LOAD MANAGEMENT OF HEAT PUMPS USING PHASE CHANGE HEAT STORAGE

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ABSTRACT

In the UK, heat pumps are often promoted as the means to provide low-carbon space heating and hot water for future dwellings as the electricity supply decarbonises. However, a major issue with growing heat pump use would be the additional load that this could place on the electrical network at times of peak heat and power demand. A means to alleviate potential demand problems is to stagger the operating times of heat pumps by integrating them with thermal buffering. However, focusing on the domestic sector, substantial volumes of thermal storage would be required to achieve the necessary level of operational flexibility in heat pumps and this poses a particular problem in the UK where the floor areas of urban dwellings are small. Thermal storage featuring phase change material (PCM) offers the potential of more volumetrically efficient heat buffering, which may be more suitable for integration into domestic heating systems.

In this paper, the potential to shift the operating time of heat pumps integrated with phase-change-material-enhanced thermal storage is assessed and compared to conventional hot water storage, where the limits of flexible operation are determined by the comfort and hot water needs of the end-user. The results indicate that the use of PCM-enhanced thermal storage can reduce the volume of the buffering required for load shifting by up to 3 times. However, thermal buffering with load shifting can increase heat pump energy demand and (at present) in the UK results in increased emissions and cost penalties for the end user.

Keywords: heat pump, load shifting, simulation, phase change material, thermal buffer.

INTRODUCTION

Heat pumps are often promoted as a means to deliver low-or-zero carbon space heating and hot water to the domestic sector (e.g. Hewitt, [1]). However, if large number of heat pumps were retro-fitted into older housing the peak electrical load in the low voltage network could be substantially increased, leading to potential power quality problems such as voltage dips and cable overloading at times of peak heating demand; this could eventually result in the need for significant and expensive network reinforcement. One means to avoid such a scenario is to provide sufficient thermal buffering such that heat pump operating times can be shifted outside periods of peak electrical demand. However, this shift in operating time has the potential to cause problems for the end-user such as low space temperatures during occupied periods or low hot water temperatures.

A previous study by Hong et al. [2], explored the flexible operation of air source heat pumps (ASHP) retro-fitted into to a variety of UK dwellings. In their study, the limits of operational flexibility were dictated by the impact on the end user, such that any shift in heat pump operating times should have a minimal effect on delivered space or hot water temperatures. Using these criteria, the study indicated that without thermal buffering, the flexibility of heat pump operating times was limited to between 1 and 2 hours. A 1-to-2 hour load shifting time-window would not allow heat the pump demand to be wholly moved to off-peak periods. However, Hong et al. [2] also indicated that more substantial shifts in heat pump operating times of up to 6-hours were feasible, but only with the addition of substantial quantities of thermal buffering (up to 500L) and only with significant improvements to the building fabric (i.e. insulation to passive house standards). The authors themselves pointed out that upgrading all houses to high insulation standards may not be possible and that accommodating buffering of this size could be problematic, particularly in a country such as the UK where there is a trend for reduced floor space in newer housing [3].

In this study, an integrated ESP-r model [4] of a conventional UK detached dwelling featuring an ASHP heating system was used to investigate the potential for thermal storage, augmented with PCM to provide practical, more volumetrically-efficient thermal buffering for the load shifting of heat pumps.

MODEL DETAILS

The heat pump system modelled in this paper featured a calibrated, high-temperature air source heat pump (ASHP) with a nominal 11kW of thermal output, supplying the space and water heating needs of the detached dwelling. The ESP-r ASHP model used in this paper has been employed in previous studies and verified using field trial data, as described by Cockcroft and Kelly in [5].

The ASHP model was integrated into buffered and unbuffered heating system variants (figures 1a and 1b, respectively). In the buffered system, an additional circulation pump was required to transfer the heat from the buffer tank to the heating and hot water circuits. The two variants shown could be retro-fitted into many existing UK dwellings as a direct replacement for the boiler-based heating systems found in 90% of UK dwellings [3]. However, existing radiators would need to be replaced to account for the lower flow temperature delivered by the heat pump modelled here of approximately 55 ^{o}C compared to water temperatures of up to 80 ^{o}C often seen in boiler-based systems [3]. It should be noted that alternative system configurations to those shown are possible, for example with the hot water load fed directly from the buffer tank. However, a study on the optimum configuration for buffering is beyond the scope of this paper.

The validated buffer and domestic hot water (DHW) tank model used in this study [6] accounts for stratification and parasitic losses to the environment. It can accommodate one or two charging circuits (e.g. from a primary and secondary heat source), two discharge circuits and variable numbers of phase change modules as illustrated in figure 1b. Hence, the same tank model can be used to represent sensible thermal buffering along with buffering incorporating different percentages (by tank volume) of PCM.

In this study, the quantity of PCM, and the volume of the buffer tank were varied to determine how each affects the heating system performance with load shifting. The PCM used was a commercially available inorganic hydrated salt with the characteristics shown in table 1; this was selected as the best-fit match for the operating characteristics of the heat pump, enabling the buffer storage to operate across the phase change range of the material and making best use of its latent heat.

The time-varying draw from the DHW tank shown in Figures 1a and 1b was calculated using a high-resolution algorithm closely based on that developed by Jorden and Vagen [7]. According to Knight and Ribberink [8] this model provides a realistic depiction of European domestic hot water draws. The nominal draw used in this study of 130 l/day is consistent with the hot water use of a family of four.

Table 1: selected characteristics of the phase change material [9].

Latent heat J/kg	210,000
Melting temperature ^{o}C	48
c solid J/kgK	2410
c liquid J/kgK	2410
ρ solid kg/m^3	1600
ρ liquid kg/m^3	1666

The control strategy adopted for the heating system differed slightly depending upon whether or not a buffer tank was present. The control settings were derived from experience gained from field trials with other ASHPs [5]. With a buffer tank, the ASHP was operated in an attempt to maintain the buffer outlet temperature between 50 and 55 ^{o}C, operating using on/off control with a 5 ^{o}C dead band. The circulating pump then provided heat to the hot water tank and heating system if there was a requirement for heat. Ideally, the DHW tank was maintained between 43-45 ^{o}C (the tank temperature can be occasionally boosted to 60 ^{o}C by an auxiliary electric coil to combat legionella) and the space temperatures within the living zone were ideally to be maintained between 19 and 21 ^{o}C using on/off control. The flow to the DHW tank was controlled using a 3-way valve; this operated giving hot water priority, so that when the water tank temperature was below 43 ^{o}C, all of the flow from the buffer tank heated the DHW tank. Only when the DHW tank reached 43 ^{o}C was any hot water supplied to the radiator circuit. The operation of the unbuffered system was similar, but the heat pump was controlled directly in an attempt to maintain the conditions indicated above in the DHW tank and living space. The hours of operation of the heating system are discussed later in the load shifting section.

The system models of figures 1a and 1b were integrated within a detached UK dwelling model [10] with a usable floor area of 136 m^2 spread over an upper and ground floor. The building featured three thermal zones: a loft space and two composite zones describing (respectively) the spaces hosting active occupancy such as the living room and kitchen; and those spaces that have low occupancy rates or are occupied during sleeping hours such as bathrooms and bedrooms. This form of model captures the key thermodynamic characteristics of the building's performance and has been deployed successfully in other studies (e.g. [11]).

For this study, the fabric of the building was subject to a modest upgrade, with 300 mm of insulation between the loft space and the occupied areas of the building; 60 mm of cavity wall insulation and 300 mm of insulation between the occupied area of the building and the void under the floor space. This thermal upgrading follows from the findings of Hong et al. [2], who indicated that without thermal improvements, the volume of thermal storage required for load shifting becomes wholly infeasible. The thermal characteristics of the building are shown below.

Table 2: thermal characteristics of the main building elements.

Fabric element	'U'-value (W/m^2K)
Glazing (14mm gap)	3.03
External walls	0.26
Ground floor	0.121
Upper floor ceiling	0.129

The average air leakage used in the model is 0.5 air changes per hour, which is typical of newer dwellings in the UK [12]. The dwelling was assumed to be occupied by a family of four with the active occupancy between 07.00-09.00 and 17.00-23.00; the occupants were assumed to be sleeping between 23.00-07.00. Outside of these periods the house was unoccupied.

METHODOLOGY

The aim of the study was to determine if the use of PCM could reduce the volume of thermal buffering needed to minimise the impact of heat pump load shifting on the end-user, specifically low space and hot water temperatures. To this end, the operating times of the heat pump were set to off-peak periods, whilst the volume of the thermal buffer was varied from 200-1200 *l* and the percentage of PCM in the thermal buffer (by volume) was varied from 0% up to 70%. Above this percentage of PCM, the space remaining in the tank for heat exchangers becomes too restrictive. Simulating the performance of the tank with no PCM allowed the performance of a purely sensible heat storage buffer to be compared against the PCM-enhanced performance.

The off peak-periods of heat pump operation correspond to the UK Economy-10 tariff [13], which offers lower electricity prices between the hours of 00.00-05.00, 13.00-16.00 and 20.00-22.00. Constraining the heat pump to operate within these hours effectively meant that (other than 20.00-22.00) it operated when the house was unoccupied or when the occupants were asleep.

The performance of both the buffered system (with and without PCM) was compared to the case with no load shifting, where the heat pump was connected directly to the heating circuit and the DHW tank. In the unbuffered case, the hours of heating operation were set to 06.00-09.00 and 16.00-23.00, corresponding to the periods of active occupancy within the dwelling plus one-hour of pre-heating at the beginning of each period. These times also tend to coincide with the UK's morning and evening peaks of electrical demand between around 08.00-09.00 and 17.00-18.00 respectively [14].

The simulations were undertaken for winter, spring and summer weeks for a warm (Southern England) and cool (North East Scotland) climate. In total, 186 simulations were undertaken (including the reference cases and buffered variants with different buffer tank sizes and PCM percentages). All were run at 1-minute time resolution, which allows the nuances of the heating system operation such as heat pump cycling and control valve operation to be captured in the results.

Table 3: typical performance data collated from a simulation (buffered ASHP system; cold UK climate; summer week).

Average living space temperature (^oC)	23.01
Average DHW temperature (^oC)	43.97
Average buffer tank outlet temp. (^oC)	47.86
Average ASHP COP (-)	3.17
ASHP heat out (kWh)	75.25
ASHP electrical (kWh)	25.26
ASHP cycles (-)	51
Low living room temperature (%)	0.00
Low DHW temperature (%)	0.95
$C0_2$ (kg)	11.13

The main metrics examined with regards to the performance of the buffering were the total number of hours of active occupancy over which zone space temperatures fell below 18 ^oC and in which hot water temperatures fell below 40 ^oC during periods of active occupancy; these were then expressed as a percentage of active occupied hours (see table 3). The performance of the buffered system was deemed adequate if the thermal comfort and hot water temperatures closely matched (within 1%) those of the reference (unbuffered) system: so, to the end-user there would be no difference between the buffered and unbuffered system performance.

Other performance-related parameters extracted from the simulations were the heat pump coefficient of performance, its electrical energy consumption and the number of on-off cycles, all of which were affected by the use of thermal buffering and the alteration of the heat pump operating times. The simulations therefore reflect the effect of load shifting on the end user *and* on the performance of the heat pump.

For each simulation, the heat pump performance data was post-processed to determine the energy costs for the end user and the carbon emissions associated with the use of the heat pump. The energy costs were determined using the data shown below [15], which shows typical on and off-peak prices from one of the UK's main electricity suppliers.

Table 4: on and off peak energy costs.

Tariff	On-peak cost £GBP per kWh	Off-peak cost £GBP per kWh
Standard	0.1308	0.1308
Economy 10	0.1817	0.1053

To determine the impact on CO_2 emissions from heat pump load shifting, it was necessary to generate time-varying carbon intensity data using a technique similar to that employed by Hawkes [16]. Data on the generation-mix at each hour of 2011 was obtained from [17]; this information along with the assumed carbon intensities for different generation types shown in table 4 was then used to calculate an average hourly CO_2 intensity using the following equation:

$$c_{ave}(t) = \frac{1}{P_{TOT}} \sum_{x=1}^{n} P(t)_x \Delta t \times c_x \quad (1)$$

Figure 2 shows a typical variation in the CO_2 intensity of grid electricity over a day from the transition season.

RESULTS AND DISCUSSION

Table 5 shows, for each of the cases simulated, the size of the sensible and PCM-enhanced thermal buffer required to shift heat pump operation to off-peak periods, whilst achieving a similar occurrence of low operative temperatures and/or hot water temperatures as the reference case.

Thermal Performance

The results indicate that in all cases the PCM-enhanced buffer offers improvements in terms of the size of storage required to achieve effective load shifting: the size of the buffer tank could be reduced by between 2-3 times compared to hot water buffering.

Table 5: buffer sizes providing effective load shifting.

	Season	Cool UK climate	Warm UK climate
Sensible-only buffering (l)	Winter	1200	1200
	Transition	700	1000
	summer	700	500
PCM-enhanced buffering (l / %PCM by vol.)	Winter	500/50	500/50
	Transition	300/50	300/70
	Summer	300/50	200/70

Without PCM, a tank size of 1200 l was required to load shift over the winter weeks for both the warm and cold climates – this would be a very large tank to accommodate within a dwelling. With PCM added, a 500 l tank is required for the winter week for both the UK climate sets (which as Hong et. al. [1] pointed out is still a large tank).

Figures 3a and 3b respectively, illustrate the impact of increasing the percentage of phase change material in the buffer tank and the corresponding reductions in the occurrence of both low hot water and living room space temperatures during occupied hours. These figures illustrate that, generally, increasing the PCM content of the tank by volume improves the performance of the ASHP system in terms of delivery of thermal comfort and hot water.

Tables 6a and 6b shows heat pump performance data from the simulations corresponding to the systems indicated in table 5 (above). Also shown is the performance of the reference system without any shift in operating times. These results indicate that there was a significant energy penalty associated with buffering and load-shifting, particularly when using the larger buffering tanks with no PCM.

The addition of sensible thermal buffering and load shifting results in an energy penalty of up to 57% in the worst instance compared to the reference case with no buffering and load shifting.

Figure 4, shows that for the case of the warm climate winter week, increasing the buffer size and the addition of PCM to the buffer tank increased the electrical energy consumption of the heat pump. This trend was evident in all of the simulations undertaken. However, as a smaller PCM-enhanced buffer could be employed to load shift the heat pump, the energy penalty associated with load shifting and PCM buffering is less compared to using hot-water buffering. In the worst case, the PCM-enhanced buffer results in a 38% energy penalty compared to the reference case.

The increased heat pump electrical energy use is attributable to two main causes. Firstly, the addition of the buffering tank introduces extra standing system losses (the buffer tank has an overall heat loss coefficient of approximately 1W/m^{2}K). Second, the coefficient of performance (COP) of the heat pump is reduced by up to 15%. This deterioration in COP is due to the addition of an intervening heat exchanger (in the buffer), so in order to maintain acceptable space and hot water temperatures, it is necessary to supply water to the buffer at a higher temperature (~5^{o}C) than would be the case if the heating circuit and hot water tank were supplied directly. Additionally, the heat pump operates at off-peak times when ambient temperatures are lower. Both of these factors increased the temperature difference across the heat pump, lowering the COP.

The addition of sensible-only buffering is beneficial with respect to the cycling of the heat pump. The large sensible store reduces heat pump cycling by up to 35% at times of heavy loading. This could have a beneficial effect on both maintenance requirements the heat pump lifespan. However, with the PCM-enhanced thermal buffer there is no clear reduction in thermal cycling. The principal reason for this is that the temperature in the buffer tank (against which the heat pump is controlled) becomes more sensitive to heat input and heat draws as the volume of water reduces with increasing PCM content.

Environmental Performance

Tables 6a and 6b also show the environmental performance of the reference and load-shifted heat pump systems. Interestingly, with 2011 UK CO_2 intensity data, load shifting of the heat pump into off-peak periods results in *increased* CO_2 emissions. This occurs because first, load shifting of the heat pump results in increased electrical demand. Second, the difference in UK grid CO_2 intensity between peak and off-peak periods in small. Indeed, in winter the CO_2 intensity in off-peak periods is occasionally higher than during peak periods, mainly due to the significant quantity of coal powered stations providing base load; at peak load times in winter more lower-carbon generation such as CCGT and pumped hydro comes on-line, reducing the CO_2 intensity of electricity per kWh generated.

Economic Performance

Tables 6a and 6b also show the cost associated with running the ASHP during peak and off-peak periods. The results indicate that with the tariffs shown in table 4, other than for periods of very light heat loading (warm climate, summer week) there is a cost penalty for the end user associated with heat pump load shifting of up to 26% compared to the reference case with load shifting. The additional heat pump demand associated with load shifting is not adequately compensated for by the reduction in electricity price between peak and off-peak periods.

CONCLUSIONS

In order to study the ability of phase change material (PCM)-enhanced thermal storage to facilitate heat pump load shifting a model of a typical UK detached dwelling complete with a buffered heat-pump-based heating system was developed. In order enact a load-shift, the operation of the heat pump was restricted to off-peak periods and the volume of storage (with and without PCM) required to deliver adequate space and hot water temperatures was investigated. The performance of the heat/pump buffer was simulated for a cool and warm UK climate over characteristic transition, summer and winter weeks. The PCM used was a commercially available inorganic salt with a melting temperature of 48 ^{o}C.

The results from the simulations have demonstrated that the addition of PCM can deliver significant benefits with regards to the buffering volume required for heat pump load shifting. The volume of the buffering required could be reduced by between 2 and 3 times during periods of high load, with insignificant deterioration in the space temperatures or hot water temperatures delivered to the end user.

However, the simulations also highlighted an energy penalty associated with load shifting. This was due to a reduction in the COP of the heat pump with thermal buffering, and standing losses were increased. Whilst the PCM-enhanced buffer had a better energy performance than the sensible buffering, the electrical demand of the heat pump with PCM-enhanced storage was still increased by up to 35% compared to the situation with no heat pump load shifting.

Further analysis also indicated that, with the current variability in UK grid electricity CO_2 intensity, there was no environmental benefit gained from heat pump load shifting to off peak periods. Moreover, there was a financial penalty from load-shifting for the end user when current standard and off-peak tariffs were applied. These two results may change in future as the energy mix of the UK electricity system changes and if tariff structures are revised to encourage load shifting.

NOMENCLATURE

Symbols
c – carbon intensity (kg/MW or g/kW)
n – number of generation sources
P – power MW
t - time
Δt – time interval (hours)

Subscripts
ave - average
x – relating to a specific generation source

Acronyms
ASHP – air source heat pump
COP – coefficient of performance
DHW – domestic hot water
GBP – Great Britain pounds
PCM – phase change material

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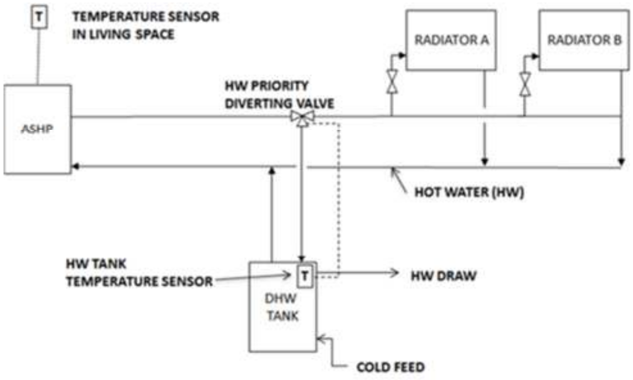

Fig 1a: the modelled heating system supplied by the ASHP (with no buffer tank).

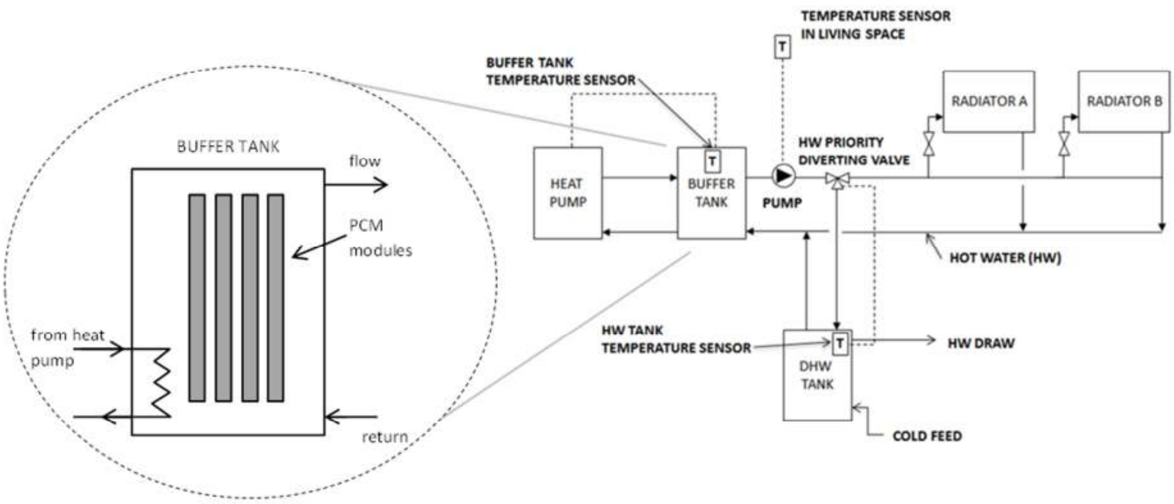

Fig 1b: the modelled heating system supplied by the ASHP (with PCM-enhanced buffer tank).

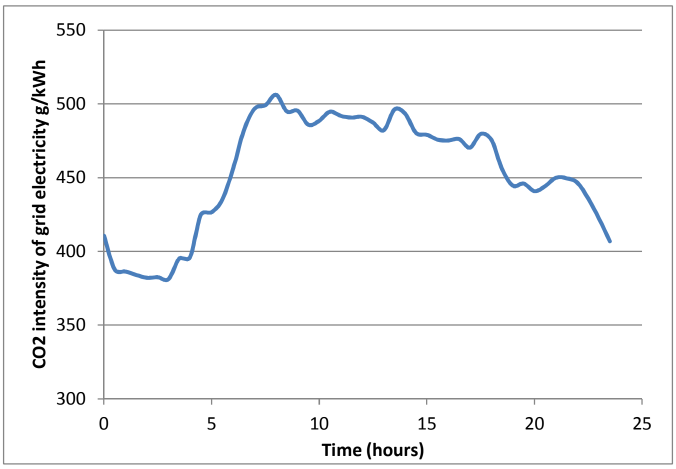

Figure 2: variation in CO_2 intensity of grid electricity – transition day 2011.

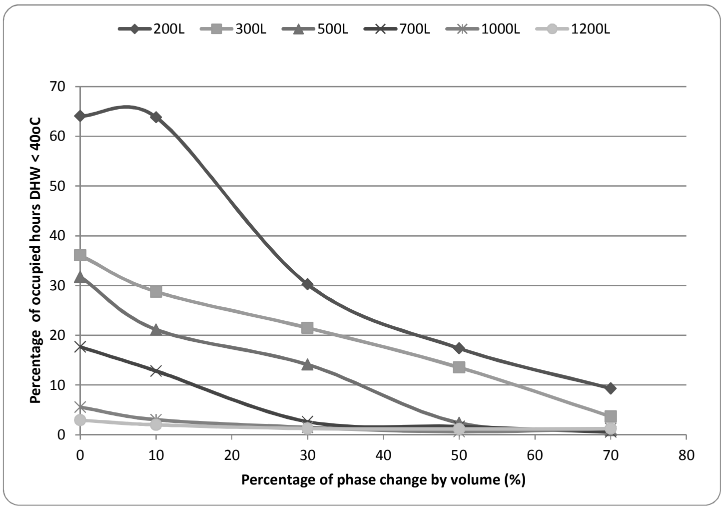

Figure 3a: occurrence of simulated low hot water temperatures for heat pump operation shifted to off-peak against %of PCM in buffer tank for different buffer tank volumes; warm UK warm climate, winter week.

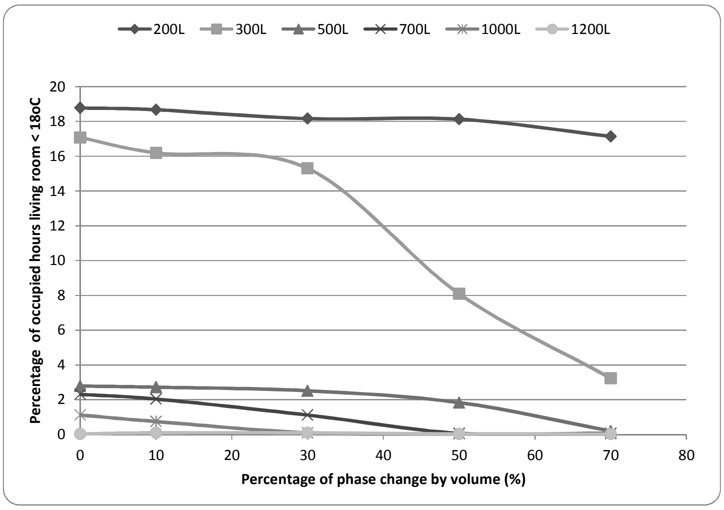

Figure 3b: occurrence of low living room operative temperatures for heat pump operation shifted to off-peak against %of PCM in buffer tank for different buffer tank volumes; warm UK warm climate, winter week.

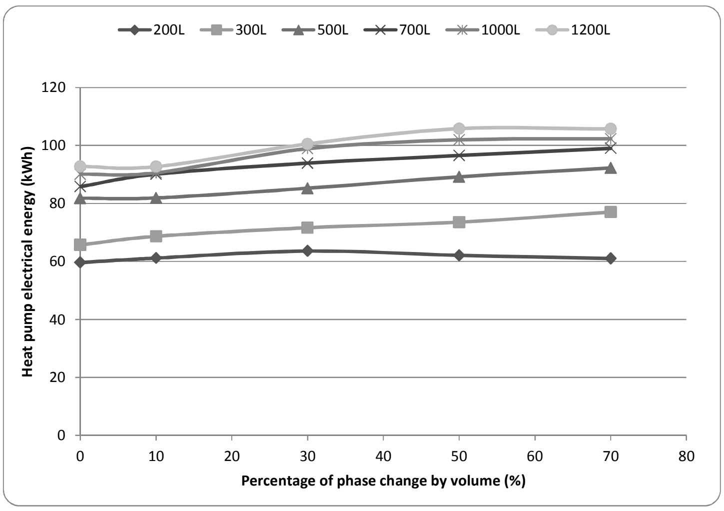

Figure 4: electrical energy consumption of heat pump for heat pump operation shifted to off-peak against %of PCM in buffer tank for different buffer tank volumes; warm UK warm climate, winter week.

Table 6a: performance of reference system (with no ASHP load shifting), sensible-only buffering and PCM enhanced buffering both with ASHP load shift to off-peak times. UK cold climate.

	Winter Week Simulations			Transition Week Simulations			Summer Week Simulations		
	Reference-winter	Sensible 1200 l	PCM-enhanced 500 l 50% PCM	Reference-transition	Sensible 700 l	PCM-enhanced 300 l 50% PCM	Reference-summer	Sensible 700 l	PCM-enhanced 300 l 50% PCM
Average living room temperature (°C)	21.05	21.31	20.98	22.55	22.52	22.68	22.94	22.96	23.01
Average rest-of-house temperature (°C)	17.53	18.96	18.57	21.25	21.36	21.69	22.63	22.73	22.75
Average buffer temperature (°C)	N/A	45.57	45.82	N/A	48.28	47.70	N/A	49.15	47.86
Average DHW temp (°C)	44.19	43.53	43.16	44.20	43.97	43.67	44.25	44.15	43.97
Average ASHP COP (-)	3.08	2.61	2.61	3.14	3.04	3.01	3.21	3.18	3.17
ASHP heat output (kWh)	218.17	293.05	255.45	80.93	105.74	108.74	56.42	74.28	75.25
ASHP electrical energy (kWh)	73.03	114.39	99.96	27.66	36.58	37.98	19.14	24.89	25.26
ASHP cycles -	164	106	131	50	55	68	42	45	51
Low living room temperature (%)	0.00	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00
Low DHW temperature (%)	2.62	2.99	3.50	0.92	0.54	1.60	0.71	0.61	0.95
CO_2 (kg)	37.84	59.62	51.84	12.68	17.31	17.61	8.12	11.05	11.13
ASHP running cost (£ GBP)	9.55	12.05	10.53	3.62	3.85	4.00	2.50	2.62	2.66

Table 6b: performance of reference system (with no ASHP load shifting), sensible-only buffering and PCM enhanced buffering both with ASHP load shift to off-peak times. UK warm climate.

	Winter Week Simulations			Transition Week Simulations			Summer Week Simulations		
	Reference-winter	Sensible 1200 l	PCM-enhanced 500 l 50% PCM	Reference-transition	Sensible 700 l	PCM-enhanced 300 l 50% PCM	Reference-summer	Sensible 700 l	PCM-enhanced 300 l 50% PCM
Average living room temperature (°C)	20.76	21.07	21.73	22.20	22.33	22.18	23.70	23.71	23.75
Average rest-of-house temperature (°C)	17.60	18.67	19.33	20.10	20.67	20.77	23.35	23.37	23.41
Average buffer temperature (°C)	N/A	46.59	46.25	N/A	47.47	47.24	N/A	49.47	47.98
Average DHW temp (°C)	44.17	43.75	43.47	44.16	43.85	43.56	44.21	44.14	43.97
Average ASHP COP (-)	2.92	2.60	2.57	3.04	2.82	2.78	3.43	3.48	3.44
ASHP heat output (kWh)	181.08	235.48	224.17	106.40	132.18	113.11	47.39	60.43	56.00
ASHP electrical energy (kWh)	64.50	92.77	89.19	36.76	48.51	42.24	15.40	18.88	17.80
ASHP cycles -	114	101	119	93	70	80	39	37	45
Low living room temperature (%)	0.00	0.03	1.84	0.00	0.00	0.00	0.00	0.00	0.00
Low DHW temperature (%)	2.35	2.93	2.38	1.90	2.86	1.97	0.41	0.71	0.88
$C0_2$ (kg)	30.82	45.51	43.36	18.14	24.48	21.19	6.53	8.31	7.75
ASHP running cost (£ GBP)	8.44	9.77	9.39	4.81	5.11	4.45	2.01	1.99	1.87