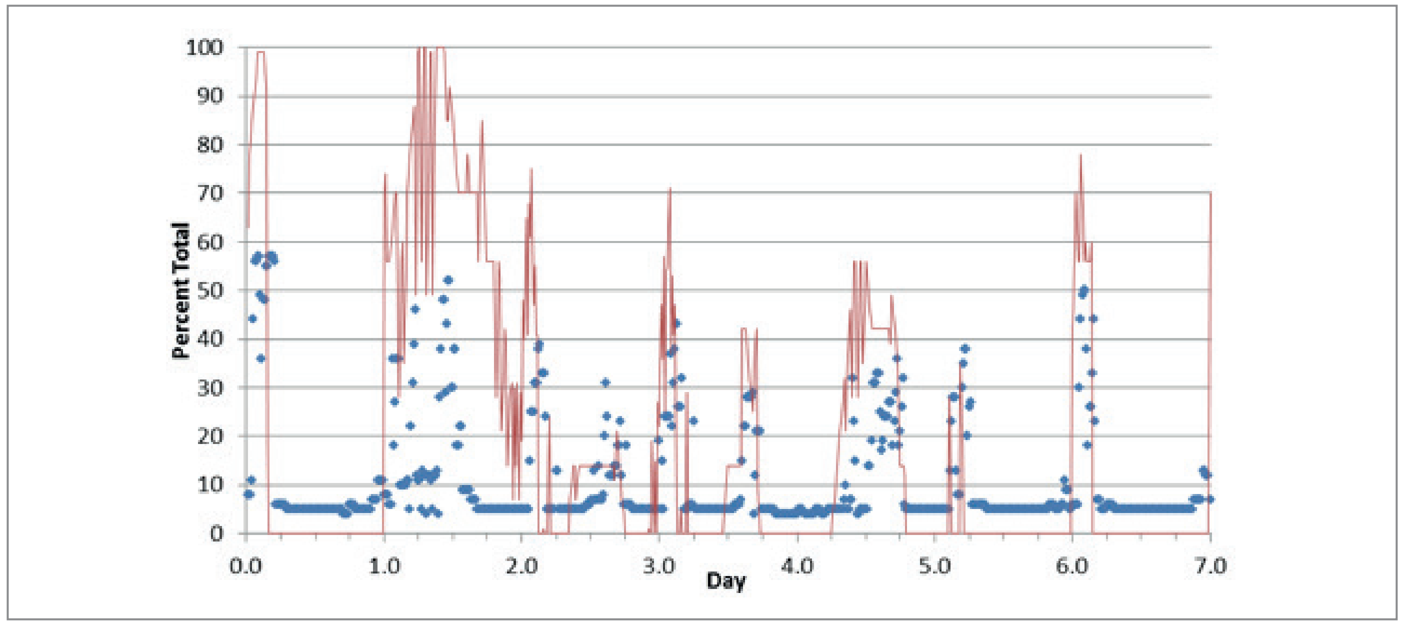


Figure 5.7 Flexibly charged groups – target schedule vs actual draw registered.

5.4 Schedule following by the Group

For all groups the peak load was generally less than scheduled, and a consistent, low level of charging took place outside the schedule. Figure 5.8 shows a typical week for each of the flexible charging space heater and hot water tank groups.

Flexible space heaters, 25 April- 1 May



Flexible hot water tanks, 16-22 May

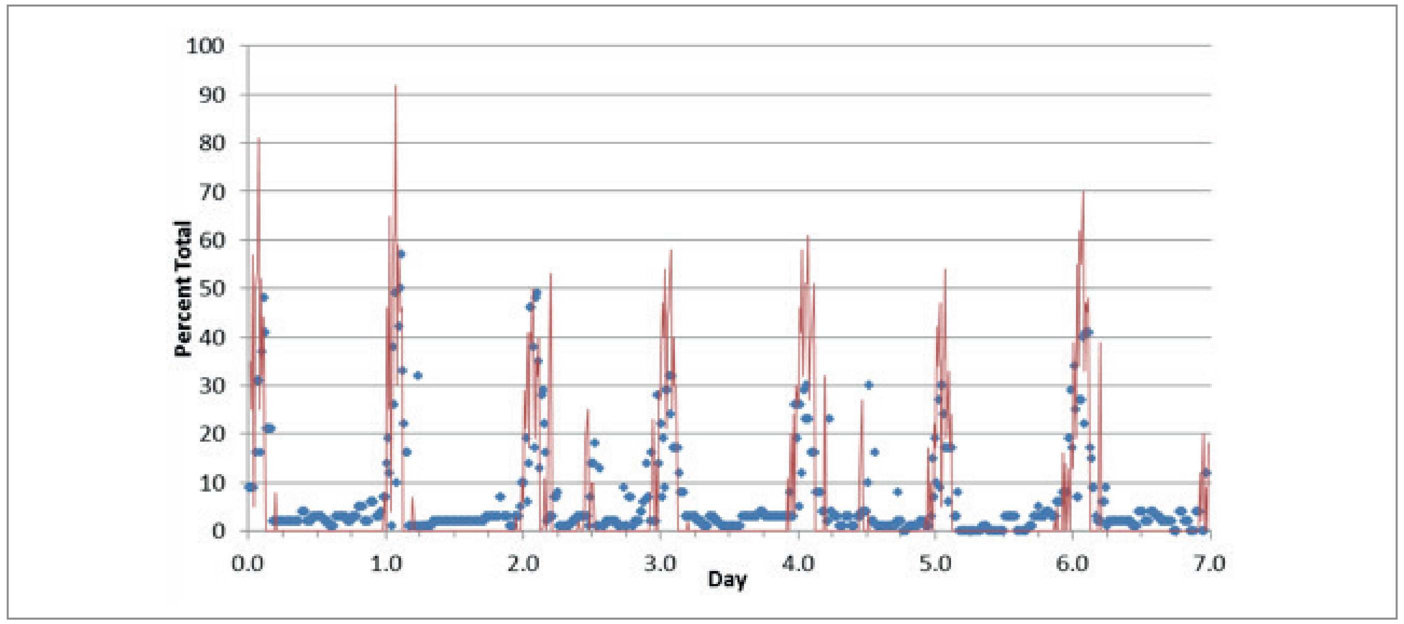


Figure 5.8 Target and actual power over a week

For space heaters this base charging level was around 5-10% of the available power. Some of this was not real: heaters with spurious DER reported a non-existent draw because instantaneous power is based on the controller setting and not the actual current to the heater. Countering that, the real draw in heaters reporting a zero rated power will not have appeared at group level.

Hot water tanks also showed a constant base level of charging, 2-5% in the flexible charging group and more in the equivalent fixed timing group. This can happen for a variety of reasons: heaters turn on when they hit their minimum energy reserve; if a device has a DER higher than the storage capacity, some of the delivery must be made outside schedule, while devices in areas prone to power outages will reset their calculation of energy delivered so far after a break in supply and draw more than scheduled.

Over the whole 12 week period analysed, the space heater group never reported drawing zero power, and the hot water tank group was off for only 12% of the time (Figure 5.9).

When the target schedule was on, the actual draw matched the target on just a handful of occasions. The space heater group spent most of its time (65%) in a state where the reported actual draw was between 5-10% above target, and was more than 10% above target for 10% of the time.

The pattern for target and actual charging in the two flexibly charged groups for all 12 weeks is shown in Appendix I.

5.5 Schedule following by devices

The individual devices follow the schedules set by the LIC quite well, much better than in the prototype where devices were charging outside schedule for 20% or more of the time[33]. The redesigned device control system does seem to have reduced the instances where device control clashes with the LIC.

Figures 5.10 and 5.11 depict the schedule following status of devices that reported least 90% data over 18 weeks and were clearly switched on. All space heaters still had periods when they were scheduled to be on but not drawing. Very little time was spent on when scheduled off. This behaviour was the same in fixed timing groups. However all groups spent a similar amount of time off when scheduled on.

Hot water tanks were even better at following the schedules set by the LIC (Figure 5.11). Only three of the tanks reported any noticeable out-of-schedule status. Independent monitoring data on hot water consumption was available for two of these, which showed that in those households the long-term average daily hot water consumption was higher than the tank capacity. Since the ANM schedules typically aim to deliver the day's demand after midnight, these tanks will not be able to deliver all the DER until the occupants have used some hot water and so will be regularly charging outside schedule. These high-demand devices cannot be distinguished in the aggregated data used for scheduling.

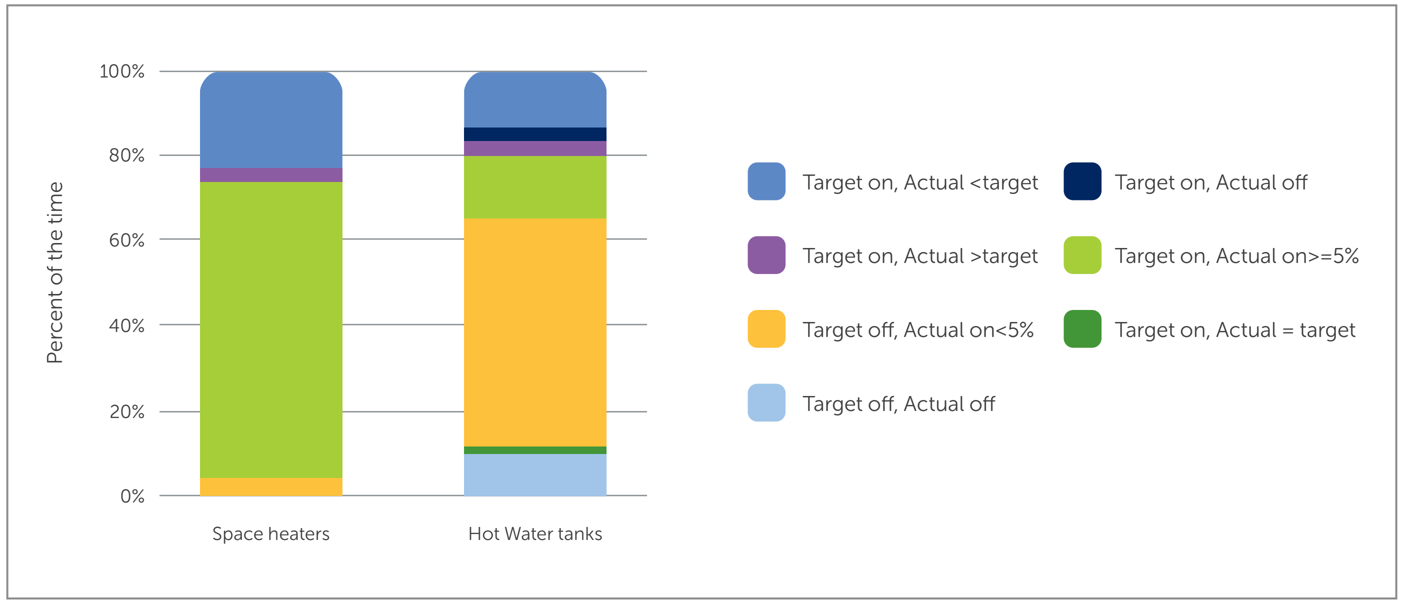


Figure 5.9 Summary of schedule following status for the flexible charging groups over 12 weeks.

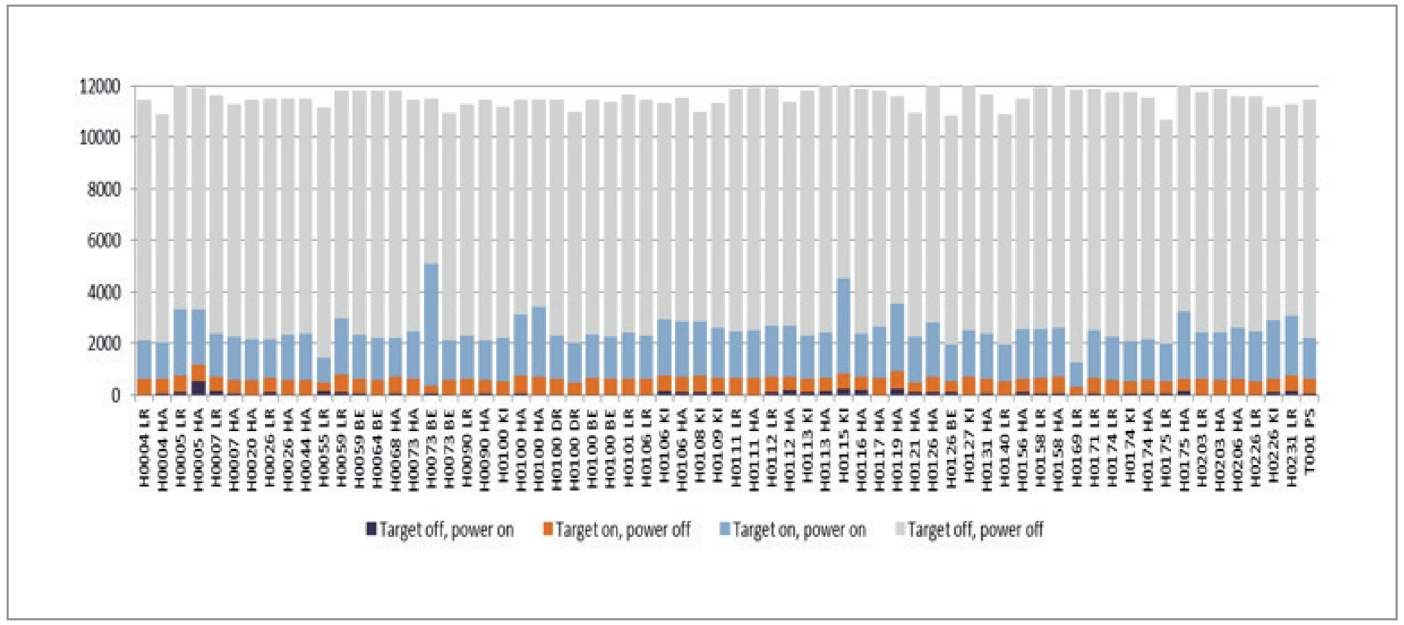


Figure 5.10 Schedule following in flexibly charged space heaters.

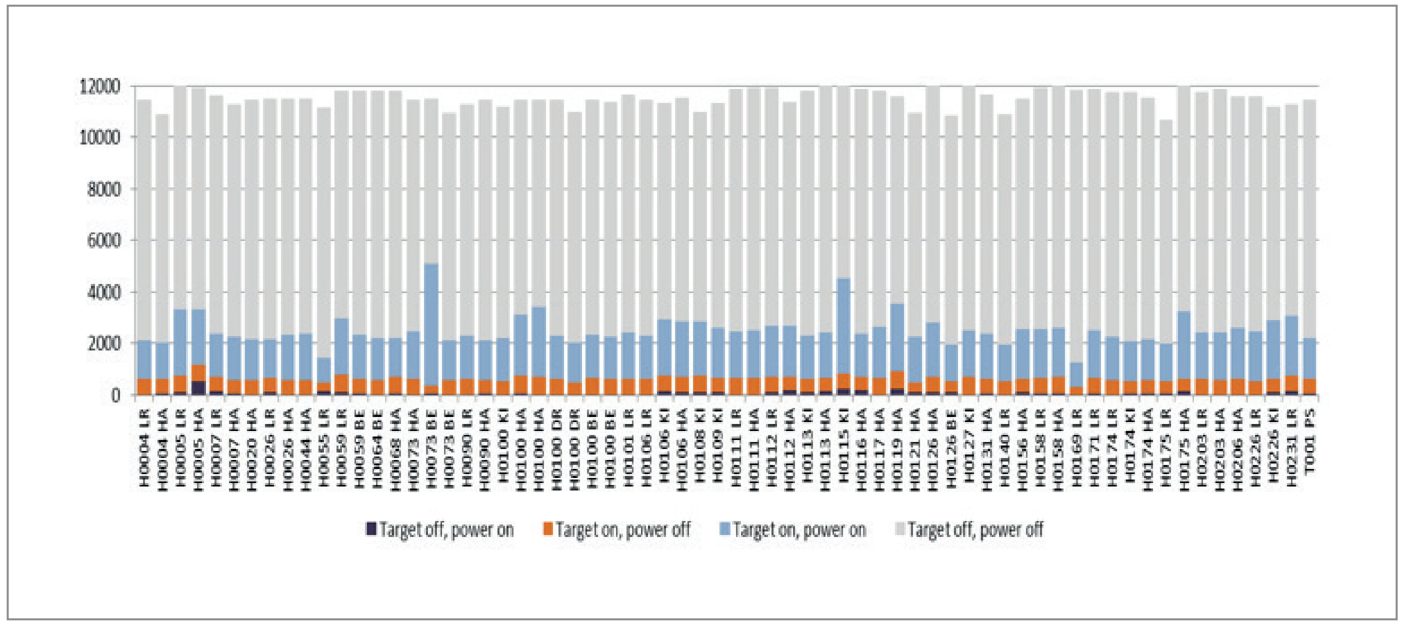


Figure 5.11 Schedule following in hot water tanks.

Figure 5.11 also shows that the flexible charging tanks are scheduled over a shorter time, on average less than 5 hours per day. The same demand would be spread over 6.25 hours for Group 4, and 8 hours for Group 8.

5.6 Group schedule following – modelling

If heaters are following LIC-set target set-points quite well individually, but a Group always has some low level of out-of-schedule charging, this is likely to be because of timing differences due to the different levels of fill at the start of the day. The process by which the LIC sets the target setpoints for the devices does not take into account the level of fill at the start, so some heaters will reach full before they have drawn their DER and then need to charge again later. Others empty and need to recharge.

Modelling studies were carried out to investigate how a small group of 3 different houses with 10 space heaters between them respond over a year to a charging schedule optimised for wind[34]. Even a group as small as this was drawing as scheduled for only 50% of the time. While the modelled schedule translation process was somewhat different to that in Version 2 of the EM/LIC system[35], the disaggregation effect was small, and the out-of-schedule behaviour occurred mainly when one or another heater had reached full and stopped charging, or reached the minimum charge reserve and started (Figure 5.12).

The modelling also looked at how the off-schedule charging in turn impacts the supported wind generation. This concluded that only 69% of the expected additional wind could in fact be supported[36].

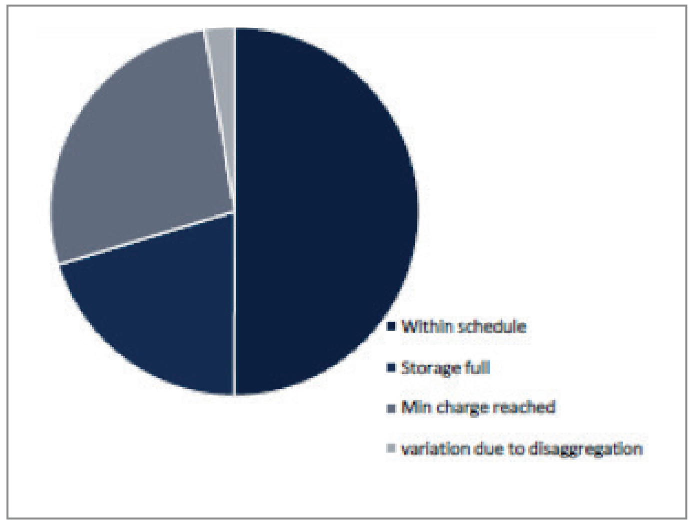


Figure 5.12 Schedule following for a DSM group with three representative house types (from: Gill et al 2014)[37].

5.7 Under- and over-draw by devices

Although the devices are switching on and off largely as instructed, the pattern of net under-draw relative to target in the space heater group is replicated at the individual device level. This net figure is made up of some over-draw and some under-draw relative to the device's target schedule.

Figure 5.13 shows the under-and over-draws for the flexibly charged space heaters, using only those with over 90% data.

Figure 5.13 Over and under draw over 18 weeks in flexibly charged space heaters.

Analysis of device level data showed that the device schedules would often schedule more than DER, but there is no obvious reason why; even if the Group DER is over-estimated, the schedule translation process should not be affected.

In hot water tanks (Figure 5.14) periods of over and under-draw roughly balanced out: when a water tank is drained, typically with baths, the tank is programmed to charge to the minimum comfort temperature whether or not this is scheduled.

The amount of over and under-draw is small, less than 5% of the total demand over the 18 weeks for most of the tanks. The two tanks in Figure 5.14 with the biggest under and over draw are those described in Section 4.2.4, where long-term average consumption is higher than tank capacity.

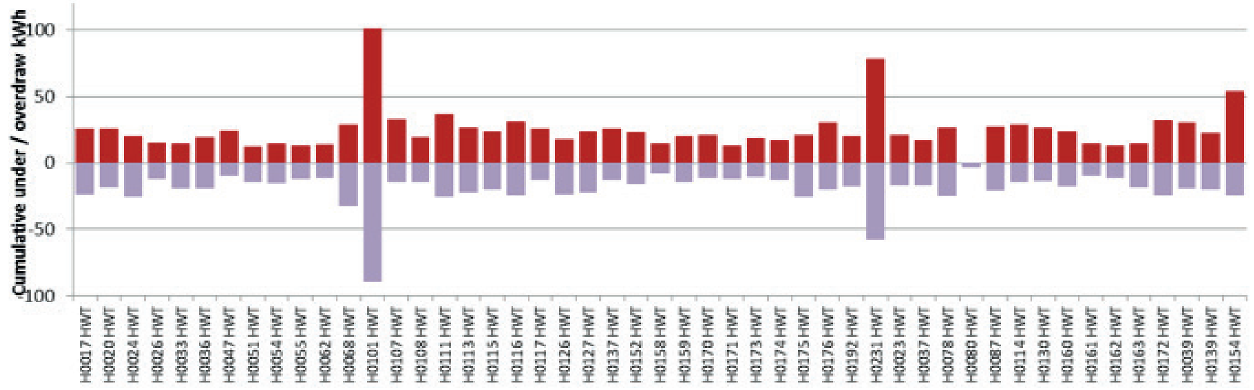


Figure 5.14 Over and under draw over 18 weeks in flexibly charged hot water tanks.

6

Storage capacity utilisation and control effectiveness

6. Storage capacity utilisation and control effectiveness

The flexibly charging groups used more of the storage capacity than those that charge at fixed times, although the absolute range was still not high. Space heaters cycled up and down just above the minimum reserve level, while hot water tanks cycled down and up from full.

6.1 Aggregate fill range in space heaters

Figure 6.1 compares energy stored in space heaters in Group 1 and the largest fixed charging Group 3. Flexible charging varied between 20-60% of capacity in winter, falling to 20-40% in summer. Group 3 had an even narrower range, 30-50% in winter.

There appears to be headroom for additional storage physically but this is not the case logically. The bottom 10% of the stored energy cannot be accessed because the minimum comfort reserve must be maintained. The maximum effective storage capacity is the DER, as the heater controllers will not accept anything above this. There are exceptions at the level of individual heaters; if, for example, DER was higher than the physical storage capacity, as was the case for 3% of device days, or if there was a power outage and the energy delivery monitor was re-set. However, the control logic that calculates DER takes into account the energy remaining in store at the end of each day and reduces the next day's demand by that amount, so it is biased to working from the minimum reserve.

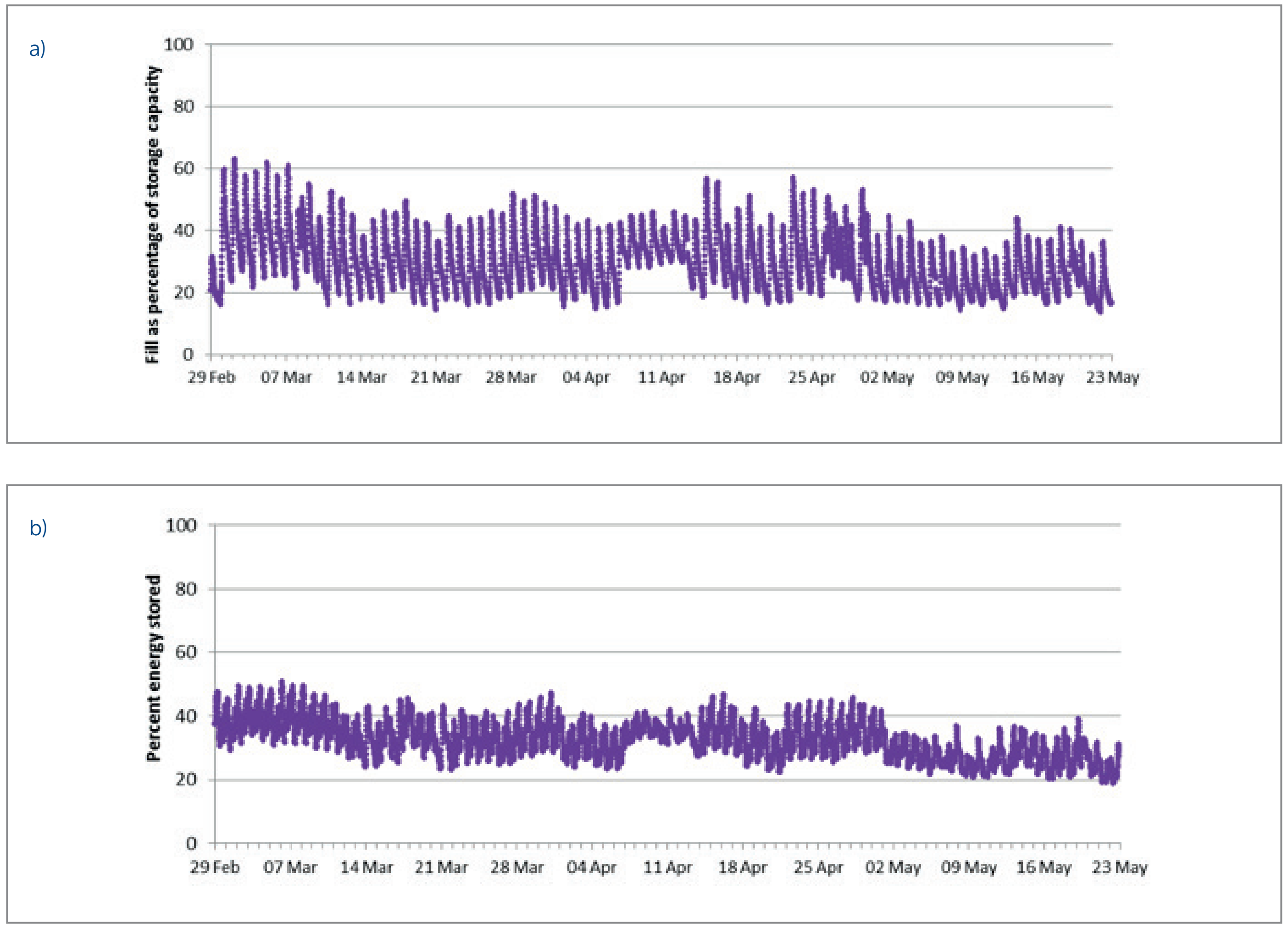


Figure 6.1 Space heaters – aggregate level of fill over 12 weeks for flexibly charged group (a) and fixed timing group (b).

6.2 Aggregate fill level in hot water tanks

Hot water tanks operate closer to full; the range for the flexible group is 60-85%, and for the fixed timing group 70-85% (Figure 6.2). There are several reasons for this. First, the tanks must cycle through 60 C, or 80% full, once a day to prevent bacterial infection. Second, the minimum comfort reserve is the equivalent of 30% full, higher than in the space heaters.

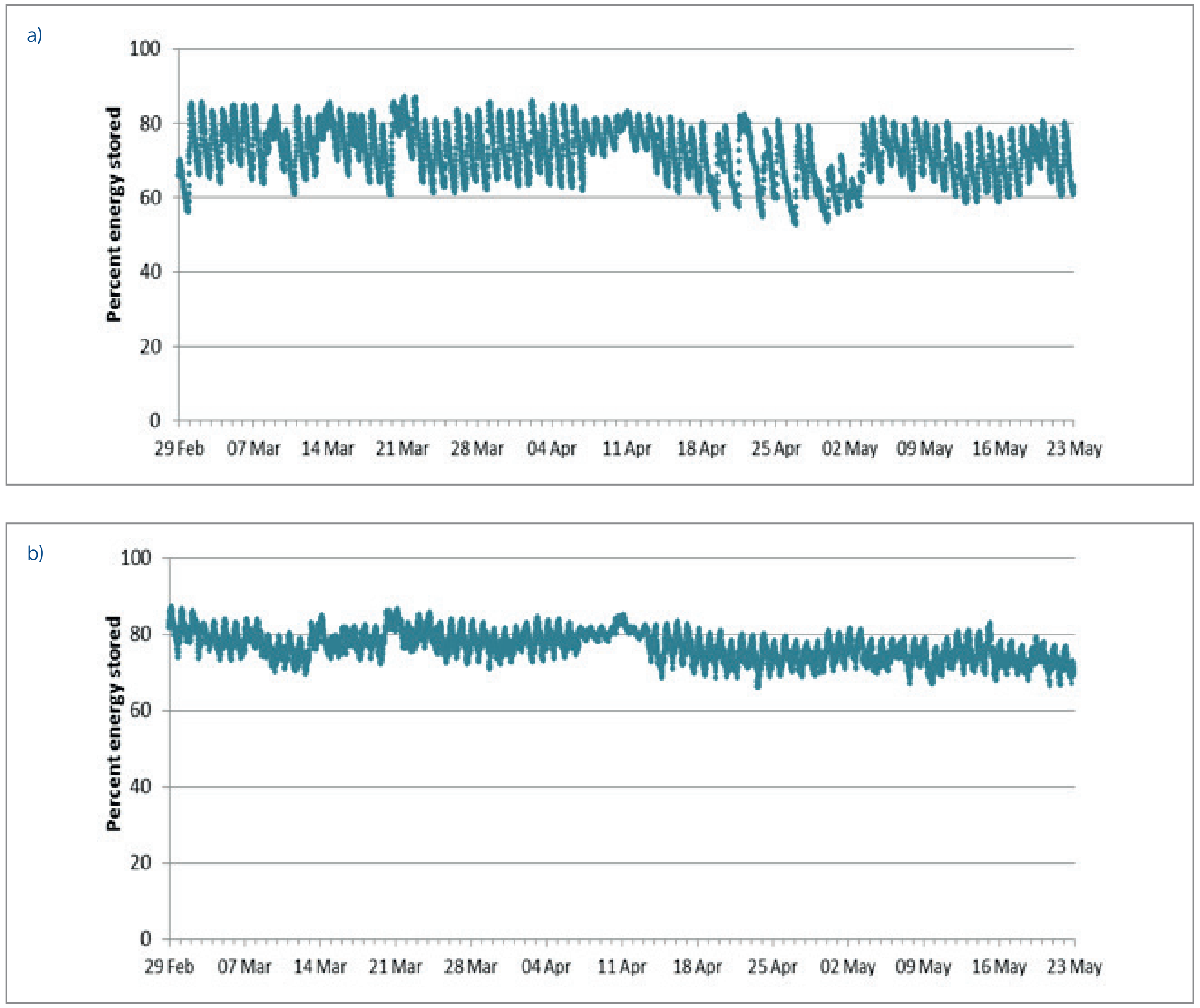


Figure 6.2 Hot water tanks – aggregate fill over 12 weeks for flexibly charged (a) and fixed timing (b) groups.

Finally, the control logic in the hot water tanks is biased to push the end of day level above the minimum reserve. DER is calculated as the average of the last three days' consumption irrespective of the level in store, but day to day consumption can vary unpredictably and hugely.

Figure 6.3 shows the variation in daily hot water consumption over 18-30 months in the 19 independently monitored households. The maximum demand (upper barred line) could be 5-10 times the median (dark line cutting the box), and this can be followed by a day with zero consumption. If DER is more than the days' actual demand, the difference will be stored if there is capacity. If DER is less than the day's demand, and the minimum reserve is reached, then the device will deliver more than DER.

If the HSE cycling requirement were to be removed, the tanks would still be operating at a higher average level relative to the minimum than the space heaters, although there should be some reduction. Quantifying the extent would require a sizeable piece of additional analysis.

6.3 Control effectiveness

The factors discussed above all affect the control effectiveness of DSM. Figure 6.4 shows how the ratio controllable power/controllable storage varied over time in the flexible storage heater group, over three different weeks.

The blue lines show the ratio calculated from the Group data reported by EM. The available storage capacity at the start of each day was the group DER, and this decreased through the day as power was drawn. Control effectiveness was highest in the early morning, followed by a steep decline whose progress was schedule-dependent. There was very little storage capacity left on most days by midday.

The red lines show the corrected values, stripping out the spurious data from devices that are turned off, and adding back the rated power of the devices that reported zero. This calculation is only approximate because the corrections were applied as daily fixed amounts rather than by matching up time series data from different data sets, but it shows how the spurious DER is the most significant confounding factor as it over-estimates the actual storage capacity available to the system.

For comparison, the green line shows what the control effectiveness would be if all the physical storage capacity could be used.

Figure 6.5 shows the same three weeks for the flexible hot water tanks.

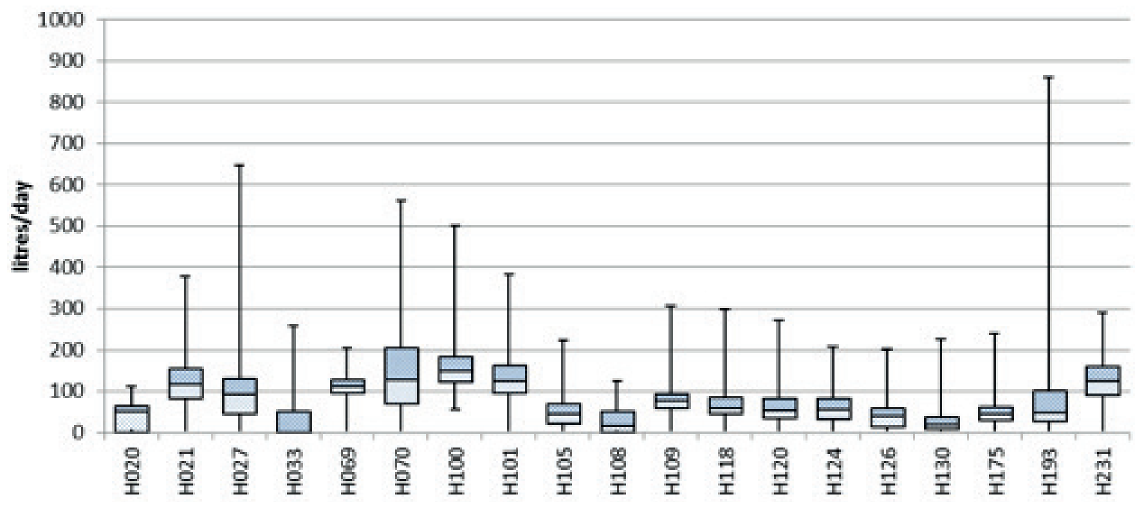


Figure 6.3 Variability in hot water consumption within each household (boxes show second and third quartile limits; dark line in the middle is the median; lines with bars show bottom and top quartiles).

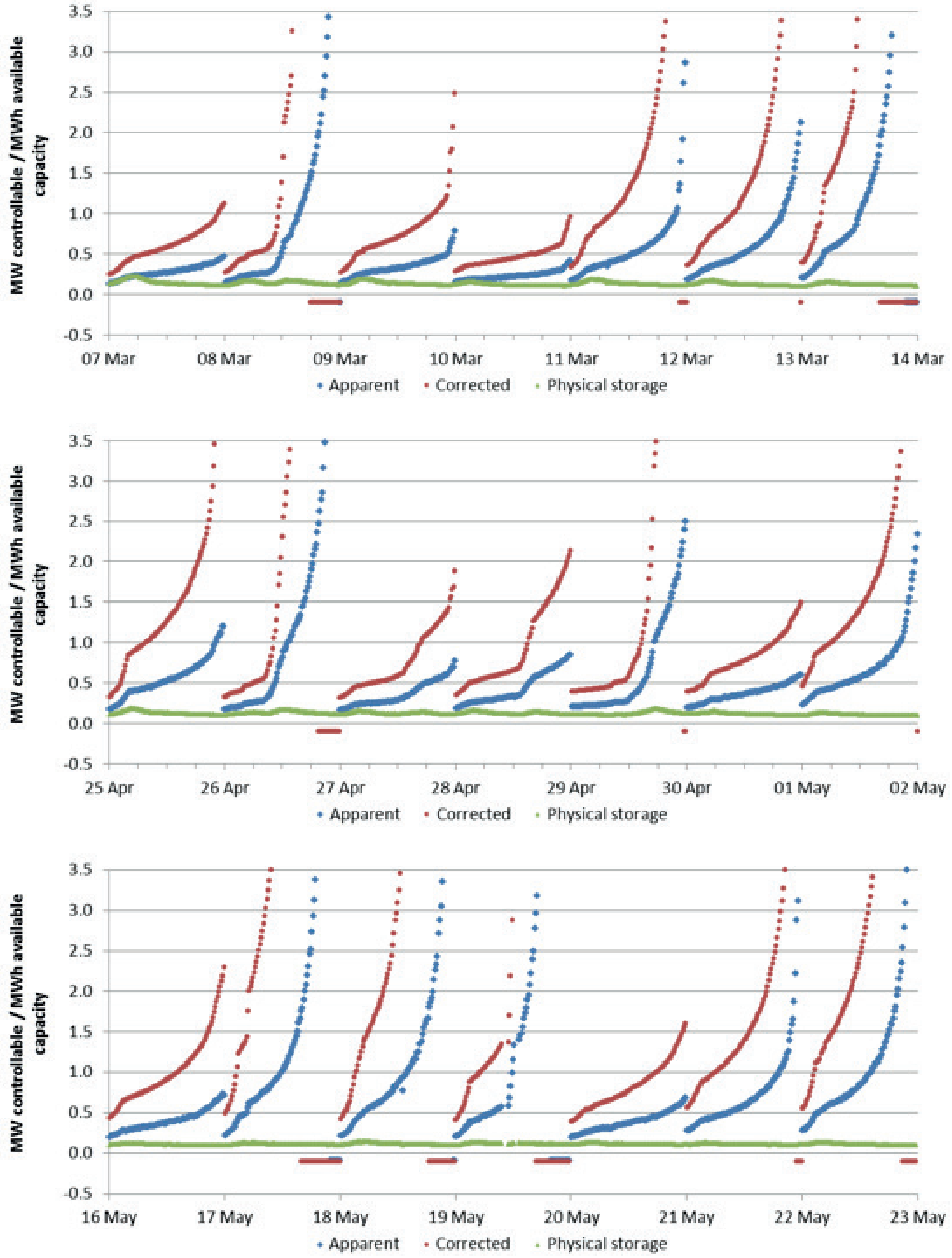


Figure 6.4 Controllable power / controllable storage, space heaters.

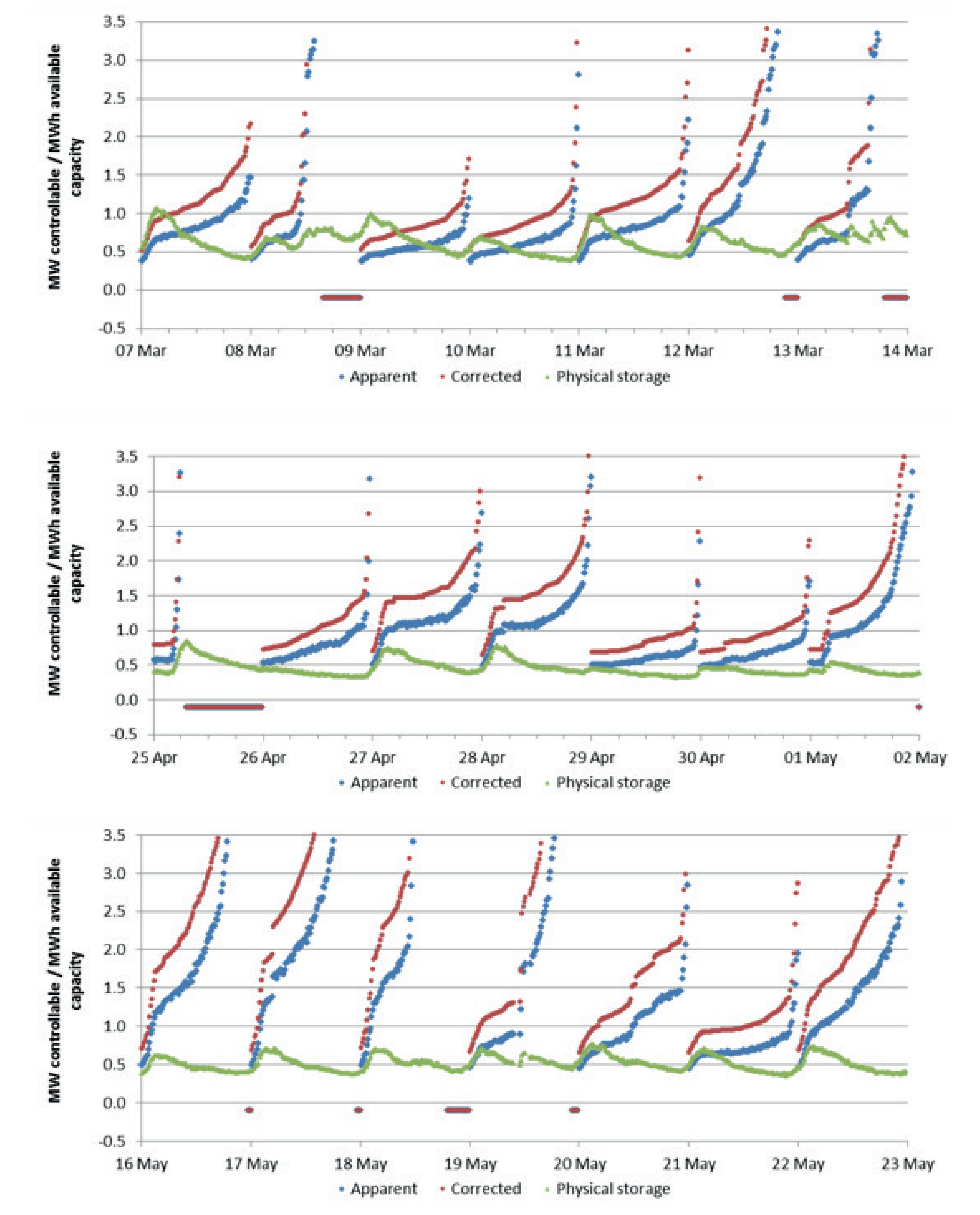


Figure 6.5 Controllable power / controllable storage, hot water tanks.

The hot water tanks did not have the problems of spurious demand, and fewer occurrences of zero rated power, so the corrected ratio is closer to the apparent. The same pattern of control effectiveness falling off rapidly through the day was repeated, although water heaters started with only around half the DER (or effective storage capacity) per unit rated power as the space heaters.

The ANM mainly scheduled the flexible groups to charge between midnight and 5 am; on average, 75% of the day's demand was scheduled in that period (Section 5.1). With only limited wind generation connected, overnight charging will work best on most days to level demand on the power station. However, this uses up the controllable storage very quickly, so that by the second half of the day there is nothing left to play with.

7

Impact on network operator's organisation

7. Impact on network operator's organisation

The introduction of DSM even at a moderate scale had an impact on SSE's staff and business processes. In particular, the role of DSM Service Operator required a set of skills that are not core to a Distribution Network Operator – although they are to an energy supplier. SSEN reported their experiences in three separate areas.

7.1 Customer relationship management

There was a fundamental change in customer relationship, which goes well beyond the meter point, as the DSM service is the provision of heat and hot water rather than electricity:

- Rolling out DSM meant having to manage relationships with many small customers and keeping track of a mass of detailed data, compounded by turnover in the social housing tenants.
- Dealing with queries and problems that are behavioural not technical, for example customers not knowing how to use the devices.
- Customer and occupants were not the same, so SSEN had to work with tenants through HHA as landlord. On the other hand, having a landlord who brought a large estate for rollout and who organized installations also took some work away.
- It became more difficult to maintain separation between energy supplier and network operator, with insight into consumption and lifestyle of users.
- Although the EM collected large amounts of data, this was not used for any proactive monitoring and problem identification. When a specific problem was identified, the raw data had to be investigated.

7.2 Installation and technical support

An extra layer of complexity came from having to manage multiple other commercial relationships: the device manufacturer, communications system provider and installation contractor. When problems occurred it was not always easy to identify the reason.

- The DSM equipment was supplied by Glen Dimplex to HHA via the installation contractor, so SSEN had to manage upgrades to third party kit with no contractual relationships established.
- Commissioning problems had to be solved through numerous individual visits, often in difficult to reach locations.
- There was at best only a limited ability to fix things if they go wrong as some customers are difficult to contact and even then may not allow access.

7.3 Control room operations

A large number of groups had to be implemented and managed, more than needed, because existing tariffs had to be maintained. Otherwise DSM was not reported to have had any impact on control room operations.

8

Future deployments

8. Future deployments

8.1 Handing over to a DSM Service Operator

In the NINES project SSEN has been dealing with one homeowner, HHA, who was running a large heater replacement programme in order to meet energy efficiency requirements on social landlords. Rolling out in the private market will however require marketing to and dealing with many individual homeowners and so the challenge of managing multiple small customer relationships will be intensified. SSEN therefore envisage that the management of DSM will be in the hands of a dedicated Service Operator[38] rather than the network. They believe that another 500 houses could be rolled out and serviced without increasing support staff, although some investment in systems will be required – this is discussed in detail in the Customer Impact Report[39].

8.2 Selection of optimal customers

8.2.1 Houses best suited for DSM

Control effectiveness depends on the energy needs of a house and on the heater configuration within it. The NINES rollout houses were relatively low-demand properties and not representative of the general housing stock in Shetland. If the rollout to the private sector focuses on larger, older hard to insulate houses that have higher heating demand then this would give a significantly higher controllable capacity per house. And because they need more heat, and have a longer heating season, the available controllable storage as set by the DER would also be higher.

Figure 8.1 shows the outcome of modelling studies on the effect of building fabric and heater configuration on control effectiveness. The modelled unit is an estate of 100 typical semi-detached houses, with different types of building fabric and insulation level. The oldest houses are on the right, in red, and buildings of the current standard on the left in violet. Three different, plausible heater configurations of size and location are modelled in each house and compared to a baseline demand from direct heating as needed.

The older, poorly insulated houses have an annual demand up to five times as much as those built to current standards, and their demand does not vary much with heater configuration. They also offer two and a half times as much flexible storage capacity per unit of flexible power. In the new houses demand is dominated by the need to maintain a minimum core temperature and the available storage is very small. A typical larger, older stone-built house with 4 heaters could provide a controllable capacity of 9.5-10 kWh/house. 500 additional houses of this kind would add 4.8 MW of controllable capacity.

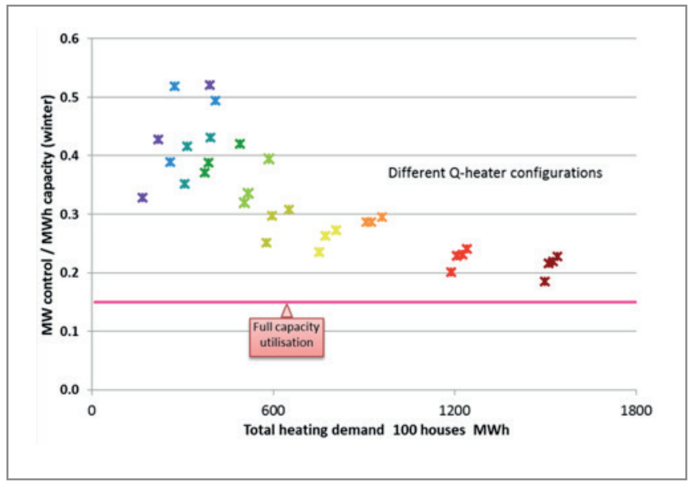


Figure 8.1 Effect of building fabric and heater configuration on heating demand and control effectiveness.

8.2.2 Location of space heaters

Where heaters are located in a house affects the degree to which they contribute to controllable capacity. Living rooms are the most effective as they are heated more of the time and to higher temperatures than other parts of the house. Bedrooms are least effective as they are less used, set at cooler temperatures and the heaters often switched off. Glen Dimplex themselves recommend storage heaters in living areas and panel heaters in bedrooms[40].

In NINES, less than half of the 43 installed bedroom heaters were ever visible, reducing to a quarter in the summer. It is probable that some were switched off the whole time. Those that were operating had an average daily demand half of that of the average living room heater. Halls and kitchens called for two-thirds. Figure 8.2 show the average daily energy required by all the visible heaters by location.

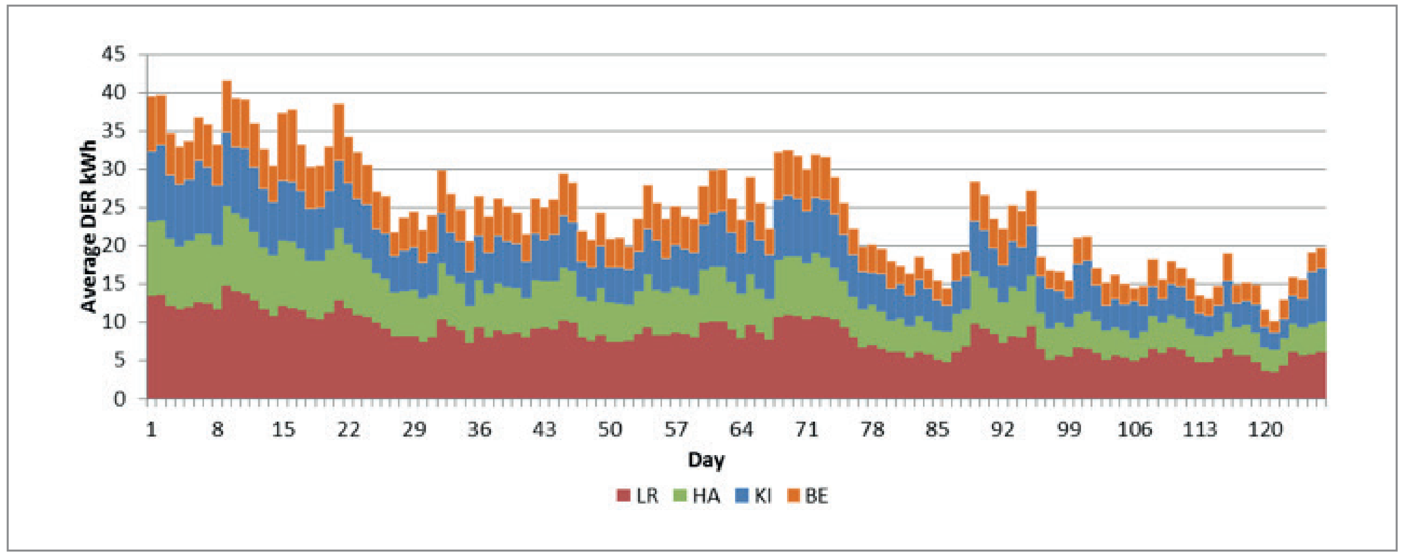


Figure 8.2 Average DER each day from all heaters in a type of room.

8.3 Enhanced EM/LIC functionality

The issues leading to inaccuracies in the data at the centre (discussed in section 4.2) could be solved or improved by changes to the some of the functionality in the current system. Spurious DER and zero rated power can easily be spotted in the data and could be compensated for in EM before aggregation. The device manufacturer Glen Dimplex has made changes to the Home Hub system, which they believe will solve the RF communications problems within the houses, although at present there are no plans to install this.

It will also be important to ensure that the LIC is flagging when a device is out of communication, and is able to respond to the EM independently of LIC-Hub communications as specified. These issues are discussed as part of the learnings in the DSM Infrastructure Report[41].

More accurate information about the energy delivered during the day would give the network a better picture of the remaining storage capacity as well as how much flexible load to expect in the next scheduled period. This ought to be possible because the LIC already has the basic functionality to integrate a load curve so it could be developed to calculate the energy delivered to date against DER. A real-time data analysis package added to EM, providing regular diagnostics on how the individual devices are behaving, would be helpful to both network operator and DSM service operator. Reliable communications and better quality data should make it possible to re-schedule during the day with confidence.

8.4 Optimum number of DSM houses

8.4.1 Wind generation enabled

The prototype studies[42] showed that with 19 MW wind connected, frequency responsive DSM could allow 4.2 TWh of fossil fuel generation per year to be replaced with energy from renewable sources if it was deployed in 1,750 houses. The average flexible load per house in the studies was 8.8 kW, giving a total 15.4 MW of DSM load. There was no benefit if the connected wind was less than 15 MW, and without frequency response the benefit halved.

Assuming that the communications problems can be fixed, 199 of the 223 live HHA houses have flexible scheduling and provide 1.4 MW of controllable power. If future rollouts are space heating only, to an estate that is representative of the older properties on the islands, then an additional 1,710 houses could give the 15.4 MW controllable load.

Simulations using detailed heater-in-house models[43] to investigate how a small group of houses and space heaters respond over a year to a charging schedule optimised for wind, showed that only around 70% of the theoretical network benefit could be achieved because of device out-of-schedule behaviour: heaters that were full stopped charging, and heaters that were empty started charging[44]. At 70% benefit, 22 MW of controllable power would be needed in total, and that translates to 2,515 additional rollout houses (Table 8.1). The study was small scale, and the evidence is that the rollout devices can follow schedule much better than the prototypes, so these findings are not necessarily typical of the current system. However, in the live system there is still around 5% charging out of schedule even after spurious effects are eliminated, and the peak load is never as high as scheduled. So some benefit degradation factor between 70-100% should be expected.

Houses	Number	Controllable kW/house	Controllable MW	Cumulative MW
Current HHA rollout	223	7.2	1.4	1.4
Required with 100% benefit	1710	8.2	1.4	15.4
Required with 70% benefit	2515	8.2	15.8	22.0

Table 8.1 Estimate of number of additional houses required with 19 MW wind.

A number between 1,710-2,515 houses is not impossible as SSEN estimate that current teleswitched demand exceeds 38 MW, and at least 17 MW is definitely known to be space heating[45]. The Scottish House Condition Survey[46] shows 4,300 poorly insulated homes in Shetland that would be suitable for DSM, and a study carried out by SSEN suggests that there are over 7,000 homes with tariffs suitable for DSM[47]. However, it does mean that one house out of every five would have to be on DSM in the best case scenario, and more than one in every four in the worst.

8.4.2 Peak load reduction and frequency response

In a large scale rollout, the maximum potential for load shifting is an average of 1 -5 kW per house depending on time of day, This assumes that all the DSM houses convert from teleswitching as the maximum possible load in the current Shetland teleswitching schedules varies from 9% of the total capacity between 20:15 and 21:15 to 69% between 07:15 and 07:45[47].

Figure 8.3 shows the envelope of the maximum potential contribution to load shifting from each house that moves from teleswitching to DSM, with 8.2 kW storage heaters and allowing for only 90% schedule following.

If more wind generation is connected, the flexible devices are more likely to be scheduled when wind is blowing so frequency response will be more available through the day. With 8.2 kW controllable capacity per house, the maximum wind supported will be 2.2 kW if all the devices follow schedule, dropping to 1.5 kW at 70%.

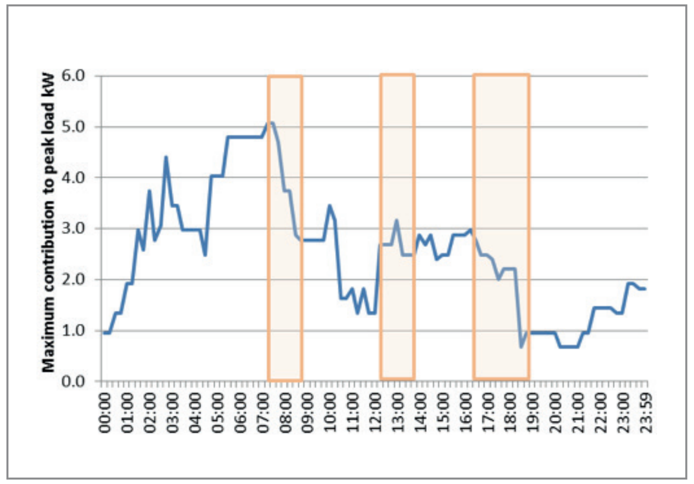


Figure 8.3 Average maximum contribution to peak load shifting when an 8.2 kW house moves to DSM (historical peak load times highlighted).

8.4.3 Infrastructure considerations

To gain maximum benefit from DSM, around 15.8 MW of controllable capacity will be required, with around 2,500 houses and 8,000 controllable space heaters. According to specification the EM should be capable of collecting data every 5 minutes from 750 houses with 10 devices each. Airwave has estimated that 4,880 LICs could be handled by their network of 9 base stations at 15 minutes if 10% of LICs are unresponsive. So both the EM and the communications network should be able to accommodate the optimal rollout at 15 minute polling. If however a shorter polling period is desired then additional base stations will be required, and possibly a parallel EM will need to be installed.

A second upgrade will also be required to the Home Hubs in the HHA houses to implement the Glen Dimplex solution to the RF communications problem. The last set of Hub upgrades was estimated to have cost £80,000. These issues are described in more detail in the DSM Infrastructure Report[48].

8.5 Costs and benefits

The rollout of DSM as envisaged by the open market model has five principal stakeholders:

- DSM Service Operator;
- customer/homeowner;
- customer's electricity supplier;
- network operator; and
- wind generator.

8.5.1 Network operator

The network operator benefits from DSM's contribution to network stability through frequency response, and also from the ability to shift some demand away from the peaks in response to changing conditions – for example, the maximum peak demand seen during the period under analysis occurred at a different time to the historical norm (Sections 3.2, 5.1).

The maximum potential benefit from load shifting is an average of 1 -5 kW per house depending on time of day. With more wind generation connected, the flexible devices are more likely to be scheduled when wind is blowing, so frequency response will be more available when most needed. With 8.2 kW controllable capacity per house, the maximum wind supported will be 2.2 kW if all the devices are following schedule, dropping to 1.5 kW at 70%.

8.5.2 Wind generator

With the full DSM capacity working as scheduled, the wind generator would be able to sell between 0.8 MWh more units of electricity per house per year – with 70% schedule following and if frequency response was not available, rising to 2.2 MWh per house year with 100% schedule following and frequency control. At a wholesale price of £40 per MWh each house would therefore be worth £32 – £88 per year; with a Contract for Difference price of £90 this goes up to £72-£198. They may be willing to pay part of this to the DNO in return for providing the DSM service.

8.5.3 Customer/Homeowner

The purchase and installation cost of new heaters, around £6,145, will be paid by the home-owner. Existing teleswitching customers will see 10-18% lower heating consumption and better regulation of temperature. Customers switching from central heating will have slightly higher consumption but this would be compensated by the low rate tariff; they will also be able to maintain heating for up to a day in case of a power cut. However, these costs and benefits will accrue to a homeowner who buys Quantum heaters whether or not they participate in DSM. For new customers therefore the only financial benefit of DSM is the incentive payment of £50 per year, enhanced by the moral benefit of knowing that they are helping to reduce fossil fuel emissions by participating. The only cost to the customer is willingness to share device data with the network. Levelisation payments made by the DNO will ensure that their electricity costs do not go up as a result of charging heaters through the day[49].

Existing customers in the HHA rollout receive no ongoing financial benefit.

8.5.4 Electricity supplier

The DSM Market Model asks the customer to move to a 24 hour rate tariff but provides for a levelisation payment to compensate for the fact that they are no longer buying at cheap rate. This payment was estimated by SSEN to average £300 per house per year. However it is not the customer but their electricity supplier who actually receives this income. It is at least double the value seen by the wind generator at no cost or effort to the supplier. Although the value was estimated based on the existing balancing mechanism in Shetland, a levelisation mechanism will always deliver the supplier something for nothing. NINES style DSM can only be sustainable if suitable DSM supportive tariffs are developed.

8.5.5 DSM Service Operator

In 2013 SSEN estimated that it would cost £1.58 million to roll out DSM to 900 private homes over 3 years. This included incentive payments to get customers to sign up and levelisation payments to balance the additional costs customers from moving to a single-rate tariff.

Based on SSEN's estimates for the Open Market Model, the long term cost of supporting a 1,700-2,500 house deployment of DSM is £650-700 per house per year once the system is in maintenance mode. This includes £350 for the annual customer incentive and levelisation payments, and another £300 per house per year for communications. The remainder are DNO operating costs, customer churn, and associated marketing.

8.5.6 DSM value to the supply chain

Table 8.1 shows that under the Open Market Model the DSM Service Operator bears all the costs of rolling out and maintaining the DSM system and sells the service to those who benefit from it – the network operator and the wind generator. The customer and his electricity supplier are suppliers to the DNO, and the electricity supplier stands to gain the most with this model. It should be noted that because the existing HHA customers neither receive loyalty incentives nor incur levelisation payments they are in effect subsidising the more costly private market customers.

The maximum net value of each house to the supply chain is therefore slightly less than £200 per year, plus the value to the network operator of 1-5 kW of flexible load and up to 8.2 kW of frequency responsive load that is however available only for part of the day. The net cost of each house is £330-£380 per year in communications and support services. All other costs and benefits are simply transfers within the supply chain. This model is not financially viable as it stands even with no customer loyalty or levelisation payments, no matter how well the DNO can manage their costs. The only way it could become viable is an order of magnitude reduction in the communications costs, and/ or additional subsidy payments.

	DSM Service Operator	Network Operator	Wind generator	Customer	Electricity supplier
Benefit	Payments from Netw. Op & Wind Gen.	Peak shifting & frequency response	£32-198 extra sales	£45 from DNO*	£272 from DNO*
Cost	£650-700	Payment to DNO	Payment to DNO	None	None

*values averaged across existing HHA and new private market customers

Table 8.2 Summary of annual benefits and costs to DSM stakeholders.

9

Learning outcomes

9. Learning outcomes

This review of the benefit to the network based on the first two years of operating Demand Side Management in social housing in Shetland contributes to the NINES learning objective:

‘How can a distribution system be securely operated with a high penetration of renewable generation?’

‘What is the relationship between intermittent generation and responsive demand, including storage?

a) Effectiveness of frequency response demand side management

b) Maintaining network stability in an operational environment

c) Interaction of numerous variables on a closed electrical system’

Despite a reduced level of DSM capability compared to the levels originally envisaged the project has delivered a significant amount of useful learning as described below.

- DSM was expected to contribute to replacing fossil fuel generation only when at least 14 MW wind is connected, and the current wind capacity is well below this. With 19 MW wind, the current deployment could in theory allow 385 MWh of fossil fuel generation to be replaced annually.
- Moving to DSM from teleswitching has reduced the maximum possible load from these houses during the periods of historical maximum peaks from 0.6-0.7MW to just over 0.1 MW, if the devices are following schedule. This results from changing the fixed and default schedule timing as much as from the capability for flexible scheduling. However, unlike with teleswitching, the Quantum heaters are able to charge outside scheduled periods.
- The expected benefit from frequency response has not materialised because the main problem is with under-frequency events, where the DSM devices need to be charging and switch off to contribute to network stability. Charging takes place over around 8 hours at most each day; and so far the Lerwick Power Station has not relied on it operationally.
- Only around 50-60% of installed capacity was reliably visible and available to the network on any given day. This is believed mainly to be because of poor RF communication between device and Hub within houses; a solution has been developed by the manufacturer but this has not yet been rolled out. Given that communications problems have persisted since the start of the prototype trials, it would be prudent to roll out and test this solution before planning any further DSM deployments.
- With 50-60% of devices regularly out of communication and unavailable the theoretical wind generation that could be supported reduces from 385 to 230 MWh.

Other learning points from the first year’s full operation include the following.

- For all groups the peak load is generally less than scheduled, and a consistent, low level of charging takes place outside the schedule at around 5% of capacity. Individual devices follow the schedules set by the LIC quite well, much better than in the prototype where devices were in unscheduled charging for 20% or more of the time. However, the heaters necessarily calculate an energy requirement using averaged assumptions but occupant behaviour is unpredictable, so there are always some devices which become full or empty at the wrong time and stop or start charging outside schedule. Modelling studies indicate that this out-of-schedule behaviour could reduce the expected network benefit by 30%, in other words, 30% more houses must be deployed with DSM to give the same benefit.
- Flexible charging uses a greater range of the physical storage capacity than fixed timing schedules. For space heaters the overall flexible range is between 20-60% of capacity in winter, falling to 20-40% in summer. For hot water tanks on flexible charging the range is 60-85%. The different control algorithms used by the two devices bias the space heaters to be working just above the minimum, and the hot water tanks to just under the maximum capacity.
- The ANM mainly schedules the flexible groups to charge between midnight and 5 am; on average, 75% of the day’s demand is scheduled in that period (Section 5.1). With only limited wind generation connected, overnight charging

works best on most days to level demand on the power station. However, this uses up the controllable storage quickly, and by the second half of the day each unit of controllable power has small controllable storage.

- In contrast to the prototype heaters, the control algorithm implemented in the production version does not allow scheduling over more than one day as the heaters will not accept more than the DER that they have calculate unless the fill level falls below the minimum reserve. SSEN have no plans at present to schedule over a longer period.

- DSM has had very little impact on control room operations; however, it has made a fundamental change in the network's relationship with customers as the DSM service is the provision of heat and hot water rather than electricity. This has meant having to manage day to day relationships with many small customers to solve behavioral as well as technical problems. It also requires keeping track of a mass of detailed data.

In terms of future rollouts:

- NINES deployed DSM mainly in small, relatively new and well insulated homes. If future rollouts target larger, hard to insulate houses which make up half of the Shetland housing stock then the controllable capacity available for each set of DSM enabling equipment could be doubled. In addition, such houses will have a longer heating season and heaters are less likely to be turned off in summer. Heaters should be deployed in living areas and halls where heating needs are high and controllable capacity is available more of the time.

- A number of functionality enhancements to the LIC and EM would improve controllability and resolve some of the current problems. Better quality data should make it possible to re-schedule during the day with confidence.

    - Calculations of Group DER and rated power in the EM should be changed so that spurious DER reported by some heaters can be identified and removed. Also, active heaters that report zero rated power should be identified and compensated for in EM before aggregation.

    - The LIC should be developed to calculate and report the energy delivered to date against DER rather than instantaneous power. This would give the network a better picture of the remaining storage capacity and how much flexible load to expect in the next scheduled period.

    - A real-time data analysis package should be added to EM, providing regular diagnostics on how the individual devices are behaving.

    - The LIC's functionality should be audited to ensure that it actually reports as specified, flagging when a device is out of communication and able to respond to the EM independently of LIC-Hub communications.

- Since benefits are expected to be eroded by up to 30% because some devices will always be operating outside schedule, around 2,500 houses would need to be deployed with DSM to provide 15.8 MW of frequency responsive DSM reliably and support the optimal amount of wind generation. This represents a quarter of all the houses in Shetland.

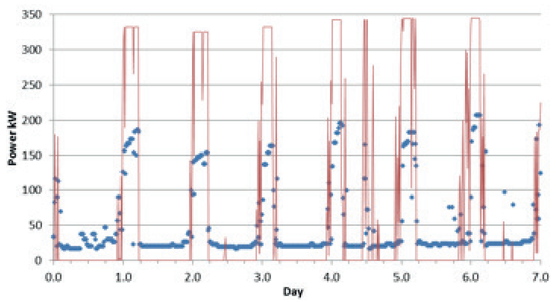
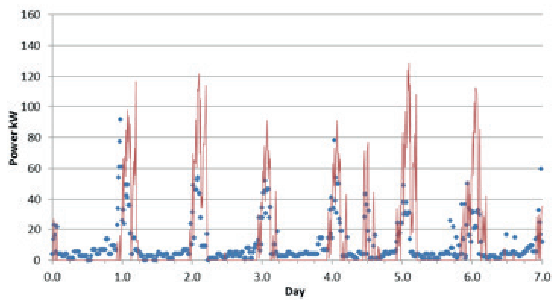
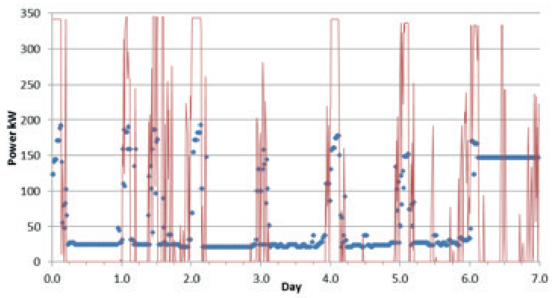
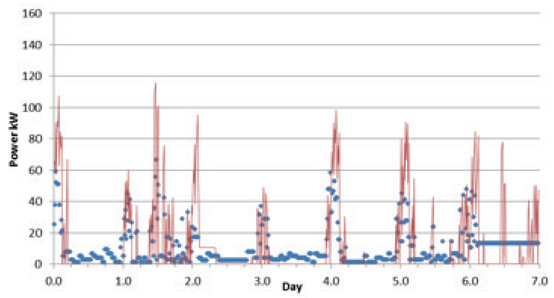
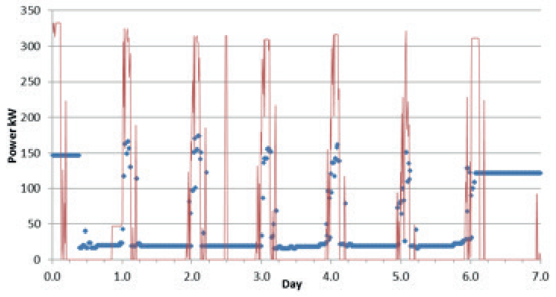
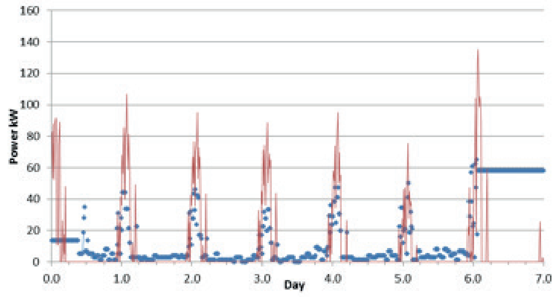
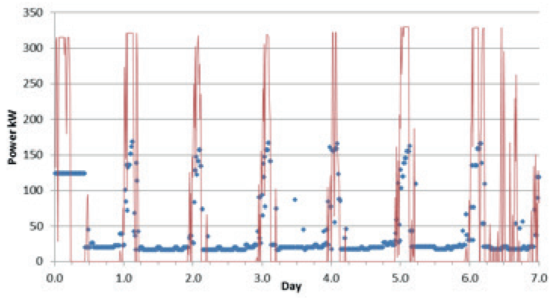
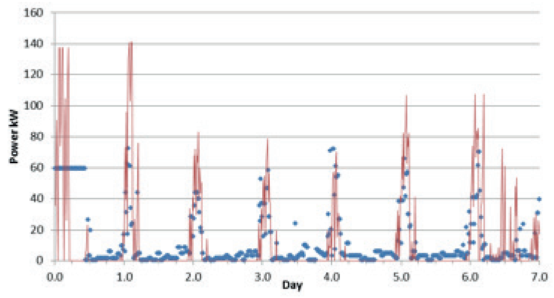
- The maximum net value of each house to the DSM supply chain is slightly less than £200 per year, plus the value to the network operator of 1-5 kW of flexible load and up to 8.2 kW of frequency responsive load. The net cost of each house to the supply chain is £330-£380 per year in communications and support services. All other costs and benefits are transfers within the supply chain. This model is not financially viable as it stands even with no customer loyalty or levelisation payments. Becoming viable requires an order of magnitude reduction in the communications costs, and/ or additional subsidy payments.

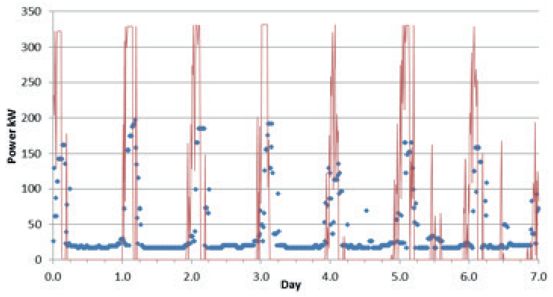
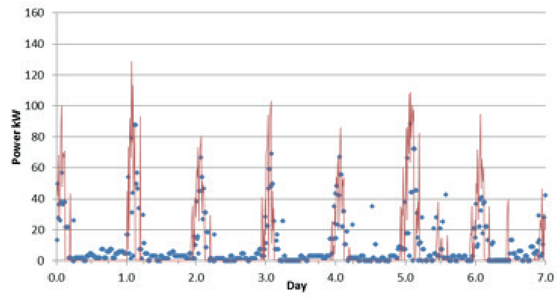
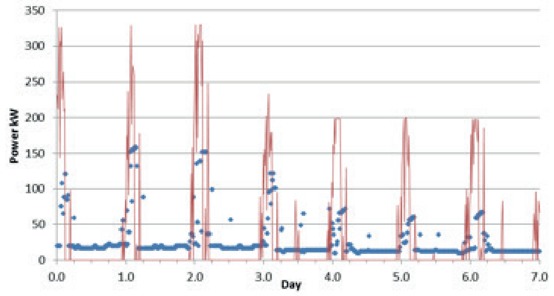
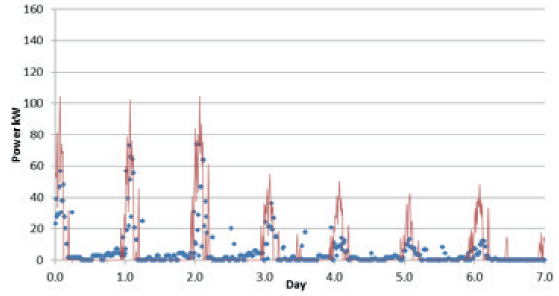
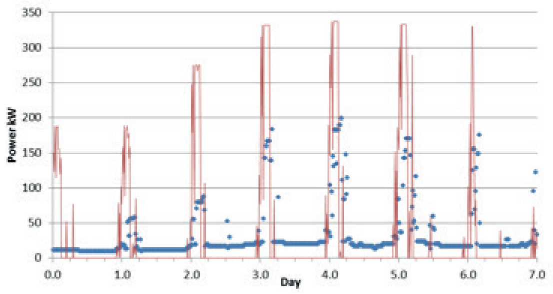
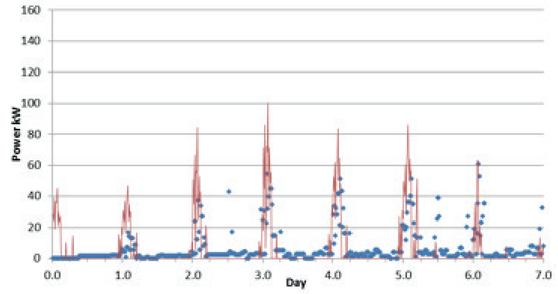
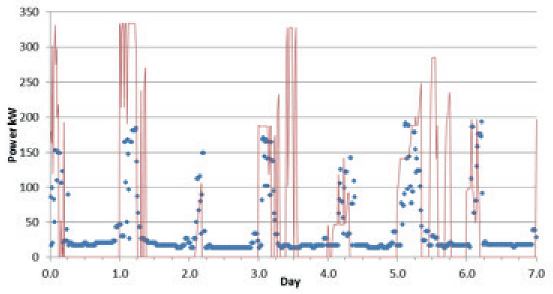
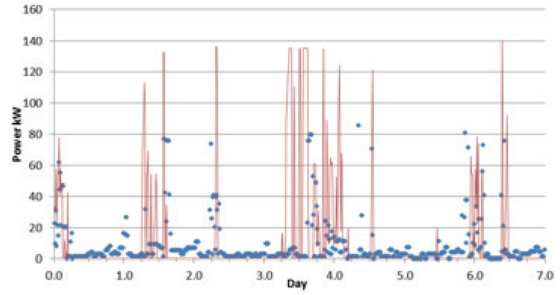
APPENDIX I

Active schedules and schedule following

9. Active schedules and schedule following

The following graphs depict the scheduled power and instantaneous power reported for the flexibly scheduled groups for each of the 12 weeks analysed. Red lines are the target schedules, blue the instantaneous power.

Date	Group 1 Space Heaters	Group 2 Hot Water Tanks
29/02 – 06/03		
07/03 – 13/03		
14/03 – 20/03		
21/03 – 27/05		

Date	Group 1 Space Heaters	Group 2 Hot Water Tanks
28/03 – 03/04		
04/04 – 10/04		
11/04 – 17/04		
18/04 – 24/04		

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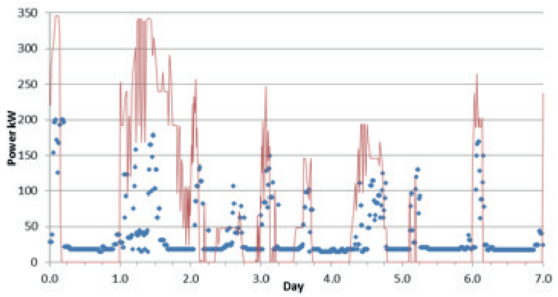
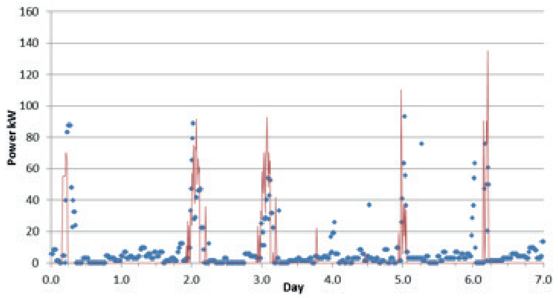
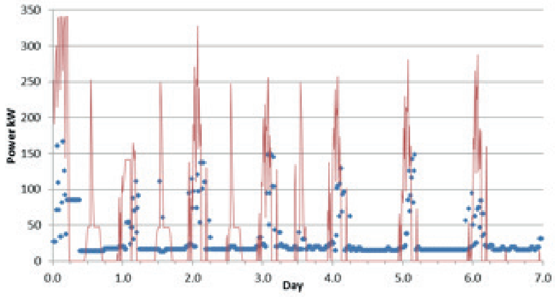
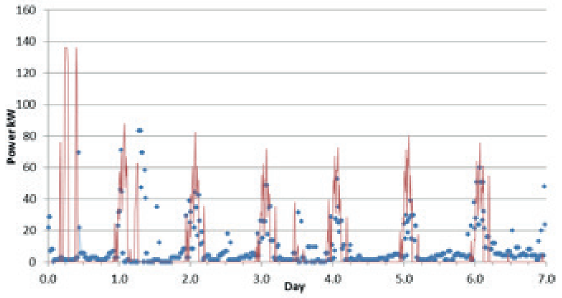
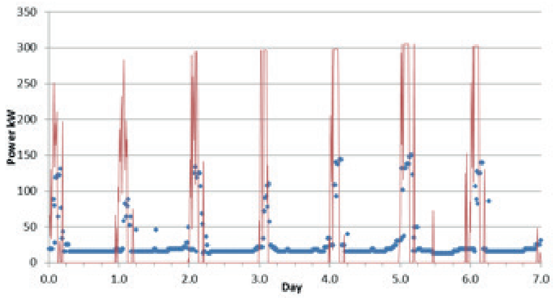
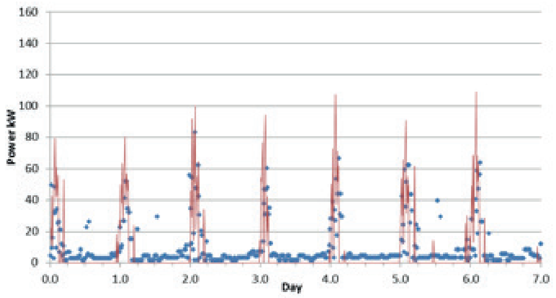
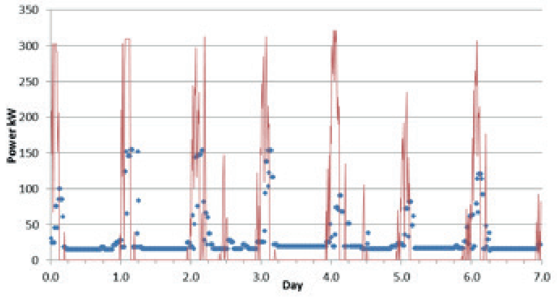
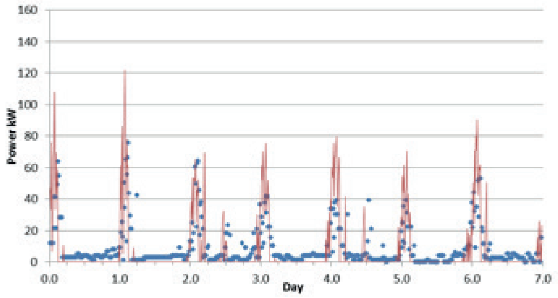
25/04 – 01/05		
02/05 – 08/05		
09/05 – 15/05		
16/05 – 22/05		

Footnotes

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15:	Technical Specification for Glen Dimplex Appliances - NINES Installation (April 2013) GD-Quantum-TS-001, Glen Dimplex Heating.	16
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