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Performance assessment of tariff-based air source heat pump load shifting in a UK detached dwelling featuring phase change-enhanced buffering

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HIGHLIGHTS

- Large thermal buffer is needed to shift the operation of a heat pump to off-peak periods.
- Using phase change material halves buffer size required for load shifting.
- Significant energy penalty associated with heat pump buffering and load shifting.
- Buffering and load shifting causes increased heat pump running costs and CO_2 emissions.
- Constraining a group of buffered heat pumps to off-peak Economy 10 operation increases peak electrical load.

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ABSTRACT

Using a detailed building simulation model, the amount of thermal buffering, with and without phase change material (PCM), needed to time-shift an air source heat pump's operation to off-peak periods, as defined by the UK 'Economy 10' tariff, was investigated for a typical UK detached dwelling. The performance of the buffered system was compared to the case with no load shifting and with no thermal buffering. Additionally, the load shifting of a population of buffered heat pumps to off-peak periods was simulated and the resulting change in the peak demand on the electricity network was assessed. The results from this study indicate that 1000 L of hot water buffering or 500 L of PCM-enhanced hot water buffering was required to move the operation of the heat pump fully to off-peak periods, without adversely affecting the provision of space heating and hot water for the end user. The work also highlights that buffering and load shifting increased the heat pump's electrical demand by over 60% leading to increased cost to the end user and increased CO_2 emissions (depending on the electricity tariff applied and time varying CO_2 intensity of the electricity generation mix, respectively). The study also highlights that the load-shifting of populations of buffered heat pumps wholly to off-peak periods using crude instruments such as tariffs increased the peak loading on the electrical network by over 50% rather than reducing it and that careful consideration is needed as to how the load shifting of a group of heat pumps is orchestrated.

1. Introduction

The UK has committed itself to radically reducing its greenhouse gas (GHG) emissions over the coming decades, with a specific target of an 80% reduction by 2050 [1]. Key to achieving this goal lies in decarbonising the space and water heating demands of the 26 million dwellings that comprise the UK domestic sector [2]. Housing accounts for over 30% of the UK's final energy consumption [3] and around 38% of its greenhouse gas (GHG) emissions [4].

The widespread uptake of heat pumps, coupled with central electricity generation from nuclear and renewable sources is often cited as a means to decarbonise domestic heating (e.g. Refs. [5,6]). However, as the vast majority of UK dwellings likely to be extant in 2050 are already constructed [7], then a radical reduction in domestic GHG emissions will require a widespread heat pump retrofit programme. Air source heat pumps (ASHPs) have the potential to act as a direct replacement for the fossil-fuelled boilers commonly found in UK housing, though their control needs to be slightly

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different and heat emitters need to be resized to account for the lower flow temperatures delivered by heat pumps [8]. The (relatively) low cost of installation and the lack of a requirement for ground works makes ASHPs a more feasible mass retrofit proposition than ground source heat pumps (GSHP).

A consequence of significant numbers of ASHPs being retrofitted into the housing stock could be substantially increased electrical load in the low voltage (LV) distribution system (e.g. Ref. [9]) leading to problems such as voltage dips and cable overloading, and potentially the need for expensive network reinforcement. One means to avoid this scenario is to shift heat pump electrical demand to off-peak periods such as the early morning, late evening or the middle of a typical working day, when domestic electrical demand is lower. However, this could have an impact on the delivery of adequate indoor temperatures and the provision of hot water. Effective shifting of heat pump operation requires that the manipulation of operating times is achieved with the minimum of inconvenience to the end user. An appropriate means to deliver effective load shifting is through the provision of sufficient thermal buffering to temporally decouple the operation of the heat pump from the space heating and hot water demands.

1.1. Review

There are many examples of electrical heating or cooling load shifting in the literature. For example, Moreau [10] studied load shifting in populations of hot water heating loads, indicating that care is required in how the load shifting was undertaken and there was a risk of exacerbating rather than reducing the demand on the network. In a study focused on wind energy, Callaway [11] assessed the potential for manipulation of large populations thermostatically controlled loads to follow variable renewable generation. Wang et al. [12] analysed 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. Focussing specifically on heat pumps, Hewitt [5] argues that their use with thermal storage could be a useful means of load management in an electricity system with increasing quantities of renewable energy generation. However, as the paper is strategic in focus, the author does not undertake any specific analysis of the load shifting potential nor of the size of thermal store required.

Whilst the aforementioned studies on large populations of devices provide useful insight into the scope for domestic load management, they do not truly examine the potential effect on the end user in terms of comfort or provision of hot water. This either is because the thermal model employed is necessarily simplified (due to the large number of loads covered in the study) or because only one aspect of heating is covered (i.e. space or water heating). Proper assessment of the effect of thermal load shifting on the end user typically requires the use of a more detailed model of the building.

Studies focused on the implications of load shifting at the level of the individual dwelling, with detailed modelling of the impact on internal conditions are less common in the literature. Bagdanavicius and Jenkins [6] use a building simulation tool to estimate the potential extra electrical load on the supply network from domestic heat pumps. They indicate that significant load shifting would be required to reduce demand peaks, though the authors do not explicitly model any load shifting nor its impacts. Hong et al., ([13,14]) examined the potential for flexible operation of air source heat pumps (ASHP) retro-fitted into UK dwellings when constrained by the need to deliver hot water and thermal comfort. They found that shifts in heat pump operating times of up to 6 hours were possible, but only with the addition of significant quantities of hot water thermal buffering (up to 500 L) coupled with extensive improvements to the building fabric: in their paper, the authors do not explicitly follow any load shifting strategy and instead use a sensitivity analysis. Further, the authors do not fully explore the implications of load shifting on the heat pump's energy and environmental performance. Arteconi et al. [15] investigated the use of buffering in detached dwellings insulated to 1990 UK building standards with both under floor and radiator-based heating systems. They calculated that up to 800 L of buffering would be required to deliver only 1 hour of load shifting. In this study, the authors only analyse sensible thermal buffering. Hong et al. pointed out the difficulty of accommodating large hot water tanks; particularly as new build UK housing is high-cost and reducing in size [16]. More volumetrically efficient thermal buffering (e.g. PCM-enhanced buffering) is therefore beneficial, as it would take up less valuable living space within a dwelling.

1.2. Objectives

By simulating the performance of a 'typical' UK family dwelling [17] equipped with a heat-pump-based heating system, the contribution of this paper is to address some of the gaps in the knowledge relating to domestic heat pump load shifting. Firstly, the volume of thermal storage (with and without PCM) required to effectively load shift heat pump entirely to off-peak periods, as defined by the UK economy 10 tariff [18], is assessed; this is the volume of storage required to achieve shifting without affecting end-user comfort and hot water delivery. Secondly, the impact of load shifting on the heat pump's energy and environmental performance is assessed along with an assessment of the effect on running costs. Finally, to assess the potential impact on electrical demand, an example is presented where a population of heat pumps are load shifted to timings dictated by the UK the Economy 10 tariff.

2. Modelling

The typical UK family dwelling was developed as an integrated ESP-r model [19], which features both the dwelling, the heat pump and its associated heating system. The ESP-r building simulation tool, allows the energy and environmental performance of the building and its energy systems to be determined over a user defined time interval (e.g a day, week, year). The tool explicitly calculates all of the energy and mass transfer processes underpinning building performance. These include: including conduction and thermal storage in building materials, all convective and radiant heat exchanges (including solar processes), air flows, interaction with plant and control systems. To achieve this, a physical description of the building (materials constructions, geometry, etc.) is decomposed into thousands of 'control volumes'. In this context, a control volume is an arbitrary region of space to which conservation equations for continuity, energy (thermal and electrical) and species can be applied and one or more characteristic equations formed. A typical building model will contain thousands of such volumes, with sets of equations extracted and grouped according to energy system. The solution of these equations sets with real time series climate data, coupled with control and occupancy-related boundary conditions yields the dynamic evolution of temperatures, energy exchanges and fluid flows within the building and its supporting systems. The validity of the ESP-r tool is reviewed in Ref. [20].

The focus of the work presented here is therefore the application of the ESP-r tool, rather than development of algorithms or new functionality: all of the models used are already available in the general release of ESP-r. The algorithms underpinning the key heating system components referred to later in this paper are documented in more detail elsewhere: air source heat pump [21],

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