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Simulation, implementation and monitoring of heat pump load shifting using a predictive controller

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ABSTRACT

A predictive load shifting controller has been developed and deployed in a low-carbon house near Glasgow, UK. The house features an under floor heating system, fed by an air-source heat pump. Based on forecast air temperatures and solar radiation levels, the controller firstly predicts the following day's heating requirements to achieve thermal comfort; secondly, it runs the heat pump during off peak periods to deliver the required heat by pre-charging the under floor heating. Prior to its installation in the building, the controller's operating characteristics were identified using a calibrated building simulation model. The performance of the controller in the house was monitored over four weeks in 2015. The monitored data indicated that the actual thermal performance of the predictive controller was better than that projected using simulation, with better levels of thermal comfort achieved. Indoor air temperatures were between 18 °C and 23 °C for around 87% of the time between 07:00 and 22:00. However, the performance of the heat pump under load shift control was extremely poor, with the heat being delivered primarily by the unit's auxiliary immersion coil. The paper concludes with a refined version of the controller, that should improve the day-ahead energy predictions and offer greater flexibility in heat pump operation for future field trials.

1. Introduction

The domestic sector faces a range of challenges as the UK attempts to drastically cut its carbon emissions by 2050. Key issues are reducing the overall demand for heat and decarbonising the residual heat loads, which encompass both space heating and hot water provision. If the supply of electricity in the UK is progressively decarbonised at the macro and micro-scales, through the deployment of renewable generation, then the electrification of heat using heat pumps would be an effective means to provide the low-carbon space heating, hot water and possibly cooling required by the domestic sector. However, the widespread adoption of heat pumps would significantly increase power flows on the electricity network. Wilson et al. [1] indicated that a shift of only 30% of domestic heating to heat pumps could result in an increase of 25% in the total UK electrical demand. To mitigate the potential negative impacts of heat pumps, particularly increased peak demand and to reduce or delay network upgrade costs, time-shifting of heat pump demand could become essential.

There have been many papers published, focusing on load shifting of household heat demands and their impacts. For example, Callaway [2] used modelling and simulation to assess the potential for manipulation of large populations of thermostatically controlled loads to follow variable renewable generation. In another modelling-based study, Parkinson et al. [3] designed a controller for distributed heat pump management that also accounted for indoor comfort constraints that often occur when load shifting. Wang et al. [4] modelled the potential for load shedding in a large population of many thousands of unbuffered domestic heat pumps by manipulating of the space heating set point. Patteeuw [5] et al. looked at the potential of load shifting in large populations of buffered domestic heat pumps to reduce carbon emissions from the power system as a whole, with their modelling study, which used linear programming and simple thermal models, showing reductions in power system CO_2 emissions of 1–7% if price based load shifting was implemented.

This paper is primarily concerned with the practicality of, and thermal impact of heat pump load shifting at the level of the individual dwelling. Again, there are many published papers in the

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Nomenclature

ΔT	hysteresis relay temperature (°C)
$\hat{C}$	estimated amount of charge (kW h)
$\bar{\Phi}_{\mathrm{sol}}$	daily average solar insolation (W/m^2)
$\bar{T}_{\mathrm{ext}}$	daily average external air temperature (°C)
σ_{f}	signal standard deviation
σ_m	characteristic length scale
Φ_{H}	heat output (W)
Φ_{on}	hysteresis controller on heat flux (W)
C	amount of charge (kW h)
C^*	enhanced estimated amount of charge (kW h)
d	number of variables in Gaussian process training set
$k(\boldsymbol{x}_i, \boldsymbol{x}_j)$	Gaussian process covariance function
$m(\boldsymbol{x})$	Gaussian process mean function
P	heat pump power (kW)
$P_{\max}$	maximum heat pump power (kW)
R^2	coefficient of determination (1)
$T_{\mathrm{H,set}}$	heating set-point temperature (°C)
t_{c}	duration of charge (h)
T_{db}	dry-bulb air temperature (°C)
T_{err}	control error temperature (°C)
$T_{\max}$	maximum temperature (°C)
T_{mean}	mean temperature (°C)
$T_{\min}$	minimum temperature (°C)
T_{mrt}	mean radiant temperature (°C)
T_{off}	hysteresis controller off temperature (°C)
T_{on}	hysteresis controller on temperature (°C)
T_{op}	operative temperature (°C)
t_{sim}	start time for simulated flexible load-shift (h)
T_{sp}	radiative set-point temperature (°C)
U-value	steady-state thermal transmittance (W/(m^2 K))

literature looking at this area. For example, Hong et al. [6,7] found that shifts in heat pump operating times of up to 6 h were possible in thermally improved dwellings, but only with the addition of up to 500 l of hot water thermal buffering. Arteconi et al. [8] investigated the use of buffering in less well-insulated buildings, indicating that up to 800 l of buffering would be required to deliver only 1 h of load shifting. Kelly et al. [9] investigated load shifting of heat pump demand to off-peak periods in low carbon housing and found that to avoid discomfort up to 1000 l of hot water thermal buffering would be required. Renaldi et al. [10] used cost optimisation to identify optimum storage sizes for load shifting heat pump operation to off peak. Their modelling used synthetic heat loads and a system that featured back up immersion heating. The resulting cost-optimised store sizes (200–300 l) were considerably smaller than those identified using engineering modelling approaches [6–8,9,10].

In all of the papers cited, the authors used modelling to assess the potential for load shifting with a variety of technologies and in different operating contexts. Whilst this provides useful data for technology development and future network planning, modelling has its limitations in that it cannot highlight practical problems associated with the application and implementation of domestic heat load shifting, such as poorly functioning equipment or failure to achieve predicted levels of thermal comfort. A range of studies have indicated that the thermal modelling of buildings and their systems tend to provide over optimistic results compared to what is achieved in reality (e.g. Norford et al. [11], Knight et al. [12]), particularly in relation to energy use. Ryan and Sandqusit [13], recommend that to improve accuracy models are calibrated against empirical data to improve performance. In this paper the performance of a load shifting system was modelled, with the results used as the basis for the design of a day-ahead, predictive load shifting controller. Importantly, the model used was calibrated using monitored data and the energy and thermal performance of the controller operating in a real building was then monitored and assessed.

1.1. Novelty of the work

The novel features of the work reported are (1) the use of a calibrated simulation model to identify the parameters for the a load shift controller, which was then implemented in a real building; (2) monitoring of the performance of the controller and heating equipment over several weeks; and (3) the performance was assessed from the perspective of both energy use and the resulting indoor thermal conditions – so the comfort conditions achieved in the test building under the load shifting control are a key metric for the success or failure of the load shifting approach.

2. Methodology

The work described in this paper involved six distinct stages of activity. These were as follows.

1. Deployment of monitoring equipment and acquisition of performance data;
2. development and calibration of a simulation model of the test house;
3. use of the model to identify the parameters for a predictive control algorithm;
4. assessing the virtual effectiveness of load shifting using simulation;
5. implementation of the load shift controller in the real test house; and
6. monitoring and assessment of actual performance under load shifting.

The results emerging from the monitoring of the load shifting controller and systems performance highlighted important issues regarding heat pump operation under intermittent load shifting control and also allowed the load shift control algorithm to be further refined.

2.1. Details of the test house

The building used for the tests the Applegreen House is located at BRE Ltd's Innovation Park, Motherwell near Glasgow (55.78°N, 3.99°W). The house is intended to be a demonstration of a mass-market, low-cost, modular-build, low-carbon house. The building is shown in Fig. 1. The house is steel framed, has a slab-on-grade concrete foundation with a flat-roof construction. The roof is weatherproofed using bituminous felt. The building is clad in insulated panels, which are externally rendered; the upper half of the building also features external timber cladding.

Windows are double-glazed. The interior of the house is finished with plaster-on-stud and carpeted throughout.

The house has a total floor area of 127 m^2 spread over an upper and lower floor and has an internal volume of 304 m^3. As the house is a test facility, it was unoccupied during the reported experiments; the implications of this are discussed later in the paper.

Heating and hot water are provided by a 3/5 kW NIBE F470 air source heat pump – the heat delivered to the house is recovered