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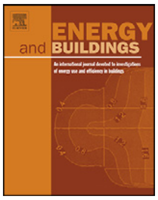

Towards low carbon homes – A simulation analysis of building-integrated air-source heat pump systems

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ABSTRACT

A comparative transient simulation analysis for domestic buildings with a floor-embedded heating system coupled to a modern air source heat-pump (ASHP) has been carried out using the TRNSYS numerical modeling environment for various UK locations. The effects of heat-pump control during off-peak electricity tariff periods in conjunction with varying building fabric characteristics were analysed and the results show that for the locations investigated, running costs and CO_2 emissions were lower for the ASHP platform than for a comparative gas boiler heating system. It was also found that by utilizing the thermal mass of a concrete floor slab or by integrating external insulation, acceptable comfort levels during the heating season were maintained when operating the ASHP solely during off-peak tariff periods. A thinner concrete floor slab containing phase change material (PCM) provided a slightly improved comfort level during winter and also reduced overheating during summer in buildings with a high level of insulation. Finally, when utilising a floor-embedded PCM material, it was found that the thermal properties of the PCM material must be carefully matched with case-specific building fabric thermal performance parameters in order to ensure effective internal environmental control.

1. Introduction

The EU faces significant challenges in meeting CO_2 emission reduction targets of up to 80% by 2050 compared to 1990 levels. In the UK, domestic dwellings alone are currently responsible for nearly 30% of CO_2 emissions. In addition to improved thermal performance of the building fabric, the integration of renewable energy technologies is seen as a key part of the solution required to significantly reduce domestic-sector carbon emissions [1]. With the additional goal to ‘de-carbonise’ the UK’s electricity supplies in the medium term, electrically powered building heating solutions (replacing gas, oil or solid fuel powered technologies) are seen as a core strand of the UK’s carbon emissions reduction strategy [2]. Within this context, heat pumps are projected to play a major role in domestic-sector heating provision, with air source heat pumps (ASHPs) seen as a particularly attractive option owing to their relatively low cost in comparison with ground-coupled alternatives. Recent research has explored the carbon saving potential of ground-coupled heat pumps, and identified possible barriers to such savings, especially with regards the domestic retrofit sector [3]. Subsequent research [4] evaluated air source heat pump performance within a UK retrofit context, and suggested that carbon emission reduction of up to 12% were feasible compared to a gas boiler system, but with a projected 10% increase in running costs, depending on specific application parameters. Therefore, within such a distributed power generation and distribution framework, the option to employ a degree of demand management by shifting loads from peak to off-peak periods offers an advantage with regards reduced need for extra generation capacity and an increased utilisation of generating plant and hence increased efficiency of generation investment [5].

Heat-pump operational efficiency is often expressed as its coefficient of performance (COP), namely

$$COP = \frac{P_{thermal}}{P_{compressor}} \tag{1}$$

Therefore, a 6 kWth heat-pump with a COP of 3 will produce 6 kW of heat for every 2 kW of electrical power supplied to the compressor and is therefore approximately 3 times more energy efficient than a 6 kW electric direct heater.

For a given electrical power supplied to an ASHP’s compressor ($P_{compressor}$), the thermal power ($P_{thermal}$) transferred to the heat distribution fluid is normally larger by a factor related to the temperature difference between the heat source and sink. Thus, the COP of an ASHP and its thermal output power decrease when the ambient air temperature decreases or when the heat distribution

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fluid temperature increases. Since air temperatures are generally lower than those of the ground during the heating season, seasonal COPs for ASHPs are in theory generally lower than for ground source heat-pumps (GSHP) that extract heat from the ground with a more stable temperature [6]. However, ASHP systems are often more convenient and economical to fit, and provided their operational efficiency is optimised, their large market penetration potential means that ASHP technology presents an important route towards significant CO_2 reductions [7]. Furthermore, recent field trial data indicates that the performance gap between air and ground source heat pumps in the UK is not as large as previously assumed [8].

Clearly, the ability to utilize a building's thermal mass in order to 'de-couple' the electrical input and thermal output of an ASHP offers an opportunity to shift electrical load to off-peak periods, thereby offering electricity system efficiency benefits [7,9]. Where electricity suppliers offer tariff options during which electricity is cheaper during off-peak periods, optimising a building's holistic design to facilitate ASHP operation predominantly during off-peak periods also gives this technology a further advantage in term of operating costs. The inclusion of carefully designed phase change materials within the building envelope further enhances these potential benefits [10–12].

To de-couple the ASHP electrical and thermal loads, emitted heat is stored in the thermal mass of the building or in dedicated storage tanks and transferred at a later time to the air inside the building or for water heating purposes [9,18]. The sensible heat stored in a material is proportional to its thermal capacity, its temperature and its volume. Thus, to increase the sensible energy stored in a material, either (a) the heating distribution temperature; (b) the material volume or (c) the material's specific heat capacity needs to be increased. The former option would not be preferred for an ASHP heating system, since higher outlet temperatures would lead to operation at a lower COP. In addition to increasing the available sensible heat capacity, a further potential option for energy storage is to use fabric-integrated phase change materials (PCMs). These have been investigated previously as a means to store both sensible heat and latent heat when they transition from one state to another (solid–liquid is the preferred transition for building applications). They also provide a stable temperature around their transition temperature when discharging heat leading to potentially improved internal comfort management [10].

The aim of this work is therefore to assess how various control schemes based around off-peak electricity tariff options impact upon the technical and economic performance of an ASHP system for three different dwelling fabric construction methods.

Using the dynamic building simulation tool TRNSYS, the objectives of the work included:

- For each building configuration, to evaluate ASHP COPs and internal temperature variations for ASHP control based upon a number of currently available off-peak electricity tariff periods;
- To investigate performance for three different UK locations in order to evaluate climatic variations;
- To assess annual performance in terms of energy consumption, CO_2 emissions and running costs for off-peak electricity tariffs, a flat-rate electricity tariff and a gas boiler respectively for each location and building type.

2. Methodology

For the purpose of this study, three contrasting dwelling fabric configurations were considered with integrated insulation layers primarily designed to provide various thermal mass and admittance/decrement properties, namely:

(a) *Externally rendered lightweight structural insulated panel (SIP)* wall and roof construction comprising plywood timber sheeting enclosing polystyrene insulation within a timber frame;
(b) *Externally rendered insulated concrete formwork (ICF)* wall and roof structure comprising a concrete core sandwiched between expanded polystyrene insulation layers and
(c) *Traditional concrete blockwork* structure with an externally rendered insulation layer.

The basic fabric parameters are described below in Table 1. For each case, an exposed concrete floor slab was assumed, the thickness of which was varied and the impact upon internal temperature variations was evaluated. Additionally, the impact of a floor-embedded phase change material (PCM) upon the thermal response of the building was also evaluated. For each fabric configuration, two differing thermal insulation and infiltration scenarios which broadly reflect current and forthcoming UK building fabric legislation were analysed, namely:

(d) A '*standard performance*' building with *U*-values of 0.27 W/m^2 K for the walls, 0.27 W/m^2 K for the floor and 0.16 W/m^2 K for the roof. Windows had a *U*-value of 1.4 W/m^2 K and a *g*-value of 0.59. The infiltration rate was set to 0.5 air changes per hour (ACH).
(e) A '*high performance*' building with *U*-values of 0.13 W/m^2 K for the roof, the walls and the floor. Windows had a *U*-value of 0.68 W/m^2 K and a *g*-value of 0.407. The infiltration rate was set to 0.2 ACH.

Table 1
Building design parameters for simulation purposes.

Height (m)	2.4	N & S
Width (m)	12	
Depth (m)	10	E & W
Window areas (m^2)	3.00	N
	6.00	S
	3.75	E
	3.75	W
Convection coefficients (W/m^2 K)	3.06	Internal walls
	17.8	External walls
	277	Floor-to-ground
Floor boundary temp (°C)	9	
Transfer function time base (h)	0.5	
Wall and roof heat capacity per dwelling (kW h/K)	2.99	SIP
	14.50	ICF
	14.20	Externally insulated

To investigate the suitability of ASHP technology for each building fabric scenario, ASHP control approaches based upon a number of standard and off-peak electricity tariffs were investigated, and the results compared in terms of daily internal temperature variations, seasonal ASHP efficiency (COPs), building electrical energy consumption, CO_2 emissions and running costs. Table 2 presents the UK electricity tariffs investigated in the study. The most widely available are Economy 10 (E10) and Economy 7 (E7), which align quite closely with widely available variable rate tariff options across a number of EU countries in addition to the UK.

Finally, to assess the impacts of climactic variations on performance, evaluations were carried out for three differing UK locations, ranging from northern Scotland to southern England, as shown in Fig. 1.

2.1. Model design principle

Using the TRNSYS transient thermal modelling and simulation software environment [12–14], a parameterised model was