Empirical evaluation of energy profiles of thermally-efficient homes with smart energy systems and controls

Rajat Gupta, Johanna Morey
Low Carbon Building Research Group, Oxford Institute for Sustainable Development, School of Architecture, Oxford Brookes University, Oxford, United Kingdom
rgupta@brookes.ac.uk

Abstract. Smart control technologies are beginning to be deployed in homes to optimise heating and alter the timing of domestic energy demand to enable residential demand side response (DSR). This paper presents before (baseline phase) and after (control phase) evaluation of the monitored indoor temperature and energy demand during the heating season in 10 new-build dwellings, each of which received a 5kWh electro-chemical battery and smart control to enable shifting of heating energy demand. The dwellings had air source heat pumps (ASHP) and 2kWp solar photovoltaic (PV) panels, and were located in a social housing estate in Barnsley, England. For eight dwellings, heat pump electricity use per heating degree day was found to decrease by 10% and narrow baseline peaks were suppressed during the control phase. Daily mean grid electricity import and heat pump electricity use in the peak period (4pm – 7pm) were measured as 4.0 kWh and 1.4 kWh during the control phase as compared to 3.8kWh and 1.3 kWh for the baseline phase. However the use of a flat tariff (single-rate) meant that battery charging-discharging capability was not fully utilised. Time-of-use tariff would further enhance cost savings associated with the change in the timing of energy demand.

1. Introduction and background

Electrification of domestic heating is an important factor for the decarbonisation of energy in the UK [1]. Electric heat pumps offer a means to achieve this and the deployment of 5.5 million heat pumps in UK homes has been proposed in The Sixth Carbon Budget [2]. Heat pumps, in conjunction with smart control and battery storage, have the potential to enable residential demand side response (DSR), the benefits of which include balancing of grid electricity supply and demand, reduction of peak demand and the integration of intermittent renewables. Electricity from the grid or local renewables, e.g. solar PV generation or wind generation, can be used to charge a battery for discharge at a later time, providing opportunity for shifting residential energy consumption.

Without some form of DSR, mass deployment of residential heat pump deployment in itself could cause increase in peak grid loads requiring network reinforcement [3]. Modelling has shown that peak demand could be mitigated with home battery storage [4]. Flexible heat pump usage is expected to require “advanced” control [5], and automation of control for space heating, water heating, and electrical appliances has evidenced a stronger demand response compared with resident-driven control [6]. However, the current literature dependence on data from DSR trials which are neither automated nor concern energy storage has been highlighted [7].

A trial of 48 dwellings located in Oxfordshire, England demonstrated a reduction in peak demand along with increased consumption of locally generated PV electricity by using a time-of-use (TOU)
tariff signal with automated control of appliances [6]. This included six dwellings where space heating was controlled and nine dwellings with battery storage. In another study, 31 dwellings in south west England with electric heat pumps underwent automated control using a smart energy management system, resulting in more even internal temperatures with increased overnight and decreased evening heat pump consumption use [8]. 75 trial homes in Wales used a combined ASHP and gas hybrid system under smart control enabling the management of flexible demand DSR to be demonstrated [9]. A case study in Denmark found that household PV generation in combination with battery storage reduced peak loads by 35-70% and estimated that controlled heat pump operation could result in a flexible load of 1 kW per household [10]. Although studies are emerging, there is still limited empirical evidence on change in energy profiles and indoor temperatures in dwellings with low carbon heating, controls, renewable energy and storage technologies.

This paper presents before (baseline phase) and after (control phase) evaluation of the monitored indoor temperature and energy demand during the heating season in 10 new-build dwellings, each of which received a 5kWh electro-chemical battery and smart control to enable shifting of heating energy demand, alongside existing air source heat pumps (ASHP) and 2kWp solar photovoltaic (PV) panels.

2. Methodology

2.1. Dwelling characteristics

The 10 dwellings were new-build (2014), well-insulated, two-storey properties (Code 4 Sustainable Homes) within the UK Government funded BREATHE (Bringing Renewable Energy Automation To Homes Everywhere) project on domestic demand side response. The dwellings were located in Barnsley, South Yorkshire, England - nine were semi-detached, one was detached. Each dwelling had a 5kW Mitsubishi Eco Dan dual purpose ASHP which provided space heating and hot water, a solar PV array (in the range 1.65 kWp – 2.25 kWp), 5 kWh Sonnen smart battery and a PassivSystems PassivLiving Hub smart control system. Dwellings were connected to a flat rate electricity tariff.

2.2. Baseline and control phases

During the baseline phase, dwellings were monitored, with residents able to manually control zone temperature set points, but with no external control. During the control phase, heating and hot water were optimised to achieve the least cost outcome whilst avoiding thermal discomfort, by the smart control of indoor temperature set points and operation of the ASHP, in combination with machine learning and a dynamic building physics model of the dwelling, taking into account resident schedules and preferences. However, residents were able to temporarily override settings if desired. The use of a flat rate electricity tariff meant that the capability for controlled charging and discharging of the battery was not utilised. In both phases, solar PV generated electricity was first used to meet household demand. When solar PV generation exceeded demand, it was used to charge the battery.

| Phase     | Number of dwellings | Start          | End            | Duration (days) | External temperature °C | Heating degree days (HDD) |
|-----------|---------------------|----------------|----------------|-------------------|-------------------------|--------------------------|
| Baseline  | 8                   | 23/10/2019     | 09/01/2020     | 79                | 5.2 (-0.7, 12.8)       | 813                      |
|           | 1                   | 24/10/2019     | 09/01/2020     | 78                | 5.2 (-0.7, 12.8)       | 806                      |
|           | 1                   | 26/10/2019     | 09/01/2020     | 76                | 5.1 (-0.7, 12.8)       | 791                      |
| Control   | 10                  | 01/11/2020     | 28/02/2021     | 120               | 4.1 (-4.7, 16.1)       | 1365                     |

2.3. Data streams and definitions

Data streams for the analysis were provided at 5 minute intervals by PassivSystems, sourced from the battery and ASHP. Internal temperatures were provided at 5 minute intervals by Secure HRT4-B thermostats. Outdoor temperatures were obtained from Emley Moor weather station at hourly intervals from which heating degree days (HDD) were calculated (with respect to a 15.5°C base temperature).
Solar self-consumption was defined as the solar energy consumption of the household, including battery charging using solar PV generated electricity. Whole home energy consumption was defined as battery discharge plus grid electricity import and solar self-consumption.

### 3. Results

#### 3.1. Daily mean temperature

Across the 10 dwellings, the daily mean temperature for the downstairs zone was measured as 22.2°C (SD 2.1°C) and 22.0°C (SD 1.7°C) for the baseline and control phases, respectively, and 22.1°C (SD 1.8°C) and 21.6°C (SD 2.3°C) for the upstairs zone for the baseline and control phases, respectively. The results for individual dwellings (Figure 1) show no overall pattern of increased or decreased daily mean temperatures for the control phase across the dwellings. Dwelling 1 (control) had 18% of days missing for upstairs temperature. Dwelling 6 (baseline) had 38% of days missing for downstairs temperature. For all other dwellings, days of temperature data missing were less than 3.5%.

![Figure 1](image)

**Figure 1.** Daily mean downstairs and upstairs temperatures – baseline and control energy consumption (Error bars are ±1 SD).

#### 3.2. Daily mean energy

Daily mean energy values across the 10 dwellings were similar for the baseline and control phases (Table 2). Across the 10 dwellings, whole home energy consumption consisted of 94.3%, grid electricity import, 5.2% solar self-consumption and 0.6% battery discharge for the baseline phase and 92.9% grid electricity import, 6.2% solar self-consumption and 0.9% battery discharge for the control phase.

| Phase   | Grid electricity import (kWh) | Solar self-consumption (kWh) | Battery discharge (kWh) | Whole home electricity consumption (kWh) | Heat pump electricity consumption (kWh) |
|---------|-------------------------------|-----------------------------|-------------------------|-----------------------------------------|----------------------------------------|
| Baseline | 23.3                          | 1.3                         | 0.2                     | 24.7                                    | 10.3                                   |
| Control  | 23.2                          | 1.5                         | 0.2                     | 25.0                                    | 10.4                                   |

Figure 2 depicts the daily heat pump electricity consumption per HDD, i.e. the heat pump consumption on a particular day plotted against the HDDs for that day, for an individual dwelling showing a trend for lower consumption per HDD for the control phase. For eight dwellings, daily mean heat pump electricity consumption per HDD decreased for the control phase as compared to the baseline phase (Figure 3). For two dwellings (Dwellings 7 and 9), daily mean heat pump electricity consumption per HDD increased for the control phase, possibly due to increase in internal temperatures. For the control phase, Dwelling 7 showed an increase in mean daily temperature of 1.6°C (downstairs) and 0.3°C (upstairs), while Dwelling 9 showed an increase mean daily temperature of 0.6°C (downstairs) and 0.4°C (upstairs) as compared to the baseline phase. Both these dwellings had relatively low mean daily baseline temperatures compared with the sample as a whole.
Figure 2. Daily (sum) heat pump electricity consumption by HDD for baseline and control phases (Dwelling 5).

Figure 3. Daily mean heat pump electricity consumption per HDD by dwelling for baseline and control phases. (Error bars are ±1 SD).

Figure 4. Daily mean heat pump electricity consumption and daily mean whole home consumption breakdown (stacked area) from 5 minute data for the baseline and control phase for two dwellings.

Overall it was found that sharper peaks of baseline heat pump electricity consumption were suppressed during the control phase due to controlled management of heating. This effect is shown in the energy consumption profiles for two dwellings (Figure 4). Baseline and control phase profiles varied between individual dwellings for heat pump electricity consumption, depending on resident heating and
hot water requirements. As regards whole home energy consumption, for the control phase, three dwellings exhibited a general trend of increasing consumption throughout the day towards an evening peak (e.g. Figure 4(d)). Two dwellings showed a constant daily profile, four showed multiple peaks throughout the day (e.g. Figure 4(b)), and one showed broad morning and evening peaks.

4. Discussion
Across the 10 dwellings, the control phase brought about little change in the downstairs daily mean internal temperature and a 0.5°C decrease in the upstairs daily mean temperature. However, for the control phase (excluding dwellings with missing temperature data), five out of nine dwellings showed a decrease in daily mean downstairs temperature of at least 0.5°C and three dwellings showed an increase of at least 0.5°C, compared with the baseline phase. Three out of nine dwellings showed a decrease in daily mean upstairs temperature of at least 0.5°C for the control phase, with two dwellings showing an increase of at least 0.5°C, compared with the baseline phase. Downstairs temperatures generally showed greater stability for the control phase as for six out of nine dwellings, the daily mean temperature range was reduced by at least 0.5°C compared with the baseline phase with only one dwelling showing an increase in range (Dwelling 7). For the upstairs temperature range there was no clear difference between the phases. For five out of nine dwellings the daily mean upstairs temperature range was reduced by at least 0.5°C for the control phase, compared with the baseline phase, but four dwellings showed an increase in range of at least 0.5°C for the control phase.

For eight out of ten dwellings, the daily mean heat pump electricity consumption per HDD decreased for the control phase compared with the baseline. For the two remaining dwellings, daily mean heat pump electricity consumption per HDD increased for the control phase; the daily mean temperatures for both downstairs and upstairs zones increased for the control phase for each of these dwellings. Across the 10 dwellings, the mean daily mean heat pump electricity consumption per HDD was 1.0 kWh/HDD (SD 0.25), decreasing by 10% to 0.9 kWh/HDD (SD 0.26), although this result was not significant. This equates to a saving of £19 over the four month control period with a flat rate electricity tariff of 13.92 p/kWh\(^1\). The control phase led to removal or lowering of baseline peaks in heat pump electricity consumption daily profiles for individual dwellings.

Interestingly there was little change in whole home energy consumption and grid electricity import between the two phases. The daily mean energy values across the 10 dwellings during the four month control phase, including grid electricity import at peak times, give an indication of the typical daily whole home consumption, and grid electricity import under smart heat pump control during the heating season, as well as the mean daily mean solar self-consumption, which, at 1.5 kWh, was 6% of the mean daily mean whole home consumption. As expected, battery energy storage and discharge was low due to the time of year as there was little surplus solar PV electricity available for battery charging. Additionally, battery operation was not controlled under a flat tariff; under a TOU tariff, the battery could be charged during the off-peak period and discharged during the more expensive peak period.

Across the 10 dwellings, the daily mean heat pump electricity consumption remained at 42% of whole home consumption during baseline and control phases, heat pump electricity consumption being a shiftable load for residential DSR. The peak period of grid electricity import lay predominantly between 4pm and 7 pm. Across the 10 dwellings, the daily mean grid electricity import and heat pump electricity consumption at peak times (4pm – 7pm) were 4.0 kWh (range: 2.7 kWh – 7.2 kWh) and 1.4 kWh (range: 1.1 kWh – 2.1 kWh), respectively for the control phase and 3.8 kWh (range: 2.6 kWh – 6.3 kWh) and 1.3 kWh (range: 0.9 kWh – 1.7 kWh) for the baseline phase. This is pertinent to DSR scenarios during the heating season, since it represents household grid demand with heat pump control under a flat rate tariff and provides a measure of potentially shiftable peak heat pump consumption. These results suggest that under a DSR scenario, e.g. with a TOU, a 5kWh battery would be able to provide heat pump electricity at peak times for each dwelling as well as a substantial proportion of non-heating related household electricity consumption. Common daily profiles for whole home energy consumption

\(^1\) Yorkshire region tariff from UK Power 2021 https://www.ukpower.co.uk/home_energy/tariffs-per-unit-kwh
included a general increase in consumption throughout the day towards an evening peak, and multiple consumption peaks throughout the day.

5. Conclusion
This study has considered the effect of smart control of heat pump space and hot water heating for 10 well-insulated new-build dwellings. Across the 10 dwellings, mean daily mean whole home energy consumption and internal temperatures were similar for both phases. However, eight out of the ten dwellings showed that heat pump electricity consumption per HDD decreased with heat pump control. Heat pump electricity consumption daily profiles for individual dwellings showed removal or reduction in magnitude of narrow baseline peaks for the control phase.

Mean daily mean whole home consumption, grid electricity import, solar self-consumption and heat pump electricity consumption across the 10 dwellings provide empirical results regarding heating season energy consumption to inform future DSR scenarios, along with grid electricity import and heat pump electricity consumption at peak times. All 10 dwellings employed a flat rate electricity tariff whereby the battery charge-discharge operation was not optimised. The peak period of whole home consumption lay predominantly between 4pm and 7pm, for both the baseline and control phases, thereby making a case for reducing the peak period consumption using price signals offered by a TOU tariff. Although controlled operation of heat pump demonstrated a 10% reduction in heat pump electricity consumption per HDD (0.1 kWh/HDD), this on its own may not yield sufficient energy cost savings for a larger take-up of heat pumps with smart controls.

During winter months, the battery was not sufficiently charged using solar PV generation to provide significant discharge during peak periods, and a TOU tariff would be essential to drive battery discharge. Future enhancement would involve heat pump control in conjunction with battery storage and a TOU tariff whereby grid electricity is used to charge the battery at cheaper times to be released during times of peak pricing/demand. Given a 4.0 kWh daily mean whole home consumption during the 4pm – 7pm peak period, this combination should allow a substantial amount of peak consumption to be met by battery storage, depending upon the exact timing and magnitude of consumption. Summer months would offer a greater potential for solar PV generated electricity to be used for battery charging which will be investigated in future research.

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