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1 **PERFORMANCE ASSESSMENT OF TARIFF-BASED AIR SOURCE HEAT PUMP LOAD SHIFTING**
2 **IN A UK DETACHED DWELLING FEATURING PHASE CHANGE-ENHANCED BUFFERING**

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9
10 **Abstract**

11 Using a detailed building simulation model, the amount of thermal buffering, with and without phase
12 change material (PCM), needed to time-shift an air source heat pump's operation to off-peak
13 periods, as defined by the UK 'Economy 10' tariff, was investigated for a typical UK detached
14 dwelling. The performance of the buffered system was compared to the case with no load shifting
15 and with no thermal buffering. Additionally, the load shifting of a population of buffered heat pumps
16 to off-peak periods was simulated and the resulting change in the peak demand on the electricity
17 network was assessed. The results from this study indicate that 1000L of hot water buffering or 500L
18 of PCM-enhanced hot water buffering was required to move the operation of the heat pump fully to
19 off-peak periods, without adversely affecting the provision of space heating and hot water for end
20 user. The work also highlights that buffering and load shifting increased the heat pump's electrical
21 demand by over 60% leading to increased cost to the end user and increased CO₂ emissions
22 (depending on the electricity tariff applied and time varying CO₂ intensity of the electricity generation
23 mix, respectively). The study also highlights that the load-shifting of populations of buffered heat
24 pumps wholly to off-peak periods using crude instruments such as tariffs increased the peak
25 electrical loading by over 50% on the electrical network rather than reducing it and that careful
26 consideration is needed as to how the load shifting of a group of heat pumps is orchestrated.

27 Keywords: load shifting; demand side management; domestic; heat pump; phase change material;
28 simulation.

29 **1. Introduction**

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

35 The widespread uptake of heat pumps, coupled with central electricity generation from nuclear and
36 renewable sources is often cited as a means to decarbonise domestic heating (e.g. [5], [6]). However,
37 as the vast majority of UK dwellings likely to be extant in 2050 are already constructed [7], then a
38 radical reduction in domestic GHG emissions will require a widespread heat pump retrofit
39 programme. Air source heat pumps (ASHPs) have the potential to act as a direct replacement for the
40 fossil-fuelled boilers commonly found in UK housing, though their control needs to be slightly
41 different and heat emitters need to be resized to account for the lower flow temperatures delivered
42 by heat pumps [8]. The (relatively) low cost of installation and the lack of a requirement for ground
43 works makes ASHPs a more feasible mass retrofit proposition than ground source heat pumps
44 (GSHP).

45 A consequence of significant numbers of ASHPs being retro-fitted into the housing stock could be
46 substantially increased electrical load in the low voltage (LV) distribution system (e.g. [9]) leading to
47 problems such as voltage dips and cable overloading, and potentially the need for expensive network
48 reinforcement. One means to avoid this scenario is to shift heat pump electrical demand to off-peak
49 periods such as the early morning, late evening or the middle of a typical working day, when

50 domestic electrical demand is lower. However, this could have an impact on the delivery of adequate
51 indoor temperatures and the provision of hot water. *Effective* shifting of heat pump operation
52 requires that the manipulation of operating times is achieved with the minimum of inconvenience to
53 the end user. An appropriate means to deliver effective load shifting is through the provision of
54 sufficient thermal buffering to temporally decouple the operation of the heat pump from the space
55 heating and hot water demands.

56 **1.1 Review**

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

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

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

93 **1.2 Objectives**

94 By simulating the performance of a 'typical' UK family dwelling [17] equipped with a heat-pump-
95 based heating system, the contribution of this paper is to address some of the gaps in the knowledge
96 relating to domestic heat pump load shifting. Firstly, the volume of thermal storage (with and
97 without PCM) required to effectively load shift heat pump entirely to off-peak periods, as defined by
98 the UK economy 10 tariff [18], is assessed; this is the volume of storage required to achieve shifting
99 *without* affecting end-user comfort and hot water delivery. Secondly, the impact of load shifting on

100 the heat pump's energy and environmental performance is assessed along with an assessment of the
101 effect on running costs. Finally, to assess the potential impact on electrical demand, an example is
102 presented where a population of heat pumps are load shifted to timings dictated by the UK the
103 Economy 10 tariff.

104 **2. Modelling**

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

121 The focus of the work presented here is therefore the application of the ESP-r tool, rather than
122 development of algorithms or new functionality: all of the models used are already available in the
123 general release of ESP-r. The algorithms underpinning the key heating system components referred
124 to later in this paper are documented in more detail elsewhere: air source heat pump [21], the
125 buffering and hot water storage tanks [22] and radiators and controls [23].

126 **2.1 Model Details**

127 *Dwelling*

128 The dwelling analysed in this paper represents a typical UK detached house [17]. This type of
129 residence comprises around 30% of the existing UK housing stock [2] and is large enough to
130 accommodate the volume of thermal buffering indicated by Hong *et al* [14] and Arteconi *et al* [15] as
131 required for load shifting. The dwelling model is shown in Figure 1. The dwelling has a floor area of
132 136 m² spread over an upper and ground floor. The building features three main spaces (zones): a
133 loft zone and two composite zones describing (respectively) the areas of the dwelling hosting active
134 occupancy such as the living room and kitchen and those areas that have low occupancy rates or that
135 are occupied at night such as bathrooms and bedrooms, respectively. The key characteristics of the
136 model are shown in Table 1; this form of model captures the pertinent thermodynamic
137 characteristics of the building's performance and has been deployed successfully in other studies,
138 e.g. [24].

139

140

Figure 1

141

142

143 This necessity of thermally upgrading the building fabric in parallel with the installation of the heat
144 pump is illustrated in the findings of Hong *et al.* [13, 14], who indicated that without thermal
145 improvements, the volume of thermal storage required for load shifting becomes impractical.
146 Consequently, The fabric of the dwelling was subject to a pragmatic and cost-effective energy

147 efficiency retrofit¹. The external cavity wall was filled with 60mm of insulation. Thermal bridging in
148 the fabric was accounted for by adding a further 10% to the external wall U-values over and above
149 the values derived from the constructions of Table 1. A total of 300mm of insulation was added
150 between the loft space and the occupied areas of the building. A further 300mm of insulation was
151 added between the occupied area of the building and the void under the floor space. The building is
152 assumed to have pre-existing double glazing, the U-value used is typical of pre-2002 UK double
153 glazing with a UPVC frame [25, 26]

154

Table 1

155 The *average* air change rate used in the model is 0.5 air-changes-per-hour, which is also the value
156 typically applied in standard dwelling assessments [26]; this value is consistent with air tightness
157 values measured in similarly thermally upgraded dwellings [27]. The air change rate represents the
158 average volume of outside air entering the dwelling under normal operating conditions and
159 comprises the construction infiltration plus the occupant's use of trickle vents, windows and doors.
160 Additionally, the infiltration model also accounts for increased window opening as indoor
161 temperatures rise, infiltration increased to mimic the effect of window opening in order to prevent
162 overheating.

163 The dwelling was assumed to be occupied by a family of four (two adults and two children) with
164 active weekday occupancy between 07.00-09.00hrs and 17.00-23.00hrs. The occupants were
165 assumed to be sleeping between 23.00-07.00hrs. Outside of these periods, the house was
166 unoccupied. During weekends, active occupancy was assumed to be between 08.00-10.00 and 16.00-
167 24.00hrs, with the family sleeping between 24.00 to 08.00 and engaged in other activities away from
168 the home between 10.00 and 16.00; the weekday and weekend occupancy profiles are derived from
169 UK time-use survey data [28].

170 *Air Source Heat Pump*

171 The ASHP supplies the space and water heating needs of the dwelling. The dynamic air source heat
172 pump model (ASHP) used in these simulations was calibrated and verified using field trial data as
173 described by Kelly and Cockroft [21]. The version of the model used here has a nominal 10kW of
174 thermal output and nominal coefficient of performance of approximately 2.8. In common with other
175 ESP-r systems component models, the ASHP algorithm is dynamic and explicitly accounts for thermal
176 inertia, the variation in the return hot water temperature and ambient air temperature and their
177 impact on heat output and compressor power consumption. The model also accounts for impact of
178 defrosting of the evaporator coils as a function of outdoor relative humidity and air temperature.
179 Illustrative performance output from the model is shown in Figure 2a, which shows the variation in
180 ASHP heat output and coefficient of performance with external temperature. AS would be expected,
181 both COP and heat output deteriorate as ambient temperature drops. The spread of these values is
182 due to the dependence of both on the ambient and the return water temperature from the heating
183 system. For example, when the heat pump starts up, the COP and heat output is initially high as the
184 heating system is cool and the temperature difference across the heat pump is at its lowest. Both the
185 COP and heat then drop as the heating system comes up to temperature. This performance mirrors
186 the performance characteristics seen in UK field trials [21].

187

Figure 2a

188 Key parameters and equations used with the model are shown in Table 2.

189

Table 2

190 *Systems Model*

191 The heat pump model described above was integrated with other ESP-r systems component models
192 to form a systems network; these in turn were linked into the building model to form an integrated

¹In principle, it would be possible to upgrade a dwelling to passive house standards [29]; however this would require extensive building modifications in order to drastically reduce the U-value of external surfaces along with infiltration of outside air and such dramatic modifications could be prohibitively expensive (e.g. [30]).

193 building and systems model. The unbuffered and buffered systems networks developed for these
194 simulations are illustrated in Figures 3a and 3b, respectively. These were applied to assess the
195 performance of the heat pump with no load shifting (reference case) and with its operation set-back
196 to off-peak periods, respectively.

197 Note that, all of the other component models (e.g. pumps, piping radiators) used in the systems
198 networks are derived using the same control volume approach that was used in the heat pump
199 model and which is also applied in the modelling of the building. All of the components shown are
200 available in the standard release of ESP-r.

201

202 Figure 3a

203

204 Figure 3b

205

206 In the unbuffered system model, the ASHP supplies hot water to the heating circuit directly (a
207 configuration seen in many UK installations e.g. [21]; the piping, valves and radiators of the heating
208 circuit are modelled explicitly using existing, validated ESP-r models [26]. The model of the radiators,
209 like other ESP-r components is dynamic, with its heat output calculated as a function of the radiator
210 surface areas, hot water inlet temperature and the surrounding building (zone) air and radiative
211 temperatures. The radiators have been sized to operate at a nominal flow temperature of 50°C from
212 the heat pump. However, as is shown later in Figures 9 and 10, as the dynamic performance of the
213 heating system is simulated, the actual temperature of water delivered to the radiators and
214 consequently their heat output varies with time.

215 *Domestic Hot Water Tank and Hot Water Draws*

216 The heat pump also services the 200 L domestic hot water (DHW) tank via an internal hot water
217 heating coil - a common set-up in the UK. The ESP-r tank model used to represent the DHW tank
218 comprises a large number of finite volumes (approximately 100), for each of which an explicit energy
219 balance equation is derived; the ESP-r tank model is described in detail by Padovan and Manzan [22].
220 The model explicitly accounts for stratification. Heat is supplied from the heat pump via an indirect
221 heating coil, and hot water is drawn directly from the tank. The heat loss from the tank is calculated
222 based on an assumed heat loss coefficient of 1W/m²K: this is typical of the insulation levels found on
223 modern UK water tanks.

224 The time-varying hot water draw from the DHW tank was calculated based on a stochastic, high-
225 resolution algorithm developed by Jorden and Vagen [31]; this calculates hot water draws at a 1-
226 minute resolution. A nominal daily hot water demand of 120 L/day is assumed (consistent with the
227 hot water use of a family of four [32]). The nominal percentage of the total daily draw taken at
228 different periods of the day is defined along with four characteristic draw types, representing draws
229 from basins, hot water appliances such as washing machines, draws attributable to showers and
230 draws associated with baths. Each of these draw types is assigned a nominal draw flow rate and
231 standard deviation along with the nominal percentage of the daily draw attributable to that type
232 (Table 3).

233 Figure 4

234

235 Table 3

236

237 *Buffer Tank*

238 In the buffered system, a circulation pump transfers the heat stored in the buffer tank to the heating
239 and hot water circuits. Like the DHW tank model, the buffer tank model explicitly accounts for
240 stratification and the heat is supplied from the heat pump via an indirect heating coil. The systems

241 variants shown could be retro-fitted into many existing UK dwellings and was employed in recent UK
242 heat pump trials [33]. The buffer tank is supplied with heat from the ASHP via a hot water heat
243 exchanger located in the bottom portion of the tank. Hot water for the heating circuit and DHW
244 (Figure 5) is taken from the top of the tank and the cold-water feed is supplied to the lower portion
245 of the tank. The buffer tank can be augmented with variable numbers of cylindrical, encapsulated
246 phase change modules (as shown in Figure 5) and so can be used to model hot-water-only thermal
247 buffering as well as hot water buffering incorporating different percentages (by tank volume) of
248 PCM. The model explicitly tracks the phase state of the PCM modules. As with the DHW tank, heat
249 loss coefficient of $1\text{W}/\text{m}^2\text{K}$ was assumed.

250

251

Figure 5

252

253 *System Control*

254 The heating system control strategy was derived from heat pump field trials and monitoring studies
255 [23, 33] and differed depending upon whether a buffer tank was present. With a buffer tank, the
256 ASHP was operated in an attempt to maintain the buffer temperature between 50 and 55°C , (on/off
257 control with a 10°C dead band). The circulating pump then provided heat to the hot water tank and
258 heating system if there was a requirement for either space heating or hot water. Ideally, the DHW
259 tank was ideally maintained between 43 - 45°C and the space temperatures within the living zone
260 were ideally to be maintained between 19.5 and 22.5°C , both using on/off control with a dead band.
261 In additionally to control of the ASHP based on space temperatures, the flow to the radiators in each
262 individual zone is modulated using a valve component to maintain space temperatures, where
263 possible, between 19.5 and 22.5°C ; this mimics the action of thermostatic radiator valves (TRVs).

264 As is common in UK heating systems, priority was given to hot water - the hot water priority valve
265 diverts all of the heat supply to the hot water tank if this was below the set point temperature. Only
266 when the hot water tank was between 43 and 45°C was heat supplied to the heating circuit. With the
267 unbuffered system, the ASHP was controlled directly in an attempt to maintain the conditions
268 indicated previously in the DHW tank and living space.

269 Note that in UK boiler-based hot water systems, the convention is that hot water is maintained at
270 60°C to prevent the growth of Legionella bacteria [34]. However, this is an inefficient practice as the
271 Legionella threat can be removed by occasionally raising water storage tank temperatures above
272 60°C [35]. In the simulations that follow the hot water tank temperature is raised to 60°C by an
273 electric heater once every 10 days at an energy cost of approximately 180kWh per annum.

274 The on-off control used with the heating system represents the type of heating control commonly
275 employed in millions of UK dwellings and the recent UK Energy Saving Trust field trial of domestic
276 heat pumps [33].

277 **3. Methodology**

278 Using the ESP-r model described, a series of simulations were run to

- 279 • determine the size of thermal buffer required to shift the heat pump operation wholly to off-
280 peak periods (as defined by the Economy 10 tariff [18]) in an extreme winter week;
- 281 • assess the overall annual performance of the load-shifted heat pump; and
- 282 • gauge the impact of heat pump load shifting using the Economy 10 tariff on the electrical
283 demand of a group of dwellings.

284 The specific details of each of these simulations is described in the following sections.

285 **3.1 Buffer Sizing and PCM-Enhanced Buffering Simulations**

286 In order to determine the size of the buffer tank required for the load shift, the performance of the
287 dwelling with heat pump was simulated over a cold winter week in January², in which the minimum
288 ambient temperature was -2.1°C, the maximum temperature was 9.5°C and the mean temperature
289 was 3.4°C. These conditions are characteristic for the UK's maritime climate in winter. The cold
290 ambient temperatures represents an extreme case, when the heat pump COP will be low, and
291 ensures that the load-shifted heat pump and buffer can adequately meet hot water and space
292 heating demands throughout the year.

293 To implement the load shift, the heat pump was constrained to operate only in off-peak periods as
294 defined by the UK economy 10 tariff, which offers lower electricity prices between the times of
295 00.00-05.00hrs, 13.00-16.00hrs and 20.00-22.00hrs. Constraining the heat pump to operate within
296 these hours means that other than the period 20.00-22.00hrs, it was operated when the house was
297 unoccupied or when the occupants were asleep. The hot water circulation pump (Figure 2) could
298 draw heat from the buffer tank at any time between the hours of 06.00-09.00hrs and 16.00-23.00hrs,
299 i.e. corresponding to the periods of active occupancy within the dwelling plus one-hour of pre-
300 heating at the beginning of each period, controlled using a timer.

301 In successive simulations, the volume of the thermal buffer was varied from 200-1200 L in 100 L
302 increments. In addition, the percentage of PCM in the thermal buffer (by volume) was varied from
303 0% up to 70% in 10% increments; above 70% PCM, the space remaining in the tank for the charging
304 heat exchanger becomes too restrictive. This approach enabled the hot-water-only buffer size *and*
305 the PCM-enhanced buffer size required for effective load shifting to be determined from the same
306 group of simulations.

307 The PCM used in these simulations was a commercially available inorganic hydrated salt with the
308 characteristics shown in Table 4; this material was selected as the best-fit match for the operating
309 characteristics of the heat pump, enabling the buffer to operate in the phase change range and
310 making best use of the material's latent heat.

311

312 Table 4 [36]

313 For the purposes of comparison, the performance of the unbuffered heat pump was simulated with
314 no load shifting imposed (the reference case). The heat pump was connected directly to the heating
315 circuit (Figure 1) and the hours of possible heat pump operation were set to 06.00-09.00hrs and
316 16.00-23.00hrs, with the heat pump free to operate at any point within the time periods. Note that
317 these times also coincide with the UK's morning and evening peaks of electrical demand between
318 08.00-09.00hrs and 17.00-18.00hrs respectively [37].

319 The times in which the heat pump is allowed to operate for both the load-shifted and reference cases
320 are shown in Figure 6.

321 Figure 6

322 The key performance criteria to be extracted from the simulation results were that 1) the living zone
323 dry resultant temperatures should not fall below 18°C and 2) hot water temperatures should be kept
324 above 40°C during occupied hours.

325 A dry resultant temperature of 18°C is towards the lower end of acceptable thermal comfort as
326 defined by Fanger [38]. Note that a dry resultant temperature (50% mean radiant temperature, 50%
327 dry bulb temperature) of 18°C does not guarantee comfort; this is dependent upon many other
328 factors including clothing and activity, hence this is an approximate metric.

329 Water supplied at 40°C is the temperature of a typical shower [39]. The buffer sizes identified from
330 this stage of modelling are the lowest buffer tank volumes (with or without additional PCM modules)
331 that satisfy the two aforementioned criteria.

² As is normal with an ESP-r simulation, to minimise the impact of initial temperatures on the simulation results, the simulated week was preceded by a 14-day "pre-simulation" period where the performance of the model was solved, but the results were not saved.

332 Other performance metrics extracted were the heat pump coefficient of performance, its electrical
333 energy consumption and the number of on-off cycles, all of which were affected by the use of
334 thermal buffering and the alteration of the heat pump operating times.

335 **3.2 Energy, Economic and Environmental Performance**

336 For the buffer sizes (with and without PCM) identified from the 1-week simulations which maintained
337 comfort and hot water temperatures, a further annual simulation was undertaken. The ASHP
338 technical performance data from these simulations was analysed to determine the heat pump
339 energy use, running costs along with the carbon emissions associated with the electrical energy use
340 of the heat pump. Table 5 shows the on and off-peak prices applied [40].

341

342 Table 5

343

344 To quantify the CO₂ emissions from the heat pump whilst accounting for the effect of load shifting it
345 was necessary to generate time-varying carbon intensity data using a technique described by Hawkes
346 [34]. Briefly, data on the UK generation-mix for each hour of 2011 was obtained from Elexon [41].
347 This information along with the assumed carbon intensities for different generation types [40] was
348 then used to calculate the average hourly CO₂ intensity (gCO₂/kW) for grid electricity for each hour
349 of the year as shown in Figure 7a. Additionally, Figure 7b shows the grid carbon intensity variations
350 over the simulated winter week. The simulated heat pump electrical demand over each hour (kWh)
351 could then be mapped to the appropriate CO₂ intensity and so the CO₂ emissions (kg) associated with
352 the operation of the heat pump over every hour of the year could be calculated.

353 Figure 7a

354 Figure 7b

355 **3.3 Load Shifting a Population of Heat Pumps**

356 The effect of load shifting on the local, low voltage (LV) network, over several hours with the aid of a
357 PCM-enhanced thermal buffer was analysed on the aggregate demand of a population of 50 similar,
358 detached dwellings. This scenario approximates the situation found in many UK suburban housing
359 estates (e.g. [42]), where the dwellings are of a similar age and type and corresponds to a worst case
360 scenario that amplifies the effect of the electrification of heat and load shifting. The analysis was
361 undertaken over the same cold winter week used to size the buffer tank capacity.

362 Each dwelling incorporated a retrofitted, buffered heat pump. In order to enact the load shift, the
363 operation of the whole population of heat pumps was constrained to Economy 10 off-peak periods.
364 The resulting aggregate demand for the 50 dwellings was then compared to the case where
365 unbuffered heat pumps were allowed to meet the dwellings' heating demand without operating
366 constraints. The occupancy of the dwellings was predominantly intermittent, with pronounced peaks
367 of electrical and heating activity in the morning and evening.

368 The load management analysed here involves very substantial load shifts using a relatively crude,
369 tariff-based approach. Consequently, the analysis that follows does not constitute an optimum
370 means of load shifting; however, it does illustrate some of the potential implications of shifting
371 thermal loads over periods of several hours using existing levers such as Economy 10. Substantial
372 load shifting of this type may be required in order to radically re-shape local, domestic demand;
373 though such a high penetration of heat pumps represents a severe test for the LV network.

374 This study required the use of ESP-r to calculate the heat pump electrical power consumption along
375 with a domestic electricity demand model (DEDM) developed by Richardson *et al* [43]. The DEDM
376 calculated the matching electrical demand of each household (excluding the heat pump demand).
377 The summation of each dwelling's heat pump electrical demand and the household appliance
378 demand gave the total (real) electrical demand.

379 *Implementing Diversity for Unconstrained Operation*

380 An important element in the determination of the aggregate demand was to introduce diversity into
381 the individual heat demands. Accordingly, for each dwelling modelled in ESP-r, the total operating
382 time of the heating system, the heating system start/stop time settings and the heating system set
383 point were randomly varied according to statistical distributions provided by Shipworth et al [44]. In
384 their survey of conventional domestic heating operating conditions, Shipworth *et al* [44] provide
385 estimated data on UK heating system operating times and heating system set points. This estimated
386 data was derived from heating system monitoring and indicated that for a detached house, the
387 mean, aggregate time over which a central heating system was active was approximately 8.7 hours
388 per day with a standard deviation of 1.4.

389 The study by Shipworth *et al.* [44] does not provide information on the specific hours over which a
390 heating system would be operational. Consequently, in order to produce specific, diverse operating
391 times for a population of heat pumps, the basic heating system start and stop times outlined for the
392 sizing simulations were each taken as a mean value and assigned a standard deviation. An iterative,
393 multi-dimensional search was then employed to calibrate the four resulting standard deviations such
394 that, when averaged over a large number of runs, the randomly generated heating system operating
395 times produced from these distributions (shown in Table 6) matched the mean heating system
396 operating time distribution observed in [44]. Note this approach explicitly assumes that the majority
397 of dwellings have two distinct heating periods; this is a common assumption in UK domestic energy
398 models such as BREDEM [45].

399 Table 6

400 To provide additional diversity, the thermal buffering for each dwelling was provided by either a
401 1000 L hot water or 500 L, 50% PCM-enhanced buffer. Further, the number of dwelling occupants
402 (and subsequent heat gains) were assigned based on household size statistics from the UK office of
403 national statistics [46]. Dwelling infiltration levels were randomly assigned based around the
404 infiltration distributions for thermally improved dwellings provided by Johnston et al [27], and set
405 points were allocated based on the monitored distribution for detached dwellings in [44].

406 *Diversity for Load-Shifted Operation*

407 For the case of the load-shifted heat pumps, the possible period of operation for each heat pump
408 was constrained to those times dictated by the Economy 10 tariff. It was assumed that end-users
409 would allow their heat pump operating times to be adjusted accordingly. However, the Economy 10
410 tariff times only define the period within which the heat pump *may* operate, whether or it does or
411 not is dependent upon the timing of the space heating and hot water demands. Recall, that in the
412 load-shifted system, the space heating and DHW load was met by a circulating pump drawing hot
413 water from the buffer tank. The operating times of the circulating pump (i.e. the times when heat is
414 required by the end user) were subject to the same diversity criteria as outlined previously for the
415 unconstrained, unbuffered heat pump operation. Therefore, whilst the potential operating period of
416 the heat pump is constrained by tariff times, the demand for heat and the operation of the buffered
417 system's hot water circulating pump is subject to diversity.

418 *Domestic Demand Profiles (excluding heat pump demand)*

419 The corresponding appliance demand profile calculated for each dwelling by the domestic electricity
420 demand model (DEDM) also generated diversity, in that it factors in the different occupant numbers,
421 variations in occupancy timings, and variations in appliance ownership into each profile generated.

422 Figure 8 shows a single DEDM profile for household electrical appliance demand over 24 hours at 1-
423 minute time resolution. Figure 8 also shows the corresponding 24-hour heat pump demand profile
424 (subject to load shifting) generated by ESP-r again at 1-minute time resolution. The combination of
425 the two time series yields a unique total electrical demand profile for one household. Profiles like
426 these were developed for each detached dwelling variant, the summation of which gave the
427 aggregate demand characteristics for the population of 50 dwellings and heat pumps.

428

429
430

431 **4 Results and Discussion**

432 **4.1 Buffer Tank Size Required for Load Shifting**

433 Table 7 contrasts the performance of the sensible and PCM-enhanced thermal buffers required to
434 successfully shift heat pump operation to off-peak periods during the simulated winter week. Also
435 shown is the performance of the reference case with no load shifting. A tank size of 500 L, with 50%
436 of the volume occupied by PCM, enabled effective load shifting without adversely affecting the
437 comfort or availability of hot water to the end-user. Without the inclusion of the PCM, a buffer tank
438 of 1000 L was required. The performance data shown was derived from the time-series simulation
439 output of the ESP-r model. Example output can be seen in figures 9 and 10, which highlight the
440 operation of the unbuffered heat pump and the heat pump with the PCM-enhanced buffer,
441 respectively over the course of a day. Note however, that the temperature scaling masks the small
442 variation on outside air temperature.

443 Table 7

444 Figure 9 shows the operation of the heat pump when directly coupled in to the space heating and
445 hot water system of the dwelling, with the heat pump initially operating to charge the DHW tank and
446 then cycling to maintain the living space temperature. The figure also illustrates the dynamic nature
447 of the model, with the variation flow and return temperatures, storage temperatures, heat pump
448 output and electrical demand.

449 Figure 10 shows the effect of buffering and load shifting, with heat pump operating to charge the
450 buffer tank, which is then discharged to meet the dwelling's space heating and hot water demands.
451 The heat pump operation is decoupled from the evolution of the living space and hot water tank
452 outlet temperatures. The discharge of the buffer tank is evident (Figure 10) through the sudden
453 reductions in temperature, as the pump taking hot water from the buffer (shown in Figure 2) first
454 charges the hot water tank and then operates to meet the space heating demand during periods of
455 active occupancy.

456 Figure 9

457 Figure 10

458 Figure 10 also shows the effect of the of the PCM, with some temperature recovery in the outlet
459 temperature of the buffer tank after the initial morning demand, as the warmer PCM modules heat
460 the surrounding, cooler water.

461 **4.2 Energy, Economic and Environmental Performance**

462 Having identified the tank sizes required to deliver effective load shifting from the winter week
463 simulation, full annual simulations were undertaken to assess the energy performance of the load
464 shifted, buffered system. The results are shown in Table 8.

465 Comparing the buffered to the unbuffered case, there was a clear annual energy penalty associated
466 with the load shift to off-peak periods. With the 500 L, PCM-enhanced tank, the annual energy use
467 was 61% higher than in the unbuffered case with no load shift. The energy use for the 1000 L tank
468 was 65% higher. The reasons for this increase in energy use were as follows.

469 Firstly, the COP of the buffered heat pumps was lower than the unbuffered case: the addition of the
470 extra heat exchanger in the buffer tank between the ASHP and the heating system means that the
471 temperature at which heat was supplied needed to be greater in order to maintain similar conditions
472 in the dwelling. This is evident when comparing the flow and return temperatures in Figures 9 and
473 10, the heat pump outlet temperature is some 5°C higher than the case with no buffer and towards
474 the upper end of the modelled heat pump's capabilities. Moreover, the load-shifted ASHP operated
475 during off-peak hours, generally during the evening and early morning when outside air
476 temperatures were lower; this, coupled with the elevated supply temperatures resulted in the

477 temperature difference across the heat pump being greater and so the COP was reduced, as is
478 evidenced in the performance characteristics shown in Figure 3. Secondly, whilst the buffer tank in
479 these simulations was well insulated (with a heat loss coefficient of $1\text{W}/\text{m}^2\text{K}$) it was still subject to
480 parasitic losses not present in the unbuffered case. The impact of parasitic losses is evident in the
481 periods of slow decay of the buffer tank temperature evident in Figure 10. The buffer tank efficiency
482 (i.e. energy input/energy delivered) calculated from the simulations was 84% for the 1000L tank and
483 92% for the 500 L PCM-enhanced tank.

484 It is also worth noting that the annual COP of the buffered, shifted systems is marginally higher than
485 their COP for the simulated winter week; this would be expected as during other periods of the year
486 the ambient air temperature is higher. The annual COP of the unbuffered system is marginally lower
487 than in the winter week. This is due to higher levels of cycling during periods of low load in warmer
488 months offsetting the benefit of higher ambient air temperatures. However, the annual COP of the
489 unbuffered system is still superior to that seen in both of the buffered, load-shifted cases.

490 Table 8 also shows the calculated CO_2 emissions for the unbuffered and buffered, load-shifted heat
491 pumps. With the 2011 UK CO_2 intensity shown in Figure 7, load shifting of the heat pump into off-
492 peak periods resulted in *increased* CO_2 emissions, primarily because load shifting increased the heat
493 pump's electrical demand and because the difference in UK grid CO_2 intensity between peak and off-
494 peak periods was generally small.

495 Table 8 shows a pronounced annual cost penalty for the end user from load shifting. The additional
496 electrical demand required for effective load shifting was not adequately compensated for by the
497 price differential between Economy 10 off-peak unit costs and the standard unit cost shown in Table
498 4. Based on the evidence of these simulations, the off peak-price would need to be approximately
499 0.0815 $\text{£}/\text{kWh}$ (i.e. 62% of the standard unit electricity cost) before the load shifting became cost-
500 neutral. The off-peak price is currently 80% of the of the standard unit price. Note that the running
501 costs shown do not include standing charges.

502 **4.3 Load Shifting a Population of Heat Pumps**

503 Two sets of simulations were run over the winter week to gauge the impact of simple, tariff-based
504 load shifting (as exemplified by Economy 10) on the net electrical demand of a hypothetical
505 population of 50 dwellings equipped with heat pumps. One set of simulations was run for 50
506 detached dwellings equipped with the buffered ASHP system (500 L tank 50% PCM) subject to load
507 shifting; and one set for 50 dwellings with unbuffered ASHP systems not subject to load shifting. This
508 latter set of simulations was used as the reference case. Each individual simulation used a variant of
509 the detached dwelling model, but with key parameters randomly varied to provide heat load
510 diversity as described previously. The case illustrated here amplifies the potential impact of heat
511 pump load management as it would be expected in most cases that the penetration of heat pumps
512 would be less than 100%.

513 In the simulations where the operation of the heat pump was unconstrained, the heat pump could
514 operate when the heating control was active during the morning and evening and whenever there
515 was a requirement for space heating or hot water in the dwelling. The time settings for active heating
516 control varied from dwelling to dwelling according to the distributions shown in Table 6.

517 In the buffered, load-shifting case, the heat pump operation was constrained; the heat pump could
518 operate *only* within the low-cost electricity periods defined by Economy 10. However, the demand
519 for heat was still subject to diversity. Heat was supplied for space heating and hot water from the
520 buffer tank via a circulating pump - the operating times for this pump were randomly varied between
521 simulations, using the same distributions used for the unconstrained heat pump shown in Table 6.

522

523

Figure 11

524

525 Figure 11 shows the net dwelling real power demands with and without heat pump load shifting over
526 a typical 24-hour period during the simulated week.

527 The plot of the aggregate real electrical demand for the 50 dwellings, when not subject to load
528 shifting, shows distinct morning and evening peaks when the heat pumps are in operation. However,
529 the operation of the heat pumps (like the demand for heat) was spread over several hours during
530 both morning and evening.

531 Shifting the operation of all of the heat pumps to off-peak periods, as defined by the Economy 10
532 tariff resulted in new and significantly increased peak demands during the constrained operating
533 periods; particularly in the short, off-peak periods of 13.00hrs-16.00hrs and 20.00hrs-22.00hrs, which
534 show limited load diversity. The lack of diversity is due to the short duration of these periods: in
535 both, the majority of the heat pumps modelled need to operate in order to replenish the buffer tank
536 depleted by morning and early evening heat demands. Therefore, an unintentional consequence is
537 that these brief, off-peak periods act to synchronise the population of heat pumps such that the
538 aggregate demand of the dwellings rises to 230 kW, compared to approximately 150 kW when the
539 operation of the population of heat pumps was not constrained by the load shifting tariff. The same
540 figure shows that if the percentage of heat pumps subjected to the Economy 10 tariff is reduced, so
541 the peak demand reduces.

542 The tendency of load management to reduce load diversity and produce “undesirable effects” was
543 highlighted by Strbac [47] and similar increases in peak loading were observed by Moreau [10], who
544 examined load shifting of electrical water-heating loads. The results presented here serve as a
545 warning that whilst instruments such as the Economy 10 tariff investigated in this study may
546 be beneficial to high-level grid operation they are not necessarily beneficial to the operation of the local
547 electrical network or to individual users.

548 **5. Conclusions**

549 To study the ability of phase change material (PCM)-enhanced thermal storage to facilitate effective
550 heat pump load shifting, a model of a typical UK detached dwelling complete with a buffered air-
551 source-heat-pump (ASHP) heating system has been developed on the ESP-r building simulation tool.
552 A series of simulations were then run using a cold UK climate week in which the operation of the
553 heat pump was restricted to off-peak periods.

554 The simulations indicated that 1000 L of hot water buffering was required for load shifting to off peak
555 periods. However, augmenting the thermal buffer with 50% PCM by volume halved the required
556 volume of buffering required to 500 L without a noticeable deterioration in the space temperatures
557 or hot water temperatures delivered to the end user.

558 In this case, the simulations highlighted an energy penalty in excess of 60% associated with the use of
559 PCM-enhanced buffering and load shifting. This was due to a reduction in the COP of the heat pump
560 when operated with thermal buffering, and the introduction of buffer heat losses.

561 Due to the increased energy use from load shifting and the peculiarities of the time-varying CO₂
562 intensity of the UK grid, CO₂ emissions were actually greater when the heat pump demand was load
563 shifted to off-peak periods.

564 Similarly, applying UK off-peak Economy 10 prices to the load-shifted ASHP energy demand indicated
565 that there was a cost penalty associated with running the heat pump during off peak periods, due
566 primarily to the increased energy requirements.

567 Simulation of a population of 50, buffered heat pumps indicated that constraining them to operate
568 only in off peak periods had the potential to substantially increase the peak electrical demand seen
569 on the LV network compared to the case where the heat pumps were unbuffered and their operation
570 was unconstrained.

571 **5.1 Limitations of the Study and Future Work**

572 This study has highlighted some potentially serious consequences associated with heat pump load
573 shifting to off peak periods for the end-user and for electricity network operators. However, these
574 conclusions need to be viewed alongside the limitations of this study as highlighted below.

575 The energy use of the heat pump was seen to increase in all of the cases simulated where buffering
576 was used. However, whilst the heat pump system modelled here is representative of field trial
577 installations (e.g. [33]), it was *not* optimised in relation to cost, delivery of both space heating and
578 hot water and alternative building and system configurations are available. For example, hot water
579 could have been delivered directly from the buffer tank, rather than a separate hot water tank.
580 Separating the hot water and space heating functions of the heat pump would allow improvements
581 such as outside air temperature compensation to be implemented. Refinement of the heating system
582 modelled here may reduce the difference in energy demand between the load shifted and non-load-
583 shifted heat pump systems, though it is unlikely that the difference between the two cases could be
584 fully eliminated.

585 With regards to the space saving achieved through use of the PCM tank, the economic benefits from
586 increased floor area availability must be offset against increased running costs and the capital cost of
587 the PCM tank. As PCM thermal stores are not yet widely available in the UK, along with their costs,
588 such a cost-benefit analysis should be the focus of future research.

589 In this study both the CO₂ emissions and running costs of the buffered, load-shifted heat pump
590 system were seen to be higher than the case with no load shifting. This was a consequence of the
591 specific time-varying carbon intensity seen on the UK network in 2011 and specific off-peak and
592 standard tariffs applied, respectively. As the UK generation mix changes towards 2050, so the time-
593 variations of grid CO₂ intensity will inevitably change and so, potentially would the CO₂ emissions
594 associated with heat pump load shifting. Additionally, off-peak tariffs could be re-designed and
595 refined to incentivise load shifting and also to minimise the risk of the load synchronisation and
596 consequent high peak demands seen in this study.

597 Finally, constraining a population of heat pumps to operate only in narrow off-peak periods was seen
598 to increase peak aggregate demand rather than reduce it. Note that, the modelling of the heat pump
599 population control presented here is illustrative of a crude tariff-based approach and does not
600 represent the optimum means of control of populations of electrical devices. For example,
601 Bagdanavicius and Jenkins [6] use an indirect control approach, attempting to control the peak load
602 of a population of heat pumps by altering housing thermostat settings; the same approach is
603 adopted by Wang et al [12]. Additionally, more subtle control may be feasible as more sophisticated
604 heat compressors are integrated into domestic heat pumps, where the compressor output can be
605 proportionally controlled based on the load (e.g. [48]). The heat pump modelled here was equipped
606 with a compressor that could only be operated in on/off mode.

607 The work presented here does strongly signal that more sophisticated load management strategies
608 than a simple tariff-based approach would be required if load shifting of populations of buffered heat
609 pumps is to bring about the desired reduction in peak demand levels, reduction in carbon emissions,
610 reduction in costs, or synchronisation with renewable generation.

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Figure Captions

- 728
729 Figure 1 geometric wireframe view of the typical UK detached dwelling ESP-r model.
730 Figure 2 Heat pump COP and heat output vs. ambient temperature.
731 Figure 3a The modelled heating system supplied by the ASHP (with no buffer tank).
732 Figure 3b The modelled heating system supplied by the ASHP (with PCM-enhanced buffer tank).
733 Figure 4 Stochastic hot water draw profile for the simulated winter week.
734 Figure 5 Detail of buffer tank with integrated phase change modules.
735 Figure 6 Reference case and load shifted heat pump operating hours.
736 Figure 7a hourly UK grid average carbon intensity (g/kWh) for 2011.
737 Figure 7b hourly UK grid average carbon intensity (g/kWh) for modelled winter week.
738 Figure 8 combined heat pump and household appliance demand over 24 hours.
739 Figure 9 Temperatures and heat pump electrical demand with no buffering and no load shift.
740 Figure 10 Temperatures and heat pump electrical demand with load shifting and buffering.
741 Figure 11 effect of load shifting of all heat pumps on the aggregate demand of 50 dwellings.

Tables

742
743 Table 1 characteristics of the main building elements.
744

Fabric element	Construction Details	'U'-value (W/m ² K)	Area (m ²)
Glazing	6mm glass/ 12mm air gap/ 6mm glass	3.3	24
External walls	110mm brick /60mm cavity fill /110 mm block/ 10mm gap/ 13mm plasterboard	0.37	134
Ground floor	300mm insulation/ 18mm flooring/10mm carpet + underlay	0.09	68
Upper floor ceiling	300mm insulation/13mm plasterboard	0.13	68
Additional Information			
Total building floor area			136 m ²
Total building volume			448 m ³
Total heated volume			326 m ³
Average air change rate (air-changes-per-hour)			0.5

745
746 Table 2 key calibrated parameters and equations used with the ASHP model.

Parameter	Value	Parameter	Value
Effective mass M (kg)	110.00	Maximum ASHP inlet temperature T _r (max) (°C)	65
Effective mass specific heat \bar{c} (J/kgK)	3700.0	Nominal water return temperature T _r (nom) (°C)	45-55
Heat loss modulus UA (W/K)	15.000	Nominal water return dead band (°C)	5

ASHP HW pump rating P_p (W)	95.000	Defrost cycle ambient temperature trigger ($^{\circ}\text{C}$)	5.5
Mass flowrate at rated pump power $\dot{m}(t)c_w$ (kg/s)	0.26	Defrost cycle RH trigger (%)	60
Evaporator Fan power P_{ef} (W)	220.0	ASHP controller power P_{co} (W)	10
<p>ASHP COP:</p> $COP = 0.0005 \times (T_r - T_{\infty})^2 - 1.022 \times (T_r - T_{\infty}) + 6.3972 \quad (1)$ <p>Compressor power demand (W):</p> $P_c = 1000 \times 2.002e^{(T_r - T_{\infty})} \quad (2)$ <p>ASHP heat exchanger energy balance (J):</p> $M\bar{c} \frac{dT_f}{dt} + \dot{m}c_w T_f = P \times COP - UA(T_f - T_c) + \dot{m}c_w T_r \quad (3)$ <p>Time between defrost cycles (s):</p> $\Delta t_d = 0.06T_{\infty}^3 + 1.23T_{\infty}^2 - 25.1T_{\infty} + 0.234T_{\infty}RH + 0.0551RH^2 - 11.6RH + 629 \quad (4)$ <p>Time of defrost cycle (s):</p> $t_d = \frac{3.6 \times 10^6}{P \times COP} (-0.000311T_{\infty}^3 - 0.00489T_{\infty}^2 + 1.65 \times 10^{-8}\Delta t_d^3 - 1.05 \times 10^{-5}\Delta t_d^2 + 0.00226\Delta t_d + 0.163) \quad (5)$ <p>T_r – return water temperature ($^{\circ}\text{C}$) T_f – water flow temperature ($^{\circ}\text{C}$) T_{∞} - ambient temperature</p>			

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Table 3 data used with DHW model to calculate hot water demand (adapted from [26]).

Appliance Draws	Basins	Appliances	Baths	Showers
Nominal flow rate (l/min)	1	6	12	8
Flow Std. deviation	2	2	0.0167	0.05
Percentage of total draw (%)	14	36	10	40
Duration (mins)	1	1	10	4
Distribution of Draws				
Time	0-6hrs	6hrs-9hrs	9hrs-17hrs	17hrs-24hrs
Percentage of total draws (%)	10%	50%	10%	30%

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Table 4 Selected characteristics of the phase change material [36].

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

k conductivity solid W/mK	0.45
k conductivity liquid W/mK	0.45

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Table 5 Economy 10 on and off peak energy costs [18].

Tariff	£GBP per kWh	£GBP per kWh
Standard unit cost (for unbuffered ASHP with no load shift)	0.1308	
Economy 10 unit costs (for buffered ASHP under load-shift)	(on-peak cost) 0.1817	(off-peak cost) 0.1053

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Table 6 Heating systems start/stop characteristics used in multiple dwelling study
(derived from [27, 44, 46]).

Start am (hrs)	Std. Dev.	Stop am (hrs)	Std. Dev.
6.0	1.08	9.0	1.4
Start pm (hrs)	Std. Dev.	Stop pm (hrs)	Std. Dev.
16.0	1.05	23.0	2.28
Set point (°C)	Std. Dev.	Infiltration	Std. Dev.
21	2.5	0.45	0.13

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Table 7 System performance and size of buffering required for effective load shifting (winter week).

	Unbuffered no load shift (reference)	1000 L hot water buffer off-peak operation	PCM-enhanced buffer 500 L + 50% PCM off-peak operation
Average living room temperature (°C)	20.9	21.2	21.0
Average buffer temperature (°C)	N/A	47.9	48.4
Average DHW temperature (°C)	44.6	44.2	43.9
Average ASHP COP (-)	3.04	2.44	2.37
ASHP heat output (kWh)	204.5	276.0	247.3
ASHP electrical energy (kWh)	69.5	115.2	106.4
ASHP cycles -	127	41	65

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Table 8 Annual performance characteristics of the load shifted and reference heat pump systems.

	Unbuffered no load shift (reference)	1000 L hot water buffer off-peak operation	PCM-enhanced buffer 500 L + 50% PCM off-peak operation
Average ASHP COP (-)	2.95	2.50	2.46
ASHP heat output (kWh)	6584	9389	8941
ASHP electrical energy (kWh)	2340	3865	3756
ASHP cycles -	3330	1775	2288
CO ₂ (kg)	1133	1892	1837
ASHP running cost (£ GBP)	306	407	395

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