Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

ELECTRICITY STORAGE WITHIN THE DOMESTIC SECTOR AS A MEANS TO ENABLE RENEWABLE ENERGY INTEGRATION WITHIN EXISTING ELECTRICITY NETWORKS

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ABSTRACT

With the present drive to add renewable generation capacity to existing electrical networks, utility providers are seeking ways to store electrical energy as a means of prioritising renewable sources against an unfavourable load profile. One way to do this is through electrical storage heaters and hot water systems within the domestic sector. This approach requires that the control of such devices be externalised and enacted on the basis of parameters relating to renewable energy availability and network power quality.

This paper reports the simulation-related aspects of a project involving the roll-out of this approach across a large estate of houses in Lerwick on the Shetland Islands, UK. The paper describes the implementation of network sensitive equipment models for space and water heating within the ESP-r system, the calibration of these models using monitored data, and the application of the outcome to identify an effective approach to equipment control and to develop a demand forecaster to enable the scheduling of network generation assets.

INTRODUCTION

Development of renewable energy is constrained by the stochastic nature of the generation and the added challenges this provides in keeping demand and supply in balance. While smart grid technologies combined with energy storage offer a potential solution, there have been limited opportunities as yet to test these in practice and at large scale.

The Northern Isles New Energy Solutions (NINES) project is presently underway in the Shetland Islands, UK. Located 160 miles to the North-East of the nearest point on the Scottish mainland, the 15 inhabited islands are not connected to the UK electricity grid, thus requiring the distribution network operator SHEPD (www.ssepd.co.uk), to balance demand and supply across a population of 22,000. Shetland has a high potential for renewable generation and has access to a significant proportion of Europe's wind, tidal stream and wave power resources. However, network stability constraints mean that no more than the single, modest 3.7 MW wind farm can currently be connected. Although the main island hosts the Sullom Voe crude oil storage facility for North Sea oil fields, most electricity is supplied from an ageing power station that runs on imported diesel. With no gas network, a large proportion of space and water heating is electric. As they prepare to replace the power station, SHEPD are deploying a number of novel technologies that together are intended to reduce fossil fuels use, increase the amount of renewable energy that can be connected, and improve the reliability and quality of the electricity supply on the islands (SHEPD 2011).

The core technology is an Active Network Management (ANM) system that not only controls the units in the power station but also switches wind generators on or off in response to demand fluctuations. This is supplemented by the deployment of energy storage devices that can be controlled centrally: a 1 MW battery, a 4 MW thermal store serving a district heating scheme, and a Domestic Demand Side Management (DDSM) system with a total input capacity of 2.1 MW that will be distributed across 235 dwellings.

The DDSM approach uses smart domestic space and water heaters to store energy during periods of excess supply. These so-called 'Quantum' devices (Figure 1), manufactured by Glen Dimplex (www.glendimplex.com), receive a centrally generated charge schedule from the ANM and relay back data on thermal store status. They can accept input power at variable but discrete levels to support close control. Note that in this context, DDSM does not equate to traditional demand side response (Ofgem 2010) because it does not alter the customer's demand for heat or hot water on the basis of price signals. Only the timing of electricity input by the utility to local storage is affected.

The basic instruction is a daily schedule for power input by quarter hour for the upcoming 24 hour period, based on anticipated supply, demand and network status. An additional novel feature of the equipment is the ability to respond automatically to short term changes in grid frequency, shutting down charging when the frequency drops below an acceptable level and increasing it when the frequency rises. The space heaters are more efficient than previous versions due to high levels of insulation and also because output power in the active mode is fan assisted and under occupant control. The water heaters offer no occupant control. The schedules can be overridden locally if they would breach a maximum safety or a minimum comfort setting for the temperature of the heater core or the water.

Figure 1: The Quantum space and water heating equipment

Prototype versions of the space and water heaters and their central controller were installed in 6 trial houses in 2011 and are presently being rolled out to 235 houses throughout 2013. Of these, 35 have been selected as statistically representative of the housing types and occupancies throughout the estate and are being monitored in detail.

ESRU's role in the project was to implement the monitoring scheme and use the outcomes to calibrate ESP-r models of the Shetland housing estate. These models were then used to a) investigate the impact of alternative charging schedules and b) generate demand profiles for dwelling/weather combinations to enable demand forecasting to inform asset despatching and scheduling.

MONITORING OUTCOMES

The monitoring scheme as depicted in Figure 2 was designed to facilitate the construction of energy balances around the heaters in order to determine their charge/discharge/storage behaviour over time; space temperatures and weather parameters were also recorded. The data collection frequency was 5 minutes and comprised 2-10 devices per dwelling and 13 data channels per device.

The field trials so far have followed the original teleswitching schedules that allow 8.5 hours of storage heater and 5.75 hours of hot water cylinder charging, at various off-peak times during the day as well as overnight: these schedules are specific to Shetland. Analysis of monitored performance gave rise to the following findings:

- The space heaters utilise only around 35% of their available storage capacity on average. Figure 3, for example, depicts a typical heater's performance over a three day period, with the vertical axis showing the full storage range. Although water heaters vary more with occupant behaviour, 50-80% capacity utilisation is typical and only occasionally is the whole tank drained.
- Although the heaters are well insulated, they still emit uncontrolled losses, averaging 120-240 W each. In the highly insulated trial dwellings this alone can largely meet the heat load except during very cold periods. Figure 3 illustrates the typical relative contributions of uncontrolled and fan-assisted heater output in one house during a cold period.
- Much charging takes place outwith scheduled periods for both space and water heaters. This is due to limitations imposed by the heater controllers, which in case of conflict will override instructions from the ANM system. They are programmed to make an estimate of the energy required next day and disable charging beyond this cap; in addition, they must maintain an energy reserve at all times. If the actual demand is different, whether because of colder temperatures, changes in occupant behaviour, or estimation algorithm inaccuracy, heaters charge during unscheduled periods or stop charging when scheduled to do so.
- From the occupants' point of view, the new heaters are more controllable than those they replace, as judged from the fact that the indoor temperature in different dwellings converged after the upgrade.
- Hot water availability is high, with temperatures at the top of the tank exceeding 40˚C for most of the time. This however means that the absolute level of standing losses is greater even though the tank is better insulated.

These smart heaters do work but not always in the manner anticipated.

ESTATE MODELLING

The 235 homes in the rollout comprise a variety of sizes, layouts, ages and constructions, although with a higher proportion of modern, well-insulated dwellings than in the Shetland housing stock as a whole. They are owned by the Hjaltland Housing Association (www.hjaltland.org.uk) who provided information about the physical nature of the houses. This allowed each dwelling to be categorised against a range of representative forms and constructions for modelling purposes.

Each house has one water heater and between 1 and 9 space heaters. Only a proportion of the space heating requirement is provided by the controllable storage heaters, the rest coming from direct panel heaters. A complicating issue in the modelling is that there can be different heater configurations in any one type of house as heaters are replaced on a like-for-like basis. This required modelling the internal layouts in greater detail than in previous applications of ESP-r to large housing estates (Clarke *et al* 2004).

In order to avoid issues around personal data, occupancy levels and behaviours were synthesised so that the rollout stock had the same statistical distribution of occupants as seen in the Shetland 2011 census (Scottish Government 2013) and the 2009/10 Scottish House Condition Survey (National Statistics 2011). Preferred indoor temperatures were randomly distributed in line with the range observed in a large scale survey of houses in England and Wales (Shipworth *et al* 2010). Average daily hot water use was allocated to each house in a log-normal distribution reflecting that observed in measurements of hot water consumption in the UK (Energy Saving Trust 2008), and daily hot water demand profiles at 15 minute time steps were generated using the DHWcalc tool (DHW 2012). The specific values associated with all model parameters are reported elsewhere (NINES 2013), while Table 1 summarises the variants considered for principal parameters to give insight into the number of simulations required.

HEATER MODELLING

Figure 4 outlines the 9-zone ESP-r model of the Quantum space heaters. The model was designed to represent the following processes:

- variable energy input to each of the three sections of the core during charging;
- heat transfer from the core to the intra-heater air stream;
- heat transfer through the insulation to the room air (uncontrolled output); and
- heat transfer from the intra-heater air stream to the room air (fan assisted output).

The heaters were represented explicitly using data provided by the manufacturer (Glen Dimplex 2011). There were three areas of uncertainty where parameters were either estimated from heater performance tests or from published data:

- specific heat capacity was derived from the temperature rise recorded during the charging cycle in laboratory performance tests;
- air flow rates around the brick core were estimated from heat outputs from laboratory performance tests when performed under uncontrolled discharge and fan-assisted operation;
- dynamic convective coefficients were determined from empirical correlations corresponding to natural convection in the uncontrolled discharge case (Alamdari *et al* 1984) and forced convection when the heaters where operating in fan-assisted mode (Fisher and Pederson 1997).

These data were then adjusted during the calibration phase utilising field trial: Table 2 shows principal parameters of the calibrated models. The specific heat capacity falls within a physically plausible range of 800-1200 J/kgK for storage heater bricks as reported by Otero & Alvarez (1994).

Table 2: Key parameters for heater models

Parameter	Model value
Heater volume (P125)	0.14 m^3
Heater surface area (P125)	2.0 m^2
Power input capacity	3 x 800 W
Specific heat capacity of core bricks	880 J/kg-K
Maximum core temperature allowed	620°C

Figure 5 shows examples of outcomes from both laboratory and field test calibrations. The left hand curves show the core temperature and heat output from one heater when charged and discharged in a laboratory test. Full charge was applied for 8 hours causing the core temperature to rise rapidly. With the power off and the fan not operating the core temperature then fell slowly: after 16 hours the thermal store was still two-thirds full. Heat loss from the heater peaked around two hours after power cessation. Of the heater model parameters adjusted during calibration, the most significant was the convective heat transfer coefficient between the heater and room air.

An example of calibration against field measurements in one of the monitored houses can be seen in Figure 5 on the right. The dwelling was a one bedroom flat in a converted building with thick granite walls and storage heaters in the living room and hall (Figure 4). An air flow network was included in the ESP-r model incorporating a kitchen extractor fan. Two significant elements emerged from this exercise: first, since the storage heaters were in effect heating the whole flat, it was important to ensure that the air within the space was well mixed; second, with the large thermal capacity of both heater and the external wall, it was necessary to run a long pre-simulation period of 50 days so that the correct starting condition was attained.

Figure 5 shows the measured and simulated core temperatures over a three day period during a cold period. The general shape of the variation is similar in measurements and simulations, although there are differences in detail. The total simulated heat output over the three days is within 10% of measured; its pattern, and the split between uncontrolled and fan-assisted modes, also agrees reasonably well. The difference between the simulation (which has longer continuous bursts of fan assisted output) and the measurements (which show frequent on-off cycling) are thought to be due to unknown specifics in the heater's control algorithm. From the results it was concluded that the model offered acceptable performance for the task in hand, which was the investigation of the impact of alternative charge control.

CHARGE SCHEDULE

In the field trials, although the level of scheduled charging was varied, the timing was not because of the requirement to adhere to existing tariffs. This meant that the day's energy demand was delivered slowly in three periods over 18 hours, and the level in the store did not build up. During the cold spell depicted in Figures 3 and 5, the heater core was not hot enough to deliver the required output, frequently hitting its programmed minimum comfort level. This then caused it to start charging at full power irrespective of schedule instructions. This schedule therefore worked badly for both the occupants and the utility.

Simulations of alternative charging schedules were run for the same period to search for better solutions. Alternative schedules were constructed that gave the same average daily energy input as the calibration run, delivered using two different approaches:

- longest possible period of input at lowest possible charging level; and
- shortest possible period of input at highest possible charging level.

Each approach was applied at three different times of day: just before the morning peak load, in the middle of the day, and overnight. The schedules were run with set-points of 21ºC in the living areas and 19ºC in the halls, the average settings found by Shipworth *et al* (2010). To investigate the impact of the daily energy cap imposed by the heater controllers, each schedule was run with 4 different maximum fill levels representing typical caps observed in the trial houses.

Figure 6 compares the situation where the whole charge was delivered in a block overnight against the low charging level schedule. The core temperature, which indicates the heat level in the store, goes up higher, utilising the storage potential more effectively and reducing the need for charging outwith the schedule. The average core temperature is higher, and so is the output when the fan switches on. So however is the uncontrolled heat output. The occupants experience warmer room temperatures but use slightly more energy.

From the simulation results it was also apparent that turning up the thermostat can actually result in less heat output and lower resultant room temperatures, especially when the heater is at low charge. This is because a higher set-point brings the fan into operation more often, lowering the core temperature, and so reducing the heat output in both uncontrolled and active mode. Counterintuitive for users, this could have an impact on how effectively charging schedules are followed in the field. Further exploration of the impact of different charging schedules and of occupant interventions is underway. This exercise will look for schedules to maximise storage utilisation while minimising uncontrolled losses.

DEMAND FORECASTING

The demand forecasting model for the Shetland housing estate operates on the basis of space and water heating profiles *a priori* generated by ESP-r and DHWcalc. By appropriately aggregating these profiles, the forecaster predicts the aggregated 24 hour ahead heat demand profile for groups of 50 - 100 houses based on the forecast temperature for the following day.

Detailed simulations were run for representative houses, with 34 combinations of building geometry, construction and heater configuration. Each house model was simulated for all day types, occupancy levels and preferred indoor temperatures as described in Table 1. For each of the 408 house and day type variants, daily reference profiles at 15 minute intervals were derived for 1˚C increments in average outdoor temperature, and separately for winter and summer seasons respectively. Up to 3 separate reference profiles were calculated for space heating in living, hall and bedroom areas, but only if these contained storage heaters. The approximately 16,000 reference profiles are stored and manipulated by the EnTrak tool (Clarke & Grant 1996), a generic information system to manage the entities associated with energy and environment issues.

One important issue in creating reference profiles is to define the typical demand profile against daily average outdoor temperature. Even with identical daily average outdoor temperatures, the patterns (magnitude and shape) of the demand profiles vary. To produce a more robust forecast, the typical demand profiles are defined through a data pre-process which calculates the average values at the same time step from the data set generated at the same range of average outdoor temperature on different days.

In addition to the demand profiles, EnTrak stores information on each house in the estate and its synthesised occupancy. This includes a mapping to the most appropriate representative house, floor areas, occupancy data, preferred comfort level and average daily hot water consumption. Based on the next day's outdoor temperature forecast by the Meteorological Office, a corresponding reference profile is selected from the database. This profile is then scaled according to the ratio of floor areas between the actual and representative house. The profiles for each house in a group are then summated to give the aggregate demand forecast. This process is intended to generate a realistic expectation of the demand that must be met by the ANM scheduler. A typical group demand profile is shown in Figure 7.

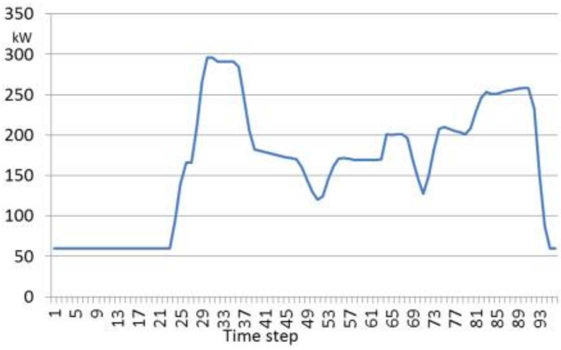

Figure 7: Example of a space heating group demand profile

CONCLUSIONS

Novel space and water heaters are being deployed in a large housing estate to facilitate electricity storage as part of active network control. This paper has reported key findings about the performance of such devices from monitoring data. Simulation models of the devices, calibrated against the monitoring data, were then used to investigate approaches to equipment charge control that maximises storage utilisation without adverse impact on customers. Representative house models were used to populate a profile database as an underpinning resource for a demand forecaster: this will inform the despatching of energy supply assets as part of active network management.

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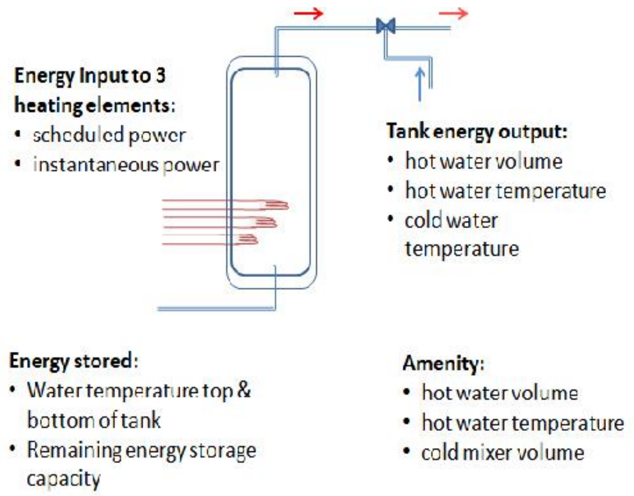

Space heaters

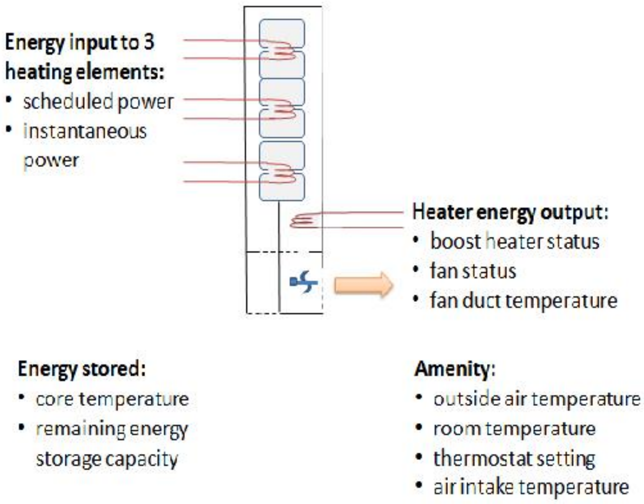

Figure 2: The DDSM monitoring scheme

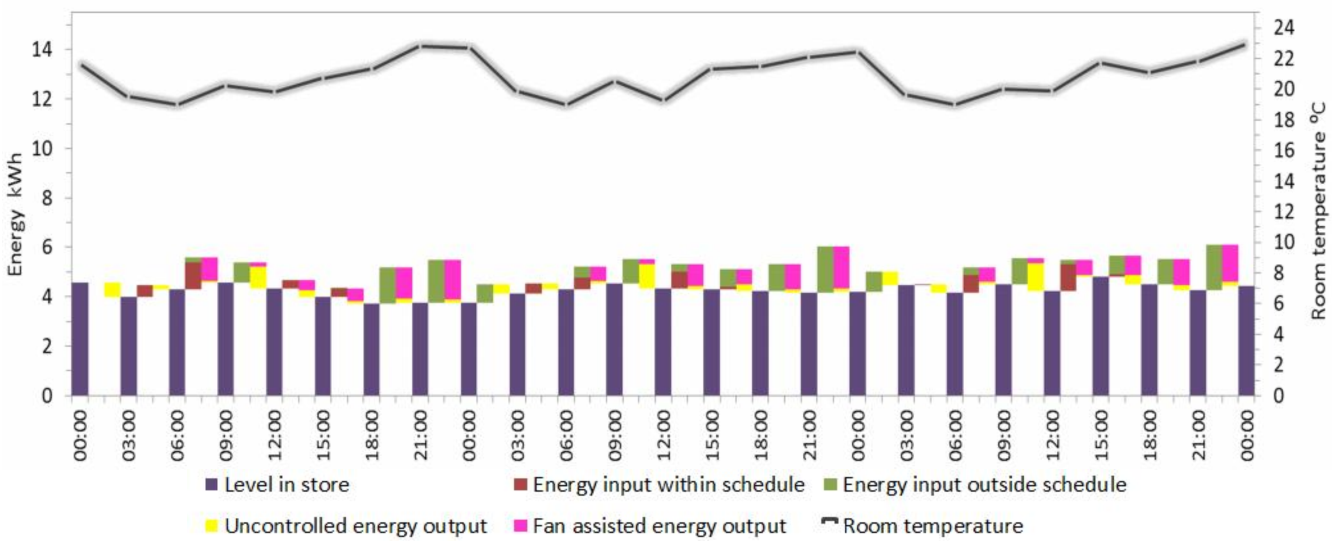

Figure 3: 3-hourly energy balances in a storage heater over 3 successive days

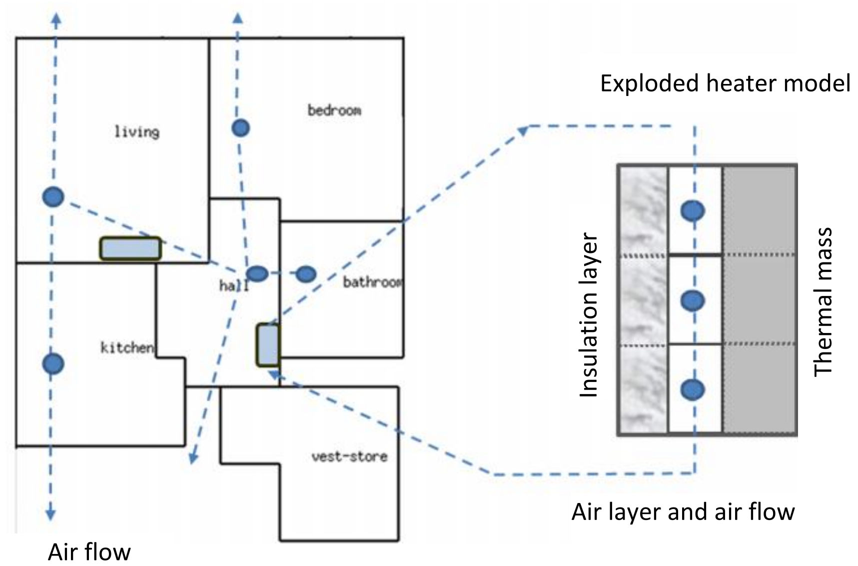

Figure 4: Simulation models for a one-bedroom flat with Quantum space heaters

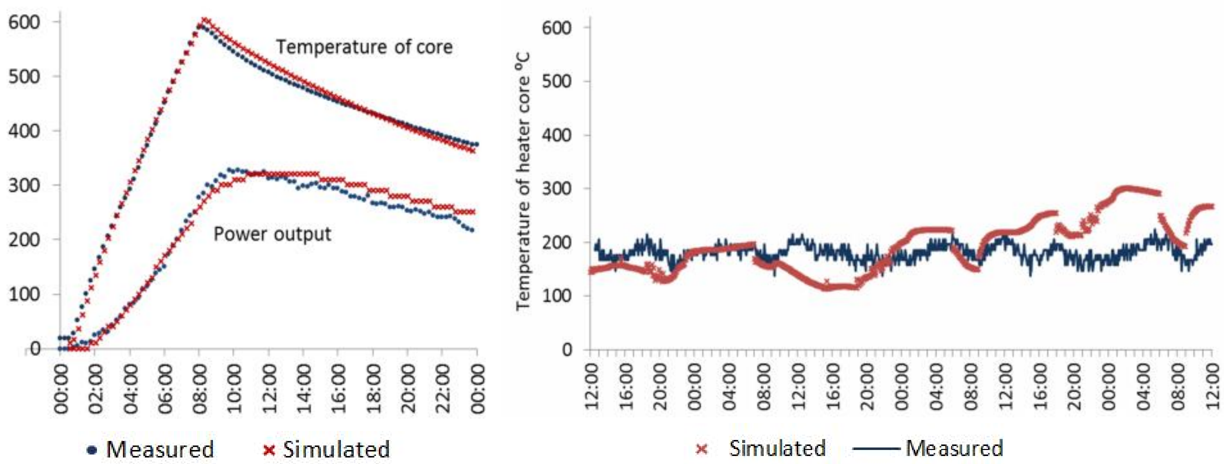

Figure 5: Calibration of heater models: a) laboratory test data for uncontrolled output and b) field measurements

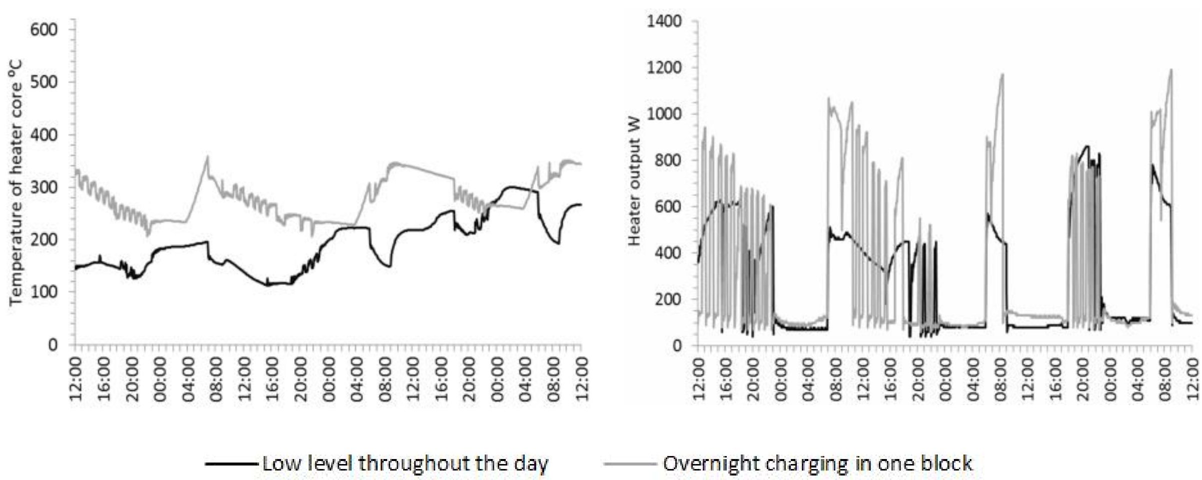

Figure 6: Impact of alternative charging schedule on storage utilisation and on heat output

Table 1: ESP-r and DHWcalc model parameter ranges for NINES

PARAMETER	RANGE	NO. OF VARIANTS
Building geometry	Bedsits, flats and houses, various layouts	11
Construction	Stone, block & render, insulated timber	8
Space heater configuration	Three heater sizes, 1-9 per house deployed in different rooms	24
Occupancy pattern	Weekday occupied/unoccupied, weekend	3
Preferred indoor temperature in living areas	Cool (19°C), average (21°C), warm (23°C) (Shipworth *et al* 2010)	3
Hot water demand timing preferences	Predominant use during one period, to use spread over day and night	5