IMPACT OF RESIDENTIAL ENERGY SYSTEM DESIGN AND CONTROL OVER HEAT PUMP'S SYSTEM COST AND RELIABILITY

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ABSTRACT

Using a simulation-based approach, this work analyses the impact that different energy unit sizing strategies and control methodologies will have on the capital and running costs of an air source heat pump (ASHP) system installed in a refurbished dwelling. A total of 3 different system operational strategies were investigated and the cumulative cash flow over a period of 10 years (including initial investment) was utilized to compare the systems from an economic perspective. Additionally, in selected cases, the cycling of the heat pump was calculated in order to estimate the likely life-span of an installation.

The building and heat pump systems were simulated using the TRNSYS energy system modelling software. The results revealed the sensitivity of the system's costs and life-span to its control and operation. For example, operating the system as a direct gas boiler replacement resulted in capital costs above £10,000 and the unit's life span reduced to almost half in comparison to more favourable operational strategies. The results highlight the fact that the successful technical and financial performance of heat pumps within the UK's residential market will depend on designers', installers' and end-users' awareness regarding optimal operational strategies for the technology.

INTRODUCTION

In the European Union the CO_2 emissions of members states must be 20% lower than 1990 levels by 2020. Additionally, at least 20% of all energy consumed should be produced from renewable resources. (European Commission, 2008).

To achieve this target governments across Europe are producing increasingly stringent energy efficiency legislation and developing mechanisms to encourage the uptake of low-carbon technologies at the small and large scale. The former is particularly important in the UK, where the domestic sector is responsible for 30% of total energy consumption with the majority of this, approximately 80%, being used for heating applications (BERR, 2009).

Heat pumps are one low carbon technology attracting a lot of interest in the UK, given the its relative maturity and its potential to directly replace fossil-fuelled boilers in dwellings. Over the last 5 years, with limited government support, the number of heat pumps sold to the residential market has increased from less than a thousand in 2005 to above 14,000 in 2009 (European Heat Pump Association, 2010).

The UK government has recently announced its Renewable Heat Incentive (RHI), which rewards the utilization of "low carbon" heating technologies with an annual payment based on the building's estimated energy consumption (DECC, 2010). It is likely that the RHI will have a similar effect on heat pump sales as the earlier feed-in-tariff had for photovoltaic systems, where installed PV capacity increased from 6MW to 96MW in 2010. (DECC 2010).

However, despite the clear incentive provided by the RHI, the UK faces significant challenges to successfully integrate technologies such as heat pumps to the domestic sector. In particular, few domestic heating system installers have experience of heat pump systems design potentially leading to many poorly performing systems being installed as evidenced by the results emerging from the heat pump field trial project run by the Energy Saving Trust (Energy Saving Trust, 2010).

Installer training, user education, appropriate energy system sizing and design methodologies must be developed in order to improve the performance of heat pump installations and maximise their carbon saving potential. The Microgeneration Certification Scheme (MCS) is important step in this direction. The scheme defines minimum standards that must be complied by both manufacturer and installers in order to make an energy system installation eligible to government's funding schemes.

However, there is still no best practice regarding heat pump sizing and operation (MIS 3001, 2009), and inappropriately sized units could have a detrimental impact upon the eventual carbon savings and general energy performance of heat pumps. A study conducted for this paper by the authors found manufacturers recommending a range of approaches to heat pump sizing. Additionally, the assumptions underpinning each methodology were not clear, leaving the designer vulnerable to applying a sizing calculation that is inappropriate to the situation being considered.

It is therefore important to clarify the impact that a selected sizing methodology and operational strategy may have into the life span, capital and running cost of a new heat pump unit.

The next sections will go through different approaches to heat pump sizing and operation, observing their impact on the energetic and environmental performance of a heat pump unit – in this case an air source heat pump system.

METHOD

A simulation model of a building and air source heat pump (ASHP) heating system has been developed. This model is used initially to size the required capacity of the ASHP. Subsequently the model is used to simulate the energy performance of the building and heat pump system over a course of a year. The last step was to investigate the compressor's behaviour for each studied scenario.During the final analysis an extra control point is included in the return flow in order to simulate the effects of a typical heat pump's internal safety system. Note that the heat pump in all cases was operated without a buffer tank, this is in line with many recent UK domestic heat pump installations (Energy Saving Trust, 2010). Additionally, no domestic hot water (DHW) is being supplied from the heat pump; the devices is being used for space heating only.

The data extracted from these simulations is then analysed to determine the economic viability and impact on reliability of three different sizing/operational strategies.

MODEL

The model chosen for the study was that of a refurbished detached house. Although new buildings can be designed and built to complement a particular heating technology, 80% of UK's dwellings date from before 1980 and therefore the majority of heat pump installations will be retrofitted into older buildings.

The fabric details for the building model used are as follows:

Table 1 Simulated dwelling parameters

Structure	**Details**	**U value [W/m2 K]**
External walls	Brick – cavity	0.45
Windows (13% of total surface area (DECC, 2009))	Double glazing pre 2000	2.83
Roof	Pitched	0.3
Floor	($104m^2$)	0.45
Heating system	Radiators	N/A
Air infiltration	$13m^3/hr.m^2$ @50pa (DTLR,2000)	N/A

The building model was developed to be representative of an 'average' UK detached dwelling and is described in more detail by Kelly and Beyer (2006).

The building model was augmented by a detailed model of the heating system, comprising radiators, piping, valves, controllers and single speed air source heat pump. The system flow rate was 42l/min. In addition to basic energy performance, this model can also simulate how the compressor will cycle based on the building's thermostat settings and the heat pumps internal safety systems.

Verification

The model's predictions for heating load were compared to that of a pre-existing ESP-r model in a series of test simulations.

The simulation results differed between 3 and 4% between the two tools, these differences were traced to limitations in the TRNSYS building model. Specifically, the TRNSYS model assumes a flat roof structure and double glazing U-values are fixed at 2.8 (the ESP-r model used 2.93). However, despite these small differences it was concluded that the model provided an adequate test-bed for the heat pump-based heating system.

SIMULATIONS

The model was simulated using a London climate data set and half-hour time steps over a one year period. Three different operational strategies for the heating system were assessed. These were:

Condition 1 – Intermittent heating: When unoccupied the heating in the building is completely switched off. During the occupancy periods the building temperature is set to 20°C.

Condition 2 – Set back heating: When unoccupied the building temperature is maintained above a minimum value. During occupancy periods it is raised to 20°C. For the modelled system it was observed that the set back temperature of 16°C gives a good balance between energy unit size reduction and annual energy consumption.

Condition 3 – Continuous heating: The building is maintained at 20°C through the entire day. This is quite usual with buildings where the thermal mass can be used towards its advantage but for refurbished buildings heated through radiators the result may be a significantly higher energy demand. Because the power output just needs to match the fabric losses this condition tends to lead to the smallest energy unit sizes.

During this analysis the temperature in the building is monitored and the heat pump controlled using and on/off control with a 2°C dead-band, where the heating system switched off whenever the room temperature is one degree above the set point. To reduce cycling the internal temperature is allowed to go 1 degree below the set point before the heating system is switched on again.

In each case the model was simulated over the course of a year in order to 1) determine the size of heat pump unit required to maintain the desired set-point conditions and 2) using the correctly sized system determine its energy performance. Further simulations were then undertaken for condition 1 to assess the effect of changing the heat pump unit's pre-heating time (the time allowed between switching the unit 'on' and achieving the desired set-point condition).

Additionally, during the compressor cycle analysis, a controller also monitored the heating fluid return temperature switching the heat pump off whenever it achieved 51°C and then on again once the temperature drops towards 49°C, as is common with many heat pump systems.

In all cases, the property was heated through radiators.

RESULTS

The output from the TRNSYS simulation is large volume of time series data giving the state of the building and ASHP heating system in the form of key performance variables such as temperatures, flow rates and heat fluxes. For the purposes of this paper, this data has been filtered and the simulated peak demand and total energy consumed over a year have been extracted for use in the discussions that follow.

The model was first used to identify the size of unit required (based on peak demand) to attain the desired set point condition. In the case of intermittent heating, the heat pump was started one half hour prior to the desired temperature being required. The simulation model was also used to quantify the annual heating energy requirement; this was turned into energy cost by applying the energy utilised in each time step (half hour) against the relevant tariff described later.

Figure 2 shows the variation in the calculated peak thermal demand with the different operational strategies. This peak demand determines the size of the heat pump system to be installed. The intermittent operating strategy results in a unit size of 11kW heat output, almost twice the capacity of the unit required if a continuous heating strategy was adopted.

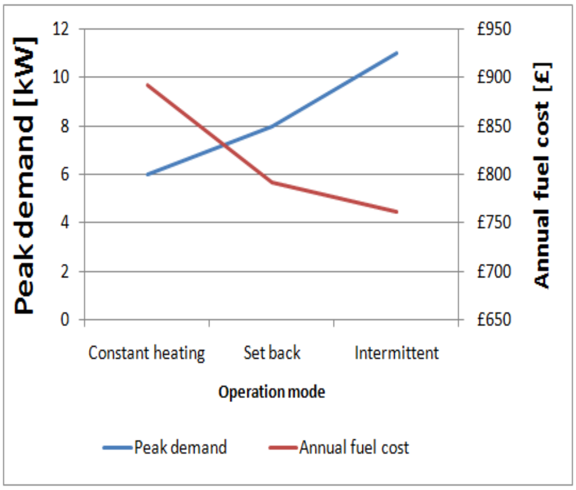

Figure 1 -– ASHP peak demand and annual fuel cost for different running conditions

Figure 1 also shows the fuel cost associated with each strategy. To calculate it, a typical UK 'economy' tariff was applied, dividing the electricity price into two groups: low rate (7p from midnight- 5 am, 1pm-4pm, 8pm-10pm) and high rate (14.9p all other periods). Additionally a standing charge of 16.3p per day was included. The resulting costs range from approximately £760 per annum for intermittent heating to around £900 per annum for a continuous heating strategy. The running costs are therefore significantly less sensitive to the operational strategy than the unit size.

The set back results and its position between the two other investigated conditions indicate that more feasible solutions may lie between the extremes. The previous analysis was then extended to 5 more intermittent heating conditions, but where a longer period of time is allowed between the heating system being switched on and the expected indoors temperature being achieved (pre-heat).

Figure 2 shows the effect of increasing the pre-heat time on the required unit size for the intermittent heating case.

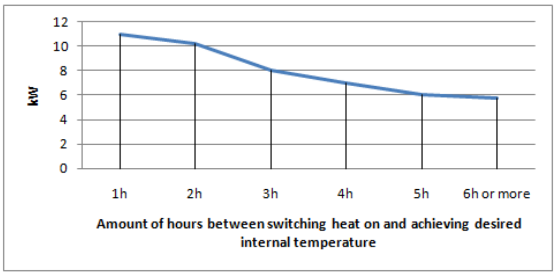

Figure 2: Required Unit size versus required heating time

DISCUSSION

The unit sizes and running costs above only give a partial picture regarding the merits of a particular operating strategy, an appreciation of the likely capital cost is also required. Prices for a range of ASHP units were therefore gathered from a range of different suppliers. These indicated that *installed* cost of a domestic ASHP device can be placed between £900 and £1200 per kW (thermal) depending on the size of the unit. The relationship utilized here will be £1200 per kW for a 5kW installation and £900 per kW for 14kW installed unit. These prices include fitting and purchasing larger radiators sized for use with an ASHP.

Applying these prices to the calculated unit sizes for the different operating strategies, it can be observed that sizing an air source heat pump system to for fast-response, intermittent heating is nearly 60% more expensive than trying to just meet the demand of a continuous heating system.

Table 2: Installed system cost

Unit size	**Estimated CAPEX**
11 kW	£10,500
10 kW	£9,800
8 kW	£8,300
7kW	£7,500
6kW	£6,700

Cumulative Costs

The merits of the different operational strategies can be compared by plotting the cumulative cash flow for each case (including the different set-back options for intermittent heating) over the first 10 years of operation. The cash flow includes the initial capital cost (year zero in the graph) and the simulated condition fuel cost (added every year to the initial capital expenditure [CAPEX]). This is shown in Figure 3. The resulting information enables a user to make an informed choice regarding the optimum economic means of operating a heat pump. Revenue from the renewable heat incentive funding scheme was not included because the current payment will be based on a simplified deemed energy demand, like that obtained through the UK's standard assessment procedure SAP for dwellings. This is pre-calculated and so is not sensitive to the small control changes being proposed in this paper. Using a SAP result gives only energy demand and so it cannot highlight any differences caused by operational strategies.

Although this kind of analysis isn't the most sophisticated way to define how successful an investment may be, its simplicity makes it quite important as a way to easily communicate to the customer what may be expected from each case. Looking into the year 10 the user will have a glance of how much he or she is expected to spend heating the property through this period of time. Also note that a typical customer won't be looking at their heat pump installation purely as an investment but will include a range of subjective factors that are hard to measure by means of a simple financial analysis.

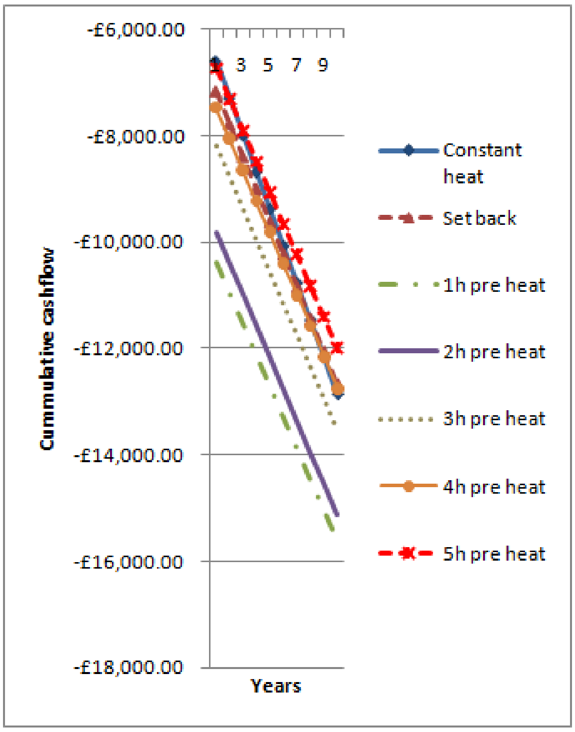

Figure 3 - Cumulative cash flow for 7 different running modes including initial capital cost

For example, a user may rather spend more in year zero as long as he or she will have the comfort of lower fuel bills while others may be short of initial cash and do not mind a slightly higher energy consumption. This simple representation may easy the communication between installer and customer making clear to all parties what are the expectations of the system and what the customer is willing to pay to achieve them.

Focusing on Figure 3, it is interesting to observe how the intermittent 1h pre-heating cases lie outwith the cluster of lines representing the more continuous heating modes. Intermittent heating only becomes competitive with above 4-hour pre-heat period, a situation that is akin to near continuous heating. Fundamentally, the energy savings accruing from intermittent heating use do not justify the initial capital cost of the larger unit required over the time scale of this analysis.

Reliability

From the energy system designer or energy unit supplier's perspective another important aspect would be how the sizing methodology adopted affects the equipment's reliability. To evaluate the system's reliability the simulated compressor on/off cycles were observed and compared to the expected number of cycles over the lifespan of a compressor. Ideally, once the heat pump compressor is switched on it should be kept running for as long as possible to minimise cycling since its life span is closely related to the accumulated number of on/off cycles.

More detailed simulations were run to analyse the cycling issue under the different operational conditions described previously. In these new simulations, the control system responsible for switching the heat pump on and off observed two variables: The heating fluid's temperature returning to the heat pump (preventing high pressure faults in the heat pumps refrigeration cycle) and the building internal air temperature. The internal temperature sensor will operate as described in the previous cases. Additionally, the return fluid temperature is sensed, with the heat pump switching off whenever it registers values above 51°C. This gives a more realistic picture of heat pump cycling as this is a typical control set up in units installed in the field.

Note that the compressor being simulated can't modulate its output therefore the results are not applicable to inverter driven heat pumps. No buffer store was included into the simulation in order to emphasise the cycling effect.

Table 2: Cycles per hour during unoccupied period (i), Occupied period (ii) and total cycles during a typical day(iii)

	Period		
System type	***i***	***ii***	***iii***
Intermittent heating	0	9	108
Set back heating	6	5	132
5h pre-heat	2~3	5	68
Continuous heating	5	5	120

Comparing the results against a typical compressor with life span of 200,000 cycles (around 10 years lifespan) means that the best lifespan is achieved with the operational strategy that provides the best financial return:

operating the heat pump intermittently but with a 5 hour pre-heat time.

Due the longer period of operation, the continuous and set back modes accumulate the highest number of cycles per day. In the latter case, the reduced internal temperature at which the building needs to be maintained during unoccupied periods (16^{o}C) results into the compressor cycling more often than if it was maintained at a higher value. Note that in all cases, cycling may be reduced by manipulating the dead band of the heat pumps' on/off controller Karlssons (2008).

Finally it should be noted that intermittent operation (with no pre-heat) results in the , shortest cycle periods; these tend to reduce the device efficiency due to factors such as refrigerant migration (vapour and liquid) into the evaporator, raising its initial temperature and affecting the heat exchange rate (McPherson, 1989).

CONCLUSIONS

A review of manufacturer's heat pump sizing methodologies revealed there was wide variation in approaches. In the worst case this would result in inexperienced installers applying sizing procedures translated from those used for boiler systems.

Using the example of an air source heat pump, a study was undertaken to highlight the consequences arising from using the sizing methods applicable to one technology such as boilers to a radically different technology such as heat pumps.

Sizing a heat pump to act as a fast-response heat source resulted in a very large unit size that would be acceptable for most gas boilers installations but when transferred to a heat pump system would result into a high capital cost, energy consumption, maintenance charges and reduced life span.

The financial and energy implications of alternative operational strategies were examined, where those strategies also dictated the size of heat pump unit to be installed.

The best performing operational strategy was allowing a 4 hour pre-heat before each heating period, with around 2 degrees temperature rise per hour is allowed, this resulted in a reduced capital cost and longer compressor running periods and least cycling.

It is important to point out the fact that the end-user must be better informed about the best operational strategy for their system, particularly if it was designed using one of the alternative strategies highlighted. For example, a set-back system is undersized if operated as an intermittent one resulting in either a cold home or higher fuel bills as the result of a less efficient auxiliary system being switched on. This situation has been observed in different studies focusing heat pump uptake and related issues in the UK (The energy saving trust, 2010) (Singh et al, 2009)

Finally, further studies may focus on replicating the analysis for systems where thermal buffers are present, exploring how to best utilize its added thermal mass.

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