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ASSESSING HEAT PUMPS AS FLEXIBLE LOAD

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ABSTRACT

In a future power system featuring significant renewable generation, the ability to manipulate domestic demand through the flexible operation of heat-led technologies such as heat pumps and micro combined heat and power (μCHP) could be a critical factor in providing a secure and stable supply of electrical energy. Using a simulation-based approach, this study examined the linkage between the thermal characteristics of buildings and the scope for flexibility in the operating times of air source heat pumps (ASHP). This was assessed against the resulting impact on the end-user's comfort and convenience. A detached dwelling and flat were modelled in detail along with their heating system in order to determine the temporal shift achievable in the heat pump operating times in present-day and future dwellings.

The simulations results indicated that the scope for shifting heat pump operating times in the existing building stock was limited, with time shifts of only 1-2 hours achieved before there was a serious impact on the comfort of the occupant. However, if insulation levels were dramatically improved and substantial levels of thermal buffering were added into the heating system, sizable time shifts of up to 6-hours were achievable without a significant impact on either space or hot water temperatures.

Keywords: load shifting; flexible demand; thermal modelling; air source heat pump

1. INTRODUCTION

Driven primarily by the country's ambitious target for an 80% reduction in greenhouse gas emissions by 2050 [1], the UK is embarking on a major expansion in renewable electricity and heat generation at both the small and large scales, coupled with a drive to improve energy efficiency in all areas of the economy. The residential sector is a particular focus of government policy due to its poor energy performance [2] and low penetration levels of renewable heat and power generation [3]. Consequently, legislative incentives have emerged to improve dwelling thermal efficiency, with building regulations across the UK radically strengthened [4]. Further, to promote a move away from conventional heating technologies such as gas boilers towards low-carbon alternatives, as well as promoting local, low-carbon electricity generation, the UK has introduced feed-in-tariffs (FIT) [5] and a renewable heat incentive (RHI) [6]. These initiatives have stimulated the rapid uptake of a range of technologies such as photovoltaics (PV), small wind energy conversion systems (SWECS), solar thermal collectors, heat pumps and micro-combined heat and power (µCHP) [7].

This shift in both the energy supply and demand characteristics of the residential sector presents significant challenges to UK electricity suppliers.

- The appearance of large quantities of non-dispatchable generation such as PV and SWECS on the distribution network could pose problems for the low-voltage (LV) network, such as fluctuating supply voltage levels and network overloading at times of significant generation [8].
- Additionally, a switch from gas heating to electrically-based heating through the widespread uptake of heat pumps could significantly increase electrical demand at times of high heating load, again leading to potential supply problems and ultimately the need to reinforce the LV infrastructure [ref].

Conversely, this switch also affords some opportunities to suppliers in that the proliferation of heat-led electrical loads such as heat pumps could offer some latitude to manipulate electrical demand if the operating times of individual devices could be controlled for the benefit of the network.

- At the local level, the firing times of heat-led devices could be altered to (for example) absorb surplus PV generation or compensate for a sudden drop in the power output from an array of small wind power devices.

- At the larger scale, the ability to control the operating times of large numbers of heat-led devices could be a useful mechanism to for supply demand matching in a future network featuring high penetrations of variable renewable generation.

Consequently, information on the limits of temporal flexibility of heating demand in dwellings and on the mechanisms by which that flexibility could be increased will be of benefit in the planning and operation of a future power system at all scales.

In the literature, there have been several studies analysing the relationship between both heat pumps and µCHP on electrical demands. Peacock and Newborough [9] looked at changes in the electrical demand characteristics of 50 UK dwellings caused by changes to the mode of operation for a population of µCHP generators. The study predicted significant reverse power flows if the µCHP was heat-led and that the reverse flow could be eliminated if the µCHP was electrically-led. However, the author's modelling approach was not detailed enough to determine any effects that the change in µCHP control could have on the end-user. Using a model featuring more than 1000 dwellings, Thomson and Infield [10] looked at the impact of high penetrations of µCHP on the distribution network, indicating that problematic voltage rises occur and (as with Peacock and Newborough [*ibid*]) that reverse power flows can occur at peak periods of heat demand. Hewitt [11] examined the use of heat pumps as flexible electrical demand in a future electrical network featuring high penetrations of wind power, indicating that heat pumps coupled with thermal storage may be a useful mechanism for enhancing stability in the transmission and distribution system. However, no quantitative analysis was undertaken to demonstrate this concept.

The studies above begin to address the idea that either heat pumps or µCHP could be used as a means to manipulate the electrical demand (or export) characteristics of a building or community. However, other than Hewitt (*ibid*), the possibility of actively manipulating the firing time of devices (whilst still meeting the end-user thermal requirements) as a mechanism for active network management was not considered.

This study therefore focused on individual dwellings and analysed the potential for manipulation of the start and stop times of a heat pump for the purposes of network management. The consequences of shifting operating times on prevailing space temperatures, hot water supply temperatures and heat pump energy consumption were assessed with a view to determining the limits of operational flexibility where those limits were dictated by the increasing thermal discomfort and loss of service (reduced hot water supply temperatures). Further, the study looked at the potential to manipulate operating times in examples of both the current and future housing stock. Note that, a heat pump, whilst being a heat source, is a significant electrical demand and hence the exercise here was one of electrical demand shifting. However, the approach taken can equally be applied to µCHP and so can also be viewed as a means to improve the flexibility of local, dispatchable electrical supplies.

2. METHOD

In order to analyse the relationship between shifting the heat pump operating time against occupant comfort, an integrated simulation approach was adopted, where the performance of the heat pump was simulated along with the building within which it operated. To achieve this end, a set of dynamic simulation models were developed on the ESP-r building simulation tool [12]. Within ESP-r, the building model is decomposed into a large number of small 'control volumes' for which energy and mass balance equations are derived. The solution of these equations at discrete time steps using real climate data and user-defined control constraints (e.g. set point temperature and heating operating times) yields the dynamic evolution of temperature, energy and fluid flows within the building and its systems. Two different building types were modelled: a larger detached house and a smaller flat (Figure 1a & b), epitomizing the range of dwellings into which ASHP could be retrofitted. Two variants of each building model were developed: one that reflected the thermal fabric characteristics and heating system of the present housing stock [13] and another representative of the emerging passive house standard for dwellings [14], providing an insight into the potential for heating load flexibility in current and future new-build or high-specification retrofit dwellings.

Figure 1a: typical detached dwelling

Figure 1b: typical flats

For the two building types, the following pragmatic operational strategies were implemented in an attempt to maximise the time-window within which the heat pump operating time could be shifted without significantly affecting comfort or the hot water supply temperatures to the end user.

1. *Base Case* - the heat pump start times were altered in both dwellings 'as-is', making use of the intrinsic thermal capacity of the building fabric and the heating system.
2. The space heating and hot water set points were increased in order to boost the quantity of heat stored, thus increasing the potential for time-shifting at the expense of increased energy consumption.
3. Thermal capacity was added to the heating system in the form of a 300L buffer tank placed between the heat pump and distribution system.
4. The buffer tank capacity was increased to 500L.

3. MODELLING

The integrated models used for this study comprised a detailed representation of each building's geometry and fabric materials, a representation of each dwelling's air leakage characteristics plus a detailed, component-based representation of heating system (featuring the air-source heat pump) and its controls. The models also incorporated details of the temporal heat gains from the occupants and equipment, and the hot water draws by householders.

3.1 Building and Fabric

The total floor area of the detached house model is 136m^2, whilst the flat has a floor area of 86m^2; both can be regarded as typical examples of their type in the UK. Each building was modelled using two functional zones: living, non-living, differentiating the areas where active and inactive occupancy (i.e. sleeping) occurs. This form of model, whist not an architecturally faithful representation of a real building, is capable of replicating its thermodynamic behaviour for the purposes of an energy analysis. Additionally, this from of model could be easily adapted to represent different building characteristics.

Standard and Passive House Insulation Levels

The thermal characteristics of the constructions used with the typical and passive house model variants are summarised in Table 1.

Construction	Typical dwelling U-Values (W/m2K)	Passive house standard U-Values (W/m2K)
Wall	0.45	0.14
Windows	3.30	0.70
Floor	0.59	0.14
Ceiling	0.39	0.14
Average infiltration rate (air changes/hour)	0.4	0.03

Table 1 ‘U-values’ for external surfaces for the typical and passive house levels of insulation.

Note that the passive house construction insulation values (representative of the future housing stock) were determined by an iterative process, whereby the insulation levels were altered until the building met the passive house standard for heating energy consumption of 15 kWh/m^2/year [14]. The average air infiltration for the Passive House cases is 0.03 air changes per hour; augmented with a mechanical ventilation heat recovery system (MVHR) with an effectiveness of 80% supplying 0.4 air changes per hour (see figure 4a & b).

The dwelling models were set up to include heat gains consistent with intermittent occupancy. The detached house is assumed to be occupied by a family of four. The flat is assumed to have three occupants. In both cases, the occupants are active between 6:00-9:00hrs and 17:00-23:00hrs and sleeping between 23:00hrs and 6:00hrs. Outside these periods the house is empty.

3.2 Heating System

Several heating system types were employed in the simulations, including an the air source heat pump supplying a hydronic heating system, representative of the type of heat distribution system currently found in current UK dwellings [15]. With the passive house model, the heat pump supplied a heating coil within the mechanical ventilation heat recovery system (MVHR) [16]. Three different levels of thermal buffering were employed (none, 300 and 500L). The buffered heating system topology was similar to that deployed in domestic microgeneration field tests undertaken by the Canadian Centre for Housing Technology (CCHT) [17]. The unbuffered configuration was similar to that employed in UK

Carbon Trust's trials of microgeneration [18]. The use of buffering and different heat delivery mechanisms required the development of four heating system model configurations; these are shown in Figures 2a-2d.

Two different capacities of heat pump were employed due to the variation in levels of space heating demand between the building model variants. A 6KW device was used with the typical flat model and all passive house model variants, whilst an 8KW device was used with the typical detached house model. Different hot water draw patterns were used in the simulations as appropriate: a 120L/day draw pattern was used with the detached house model. A 90L/day draw pattern was used with the flat model, due to its lower occupancy level. These draws were based on those developed within IEA ECBCS Annex 42 [19] and are characteristic of typical European hot water draws.

The different model combinations used in the simulations are illustrated in figure 3.

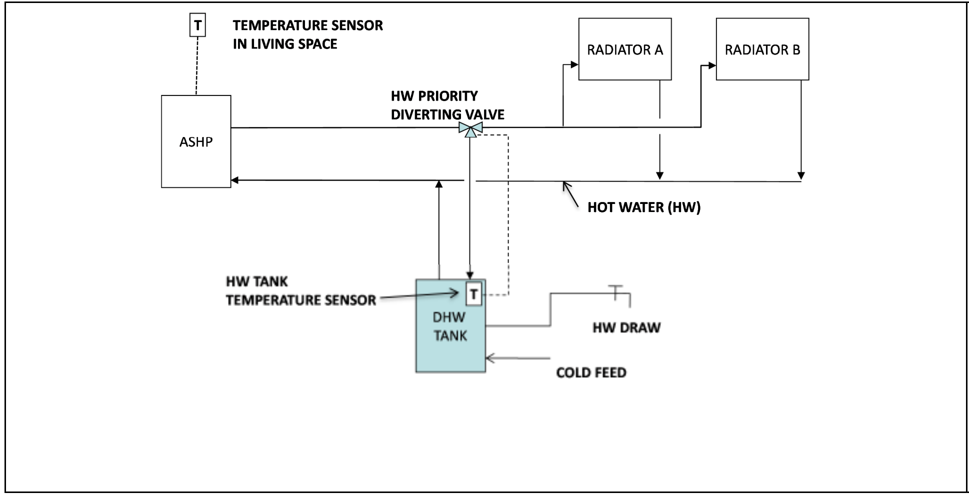

Figure 2a the unbuffered conventional heating system configuration

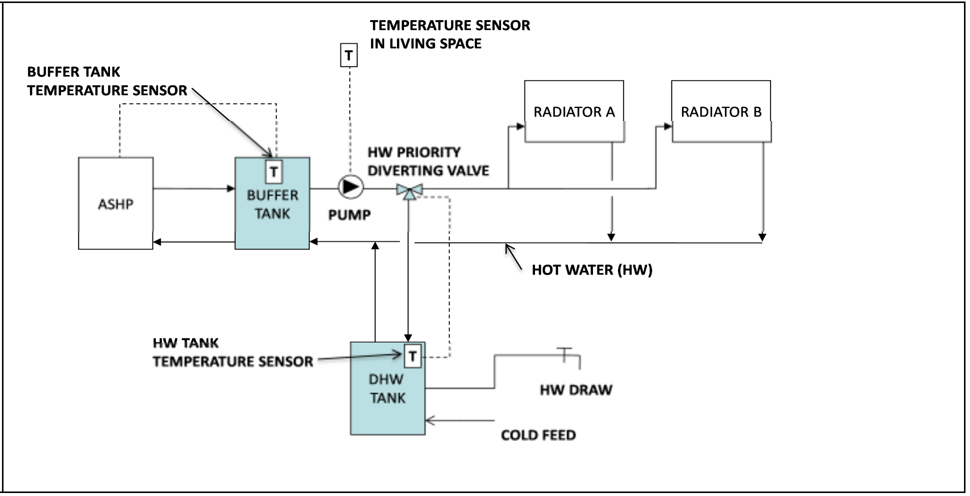

Figure 2b the buffered conventional heating system configuration

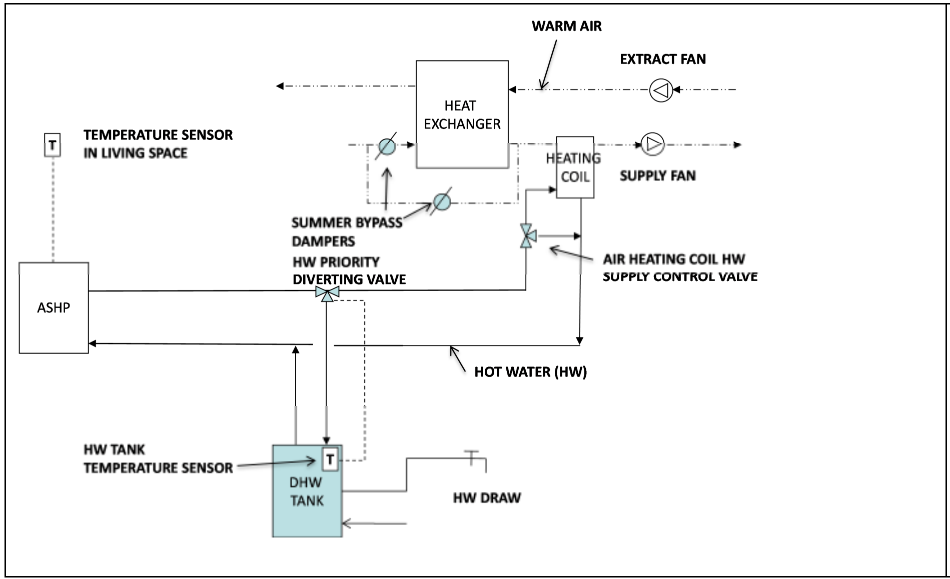

Figure 2c the unbuffered MVHR system configuration

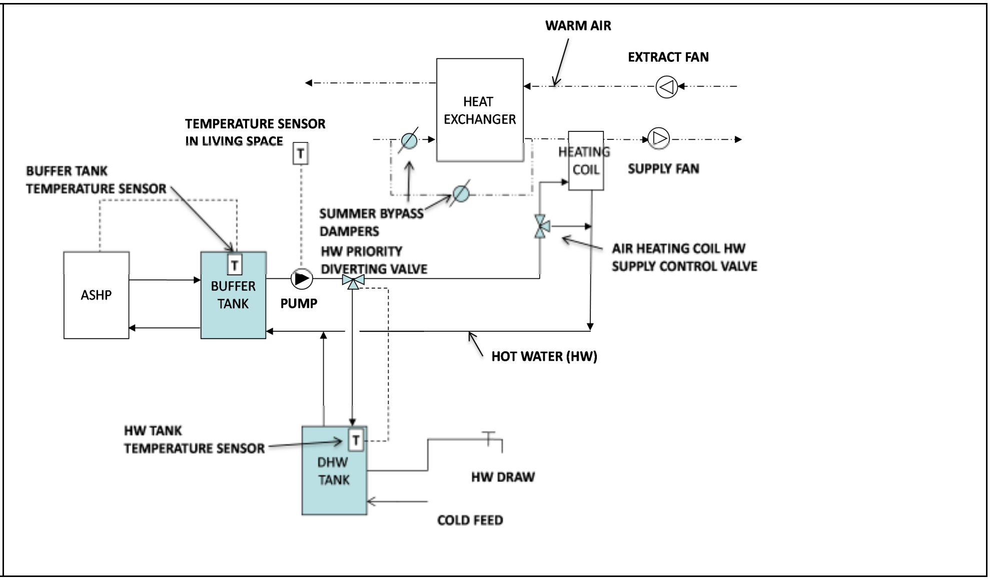

Figure 2d the buffered MVHR system configuration

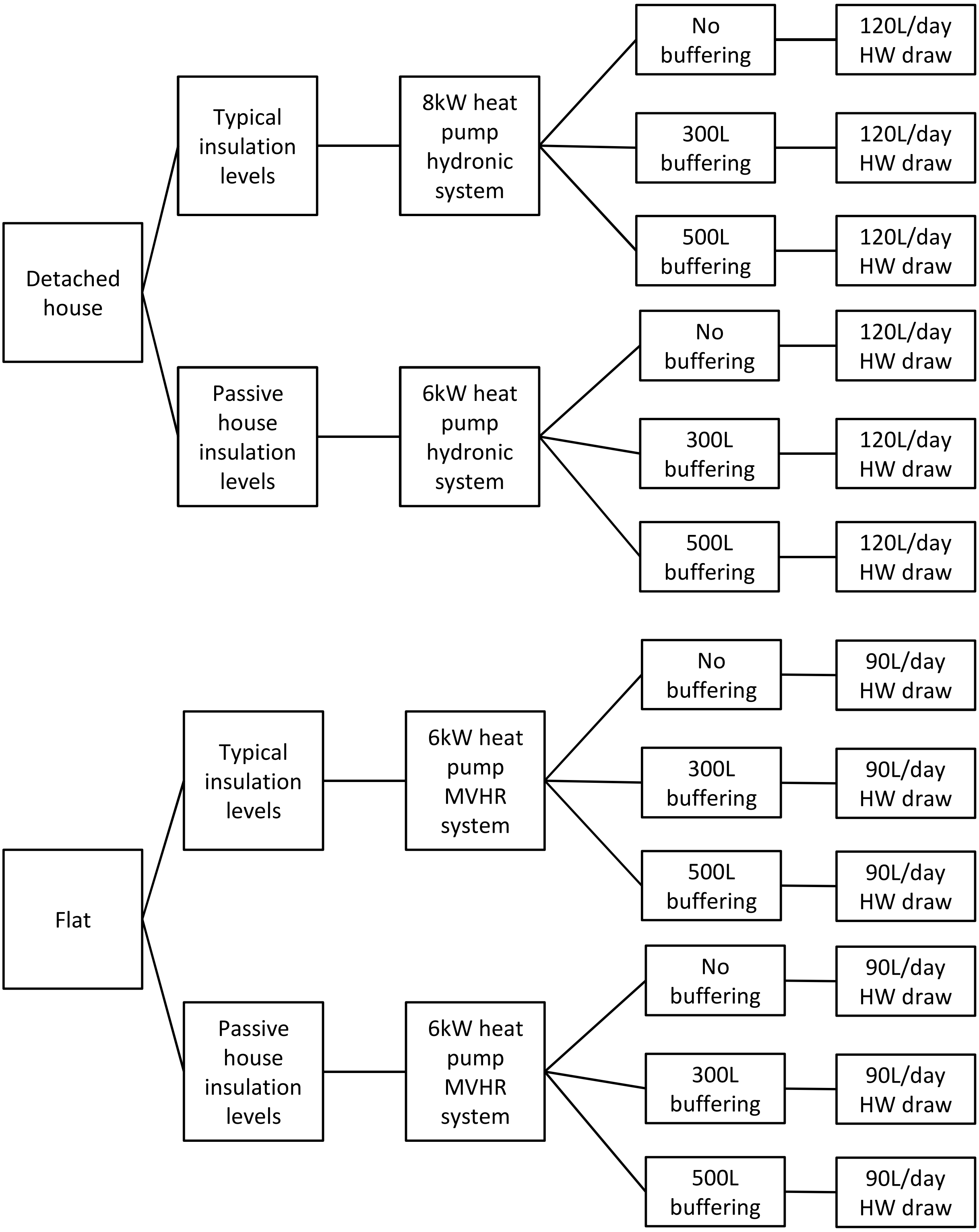

Figure 3 model combinations used in simulations.

3.3 Heating System Control and Operation

The heating system incorporated a number of controllers that dictated its operation. First, the heat pump was subject to on/off control with a 4°C dead band, attempting to maintain the air temperature in the living room between and 19-23^{o}C. Note that for some of the simulations, the dead band set points were altered to 21-25^{o}C in an attempt to increase the heat storage on the building fabric. Second, a hot water precedence control was employed that attempted to maintain the hot water storage tank temperature between 40-45^{o}C (boosted to 45-50^{o}C in some simulations, again to increase thermal storage). If the hot water tank temperature was below this set point range, heat was diverted to it in preference to the radiators (or heating coil in the case of the MVHR system). Third, the heat pump featured an internal safety control that switched the device off if return water temperatures exceeded 55^{o}C; in a real device this prevents excessively high pressures in the refrigerant loop.

Where a buffering tank was added to the heating system, the operation of the heat pump was controlled based on the buffer tank temperature, which was maintained between 50-55^{o}C. An additional circulating pump drew heat from the buffer tank to maintain the living room air temperature and hot water temperatures at the set points indicated previously.

The initial 'on' period specified for the controllers mirrored the house occupancy, with the heat pump initially scheduled to turn on 1-hour prior to active occupancy: 0600hrs and 1600hrs, and turn off at the end of occupied periods: 0900hrs and 2300hrs. The controller settings were drawn from UK ASHP field trials [20].

4. SIMULATIONS

With reference to the different building variants and heating system configurations, the following groups of simulations were run to quantify the potential for flexibility in the heat pump operation.

1. An initial base case simulation with the dwellings insulated to typical UK levels, the heating system on/off set point temperature range was 19-23^{o}C, whilst the hot water tank set point temperature range was 40-45^{o}C.
2. As case 1. However, the heating on/off set point temperatures were altered to 21-25^{o}C and hot water tank set point temperature range was increased to 45-50^{o}C.
3. As case 1. However, a 300L buffer tank was introduced (in addition to the hot water storage tank – see Figure 3b) and maintained between 45-50^{o}C. Heating set point temperatures were the same as in case 1.
4. Case 3 repeated with a 500L buffer tank.

5. Cases 1-4 repeated with both dwellings insulated to passive house standard and equipped with an MVHR-based heating system (see figures 3c and 3d)..

The simulations were run for week-long periods: 9-15 January (winter), 17-23 April (transition) and 4-10 July (summer) using a simulation time step of 1-minute. Such a fine time resolution (for thermal systems simulations) was required to capture those phenomena that affect the ASHP energy and environmental performance such as on/off cycling and the defrost action. In successive simulations, the start-stop times for the ASHP were advanced in 30-min increments up to a maximum of 6-hours. Advances of more than 6-hours moved some of the heat pump demand back into peak morning or evening periods and so were viewed as counter-productive. All of the simulations undertaken used a temperate, maritime UK climate data set.

5. RESULTS

Each simulation gave rise to a large results datasets containing thousands of temperature and energy flux time series for the different elements of the building fabric and plant system components. These were processed to extract the key quantities pertinent to this analysis, namely the dry resultant temperatures within the dwelling (this is the average of the air and mean radiant temperatures), hot water tank temperatures and heat pump energy consumption.

Figure 4a and 4b show an examples of the raw time series data obtained from the simulations of the detached dwelling insulated to average and passive house levels, respectively. These show the variations in living space (dry resultant) temperature and hot water tank temperature in response to advancing input from the heating system. Also shown are some of the other excitations that impact upon air temperature, in particular internal gains and solar gains.

In the analysis of the results, the two metrics used to gauge comfort and service (i.e. the ability of the system to supply hot water) were the living room dry resultant temperature of 18^{o}C and a hot water temperature of 40^{o}C, both of which are analysed during the periods of *active* occupancy (0600-0900hrs and 1700-2400hrs).

An operative temperature threshold of 18^{o}C can be regarded as towards the lower end of acceptable thermal comfort as defined by Fanger[1] [21], whist water supplied at 40^{o}C[2] is the temperature of a typical shower [22].

Both of these temperature limits are superimposed on figures 4a and 4b. Figure 4a illustrates how the space temperature starts to drop below 18^{o}C in this case, when the heat pump firing time is advanced by 2-hours i.e. the heat pump operating times change from 0600 - 0900 and 1800-2300 to 0400 – 0700 and 1600-2100. Figure 4b illustrates how the hot water supply temperature drops below 40^{o}C in this case, again when the heat pump firing time is advanced by 2-hours. The limit on heat pump advance in this case would therefore be 90 minutes.

Figures 5a and 5b show the same situation, but with the house insulated to passive house, standards. Figure 5a shows how that space temperature does not drop below 20^{o}C, the heat pump operation is dictated only by the temperature of the water tank shown in Figure 5b. In this case all of the heat output from the heat pump is diverted to the water tank. Note that with a 120-minute advance, the altered operating times of the heat pump are such that it cannot respond to the large draw of water occurring first thing in the morning, consequently hot water temperatures drop below 40oC during the morning occupancy period, thus limiting the possible advance.

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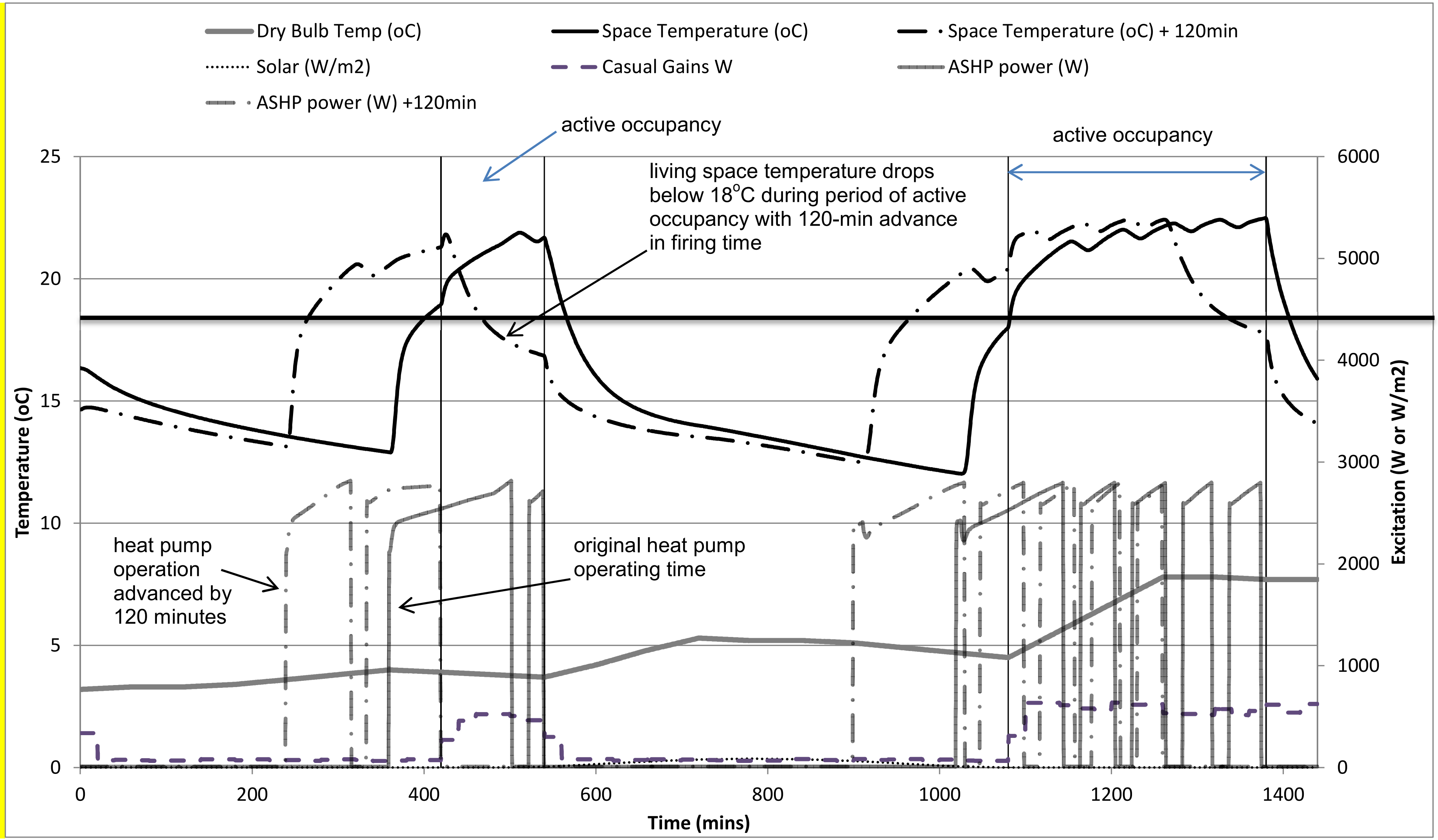
[1] A dry resultant temperature of this magnitude does not guarantee comfort; this is dependent upon many other factors including clothing and activity, hence this is a rather approximate metric. Whilst acceptable within the context of this paper, a more serious comfort analysis would require a more sophisticated approach. Also note that Fanger's concept of static comfort [20] criteria has been challenged by the more recent concept of adaptive comfort [21].

[2] In many boiler-based hot water systems, hot water is stored at over 60^{o}C to prevent the growth of Legionella bacteria. However, this is an inefficient practice as the Legionella threat can be removed by occasionally raising water storage tank temperatures above 60^{o}C. Additionally, hot water at 60^{o}C must be mixed with cold water prior to use to prevent the risk of scalding, so a 40^{o}C supply temperature is both safer and more energy efficient.



active occupancy

active occupancy

living space temperature drops below 18°C during period of active occupancy with 120-min advance in firing time

heat pump operation advanced by 120 minutes

original heat pump operating time

Figure 4a typical impact of heat pump firing advance on living space temperatures in detached dwelling insulated to average UK standard.

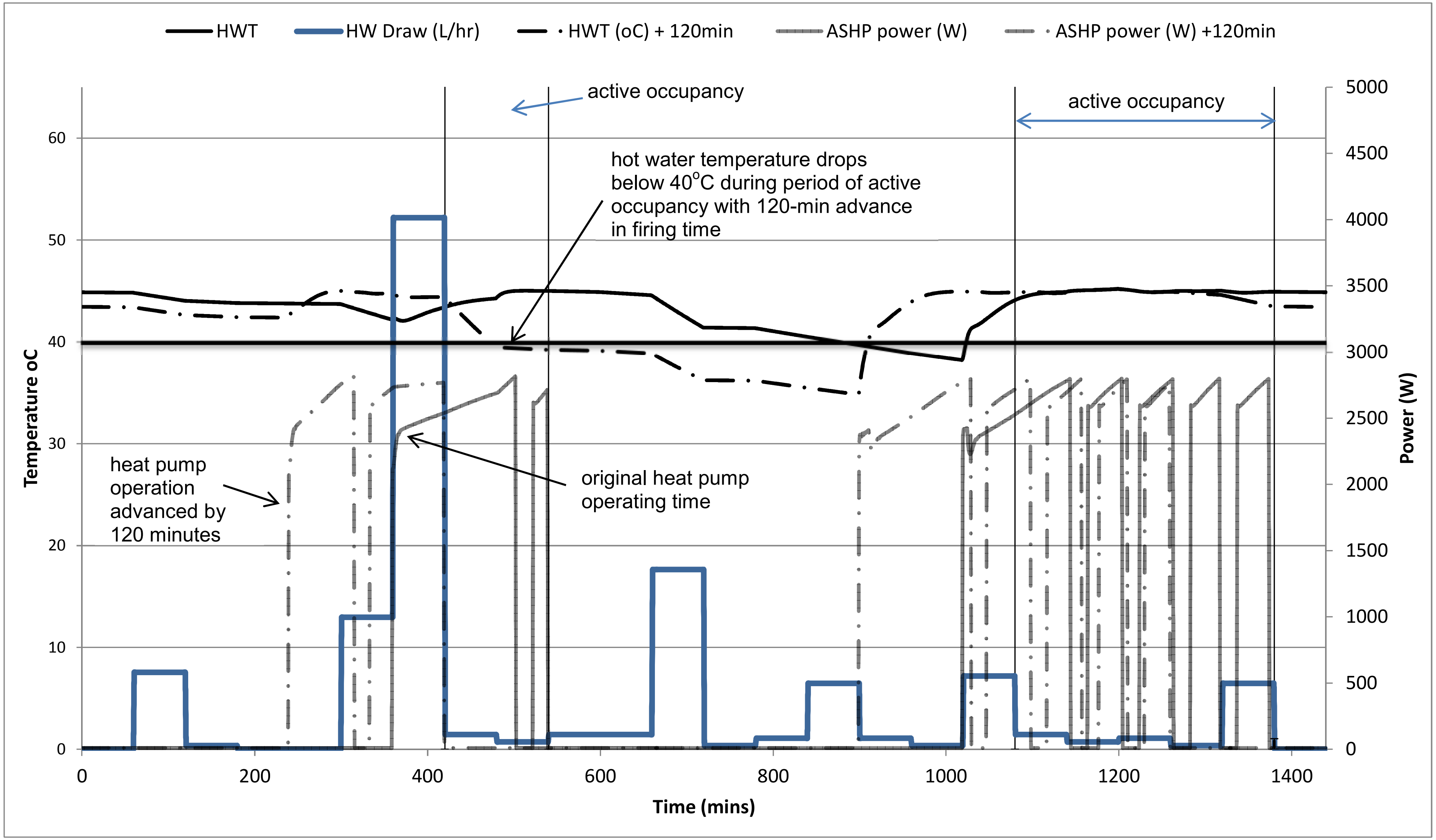


Figure 4b typical impact of heat pump firing advance and hot water draw on hot water temperatures in detached dwelling insulated to average UK standards.

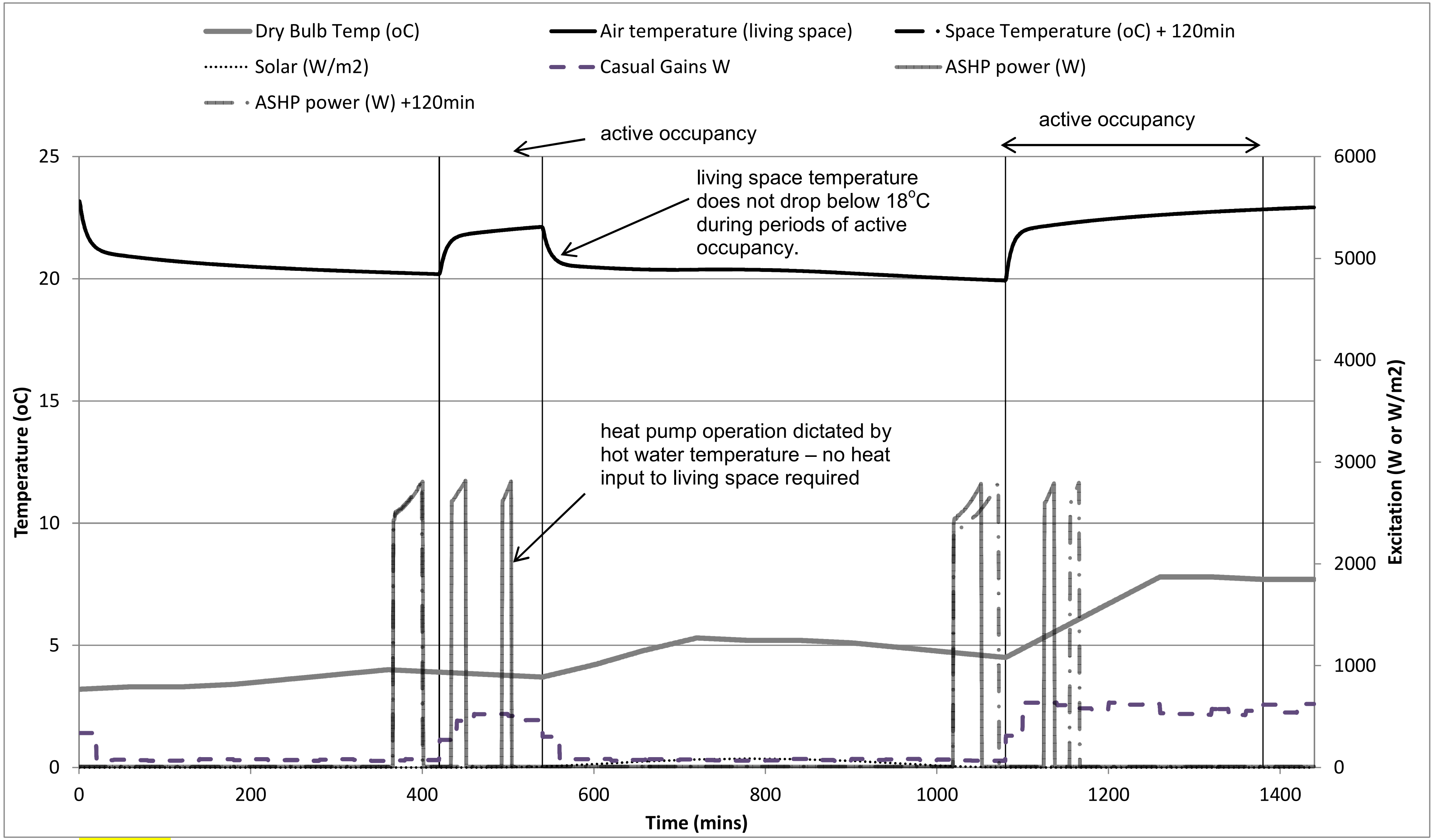


Figure 5a typical impact of heat pump firing advance on living space temperatures in detached dwelling insulated to passive house standards.

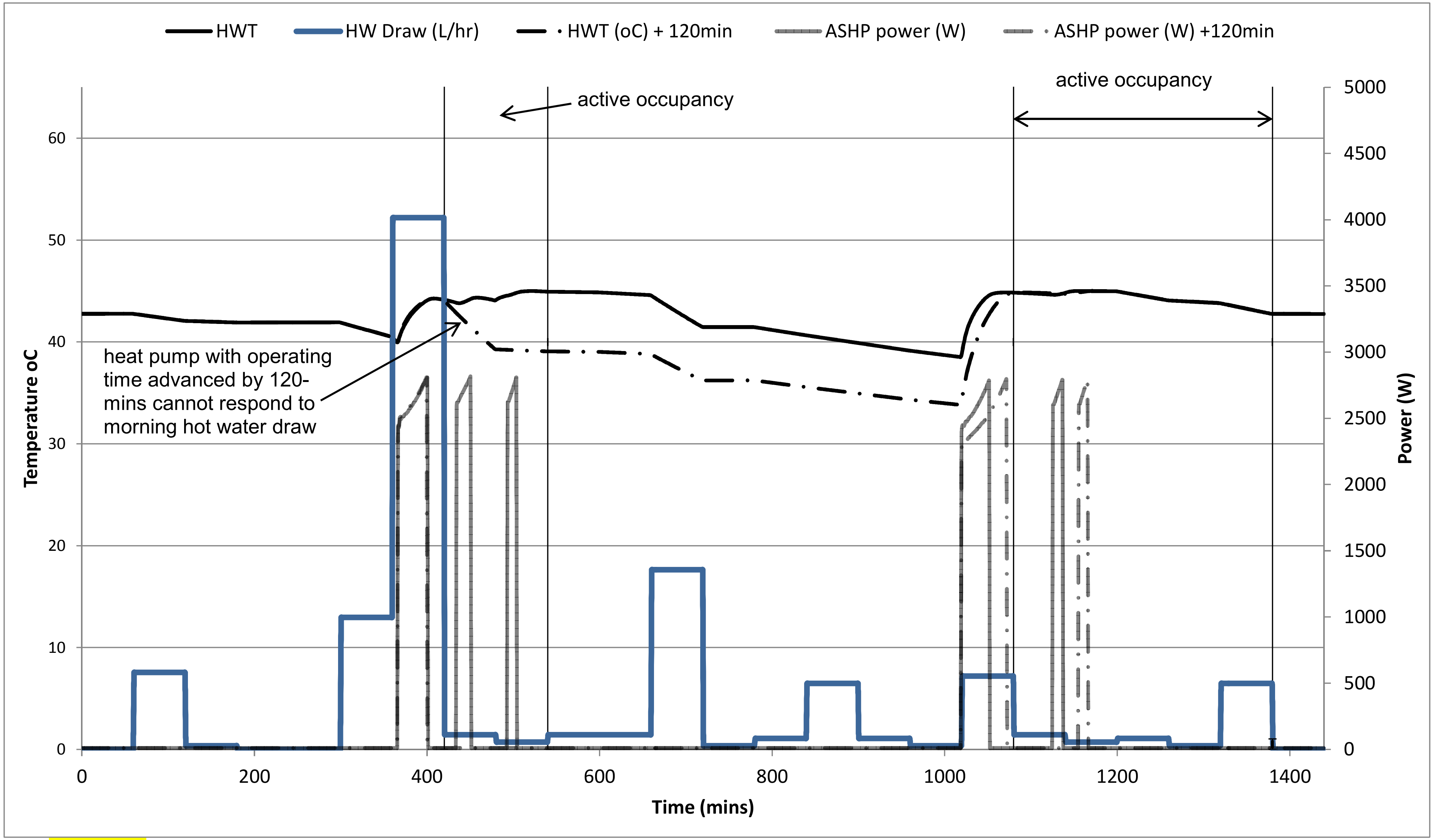
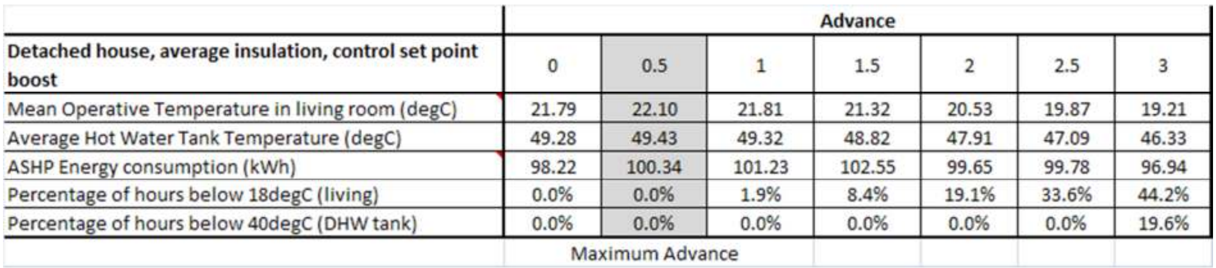


Figure 5a typical impact of heat pump firing advance and hot water draw on hot water temperatures in detached dwelling insulated to passive house standards.

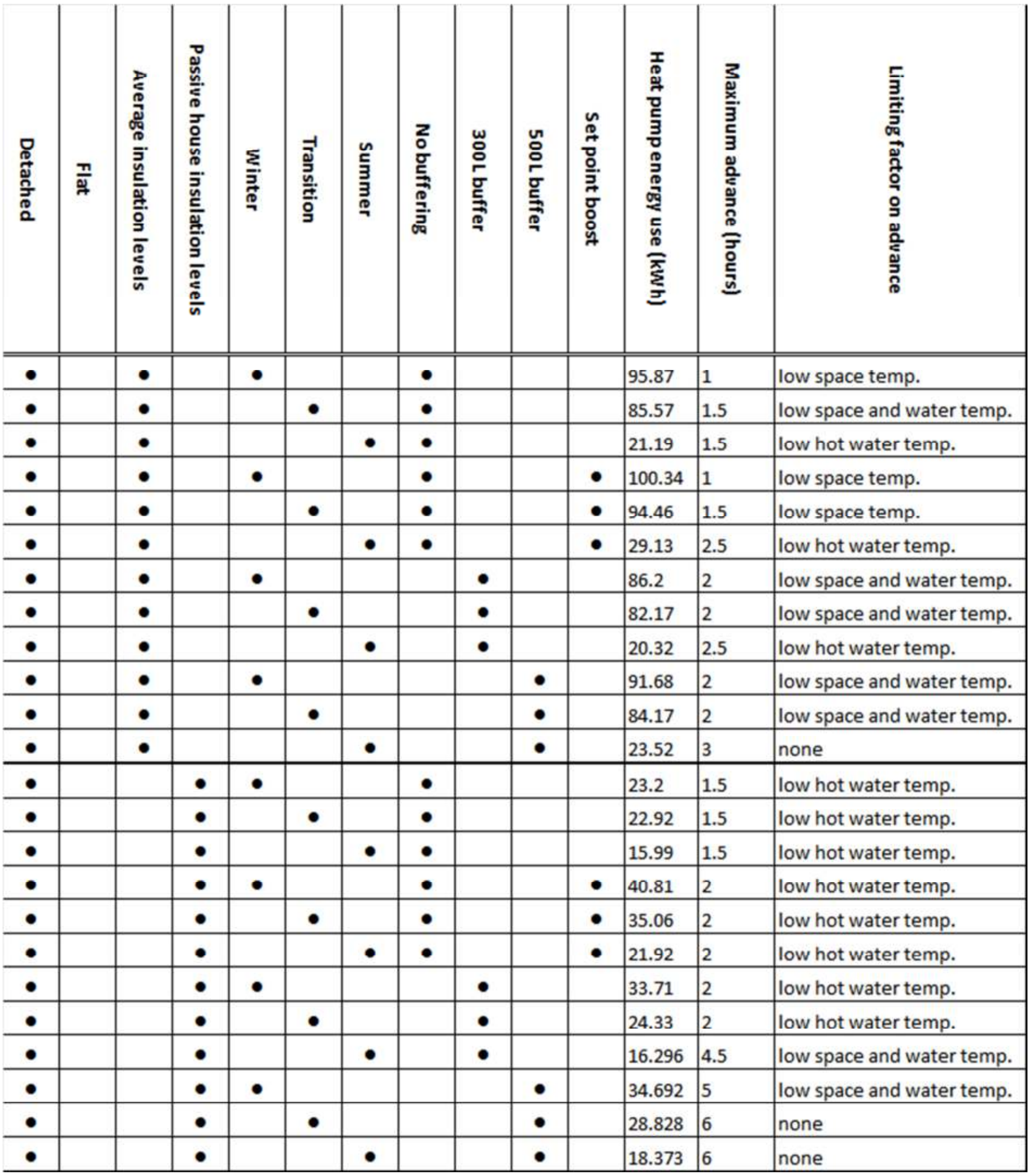
Table 2 shows an example of the processed results for a simulation - in this case the detached house with typical insulation levels simulated in winter. The table shows the total electricity consumption of the heat pump for the simulated week, the average living room dry resultant temperature and hot water temperature and the total number of actively occupied hours in which the living room dry resultant or water temperature fell below 18^{o}C or 40^{o}C respectively. The indicated maximum advance is the operating time advance (in hours) achievable before either of these temperatures fell below their limits for a non-trivial period of time (>1 hour over the simulated week). The maximum advance is therefore not a physical limit; it merely indicates the advance achievable before there is a noticeable effect on space or hot water temperatures. Longer advances may be possible if the occupant was prepared to tolerate lower temperatures.



	Advance						
Detached house, average insulation, control set point boost	0	0.5	1	1.5	2	2.5	3
Mean Operative Temperature in living room (degC)	21.79	22.10	21.81	21.32	20.53	19.87	19.21
Average Hot Water Tank Temperature (degC)	49.28	49.43	49.32	48.82	47.91	47.09	46.33
ASHP Energy consumption (kWh)	98.22	100.34	101.23	102.55	99.65	99.78	96.94
Percentage of hours below 18degC (living)	0.0%	0.0%	1.9%	8.4%	19.1%	33.6%	44.2%
Percentage of hours below 40degC (DHW tank)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	19.6%
	Maximum Advance						

Table 2 Example of results extracted from each simulation.

Tables 3a and 3b show the collated results for all of the simulated cases.



Detached	Flat	Average insulation levels	Passive house insulation levels	Winter	Transition	Summer	No buffering	300L buffer	500L buffer	Set point boost	Heat pump energy use (kWh)	Maximum advance (hours)	Limiting factor on advance
●		●		●			●				95.87	1	low space temp.
●		●			●		●				85.57	1.5	low space and water temp.
●		●				●	●				21.19	1.5	low hot water temp.
●		●		●			●			●	100.34	1	low space temp.
●		●			●		●			●	94.46	1.5	low space temp.
●		●				●	●			●	29.13	2.5	low hot water temp.
●		●		●				●			86.2	2	low space and water temp.
●		●			●			●			82.17	2	low space and water temp.
●		●				●		●			20.32	2.5	low hot water temp.
●		●		●					●		91.68	2	low space and water temp.
●		●			●				●		84.17	2	low space and water temp.
●		●				●			●		23.52	3	none
●			●	●			●				23.2	1.5	low hot water temp.
●			●		●		●				22.92	1.5	low hot water temp.
●			●			●	●				15.99	1.5	low hot water temp.
●			●	●			●			●	40.81	2	low hot water temp.
●			●		●		●			●	35.06	2	low hot water temp.
●			●			●	●			●	21.92	2	low hot water temp.
●			●	●				●			33.71	2	low hot water temp.
●			●		●			●			24.33	2	low hot water temp.
●			●			●		●			16.296	4.5	low space and water temp.
●			●	●					●		34.692	5	low space and water temp.
●			●		●				●		28.828	6	none
●			●			●			●		18.373	6	none

Table 3a Summary simulation results for the detached dwelling model.

Detached	Flat	Average insulation levels	Passive house insulation levels	Winter	Transition	Summer	No buffering	300L buffer	500L buffer	Set point boost	Heat pump energy use (kWh)	Maximum advance (hours)	Limiting factor on advance
	●	●		●			●				61.81	2	low hot water temp.
	●	●			●		●				49.97	2	low hot water temp.
	●	●				●	●				12.48	2	low hot water temp.
	●	●		●			●			●	78.62	2.5	low hot water temp.
	●	●			●		●			●	60.66	2.5	low hot water temp.
	●	●				●	●			●	16.81	2.5	low hot water temp.
	●	●		●				●			67.04	2.5	low hot water temp.
	●	●			●			●			52.784	2.5	low hot water temp.
	●	●				●		●			15.12	6	none
	●	●		●					●		63.32	3	low hot water temp.
	●	●			●				●		41.169	3.5	low space and water temp.
	●	●				●			●		12.283	6	none
	●		●	●			●				13.68	2	low hot water temp.
	●		●		●		●				10.05	2	low hot water temp.
	●		●			●	●				10.67	2	low hot water temp.
	●		●	●			●			●	20.59	2.5	low hot water temp.
	●		●		●		●			●	18.4	2.5	low hot water temp.
	●		●			●	●			●	12.43	2.5	low hot water temp.
	●		●	●				●			20.02	6	none
	●		●		●			●			18.47	6	none
	●		●			●		●			9.48	6	none
	●		●	●					●		16.68	6	none
	●		●		●				●		15.04	6	none
	●		●			●			●		10.37	6	none

Table 3b Summary simulation results for the flat model.

5.1 Base Case Simulations

In the detached house base case winter simulation (with no thermal buffering and typical UK insulation levels) an advance in the heat pump firing time of only 1-hour was achieved before the living room dry resultant temperature fell below 18°C at some point during occupied periods. In the transition week, an advance of 1.5 hours was achieved due to higher external temperatures and the subsequent reduction in the decay rate of internal space temperatures at the cessation of heat pump activity. In the summer, the hot water supply temperature became the limiting factor, with a maximum advance of 1.5-hours being achieved without hot water supply temperatures dropping below 40^{o}C during the occupied period. In the case of the flat, the limiting factor for advancing the firing time was always the hot water supply temperature, with an advance of 2-hours being achievable in all seasons. The flat's dry resultant temperatures were more resilient to changes in firing time mainly due to flat having a significantly smaller surface area exposed to the external environment, resulting in a slower decay rate of indoor temperatures occurring after the heat pump was switched off.

5.2 Boosting Set Points

For the detached dwelling with typical insulation levels, boosting the temperature set points of both the space heating system and the hot water storage had a limited effect on the maximum advance achievable. Only in summer was the effect noticeable, with the maximum advance increased from 1.5 hours to 2.5 hours at the expense of a 37% increase in the heat pump energy consumption. In the winter and the transition seasons, low dry resultant temperatures were the limiting factors for advancing the heat pump operation. In summer, low hot water temperatures limited the time of advance. In the flat, boosting the set points meant that heat pump operating time could be advanced by 2.5-hours in winter, transition and spring simulations, as opposed to 2-hours in the base case simulations, though boosting the set points resulted in more than a 30% increase in the heat pump energy consumption in each case.

5.3 Addition of Thermal Buffering

For the detached dwelling, adding 300L of thermal buffering into the heating system had a limited effect on the maximum advance achieved, with a 2-hour advance possible in the winter and transition periods and 2.5-hours in summer. The addition of 500L of thermal buffering achieved similar improvements in heat pump advance times, except in summer where (with a very small space heating load) an advance of up to 3-hours was possible without compromising either comfort or hot water temperatures. In the case of the flat, the addition of 300L of buffering further increased advance times from 2 to 2.5-hours over the winter and transition seasons and a maximum 6-hour advance was achieved in summer. A 500L buffer enabled advance times of 3, 3.5-hours and 6-hours to be achieved in winter, transition and summer seasons, respectively.

5.4 Improved Insulation and Airtightness

Insulating the detached dwelling to passive house standards had a marginal effect on the achievable advance time, with the potential winter advance increasing from 1 to 1.5 hours. In all cases the heat pump energy consumption was significantly reduced: for example, winter heat pump energy demand was reduced by 76%. The limiting factor for advancing the heat pump operation was always low hot water temperatures as opposed to low dry resultant temperatures. Similar results were obtained for the flat, with advance times remaining largely unchanged and energy consumption was significantly reduced. Increasing the hot water and space heating set points in both of the dwelling types had little effect on advance times but significantly increased energy consumption (up to 70%).

The combination of additional thermal buffering along with improved insulation and airtightness yielded the greatest increases in heat pump operation advance times. For the detached dwelling, the addition of 500L of thermal buffering enabled advance times of 5-hours in winter and 6-hours in summer and the transition seasons. For the flat, the addition of 300L or 500L of thermal buffering enabled advance times of up to 6-hours in all seasons with little effect on dry resultant or hot water temperatures.

5.5 Supplementary Hot Water Heating

In the majority of the simulations undertaken, the hot water tank temperature proved to be the limiting factor for advancing the operating time of the heat pump. A reason for this was that the effective capacity of the tank was small due to the low storage temperatures (45-50^{o}C) and this resulted in the tank temperature quickly dropping below 40^{o}C when subjected to a hot water draw. Some additional simulations were undertaken where the hot water tank temperature was boosted by a direct electric immersion heating coil to 60^{o}C, increasing the effective capacity of the tank, at the expense of increased energy consumption. The results indicated that boosting the hot water temperature to 60^{o}C virtually eliminated low hot water temperatures as a limiting factor to advancing the heat pump operating time. However, this was at the expense of significant extra energy consumption: e.g. the combined heat pump and auxiliary coil energy consumption for the detached dwelling insulated to typical UK levels was 70% greater than the base case. In the corresponding simulations with the flat model, the potential advance time reached the maximum 6-hours in all simulations, with neither the space operative temperature falling below 18°C, nor the water supply temperature falling below 40°C at any point; however, again, energy consumption was significantly increased.

Detached	Flat	Average insulation levels	Passive house insulation levels	Winter	Transition	Summer	No buffering	300L buffer	500L buffer	Additional set point boost	Heat pump and auxiliary coil energy use (kWh)	Maximum advance (hours)	Limiting factor on advance
●		●		●			●			●	133.1	1	low space temp.
●		●			●		●			●	118.05	1.5	low space temp.
●		●				●	●			●	54.97	6	none
●			●	●			●			●	64.7	6	none
●			●		●		●			●	51.99	6	none
●			●			●	●			●	48.9	6	none
	●	●		●			●			●	81.28	6	none
	●	●			●		●			●	69.21	6	none
	●	●				●	●			●	22.34	6	none
	●		●	●			●			●	22.7	6	none
	●		●		●		●			●	22.7	6	none
	●		●			●	●			●	22.1	6	none

Table 4 Summary simulation results for tank with additional hot water heating from electrical coil.

From the point of view of energy efficiency and to minimize load on the low voltage (LV) network it would be preferable if the higher water temperatures were delivered by the heat pump itself, rather than a resistance heating coil. Conventional vapour-compression heat pumps using a single HCFC or HFC refrigerant (as modelled in this paper) deliver hot water at 40-50°C, with the coefficient of performance (COP) decreasing as the delivery temperature increases (e.g. [ref]). However, heat pumps are emerging using HFC refrigerant mixtures or HFC alternatives such as CO2 (e.g. [stene]) which can deliver hot water at over 60°C and at COPs above 3; these embryonic devices may be more suited to residential load shifting applications particularly where hot water constitutes a significant portion of the demand [stene].

6. CONCLUSIONS

Recall, that the objective of this paper was to examine the potential for shifting the operational times for heat pumps in current and future UK dwellings, thus enhancing the flexibility of demand; this ability to manipulate operating times could prove useful in future energy systems featuring high penetrations of renewable electricity generation. The limiting factor for moving the operational times of a microgeneration device was avoiding discomfort or inconvenience to the end-user through the occurrence of low dry resultant temperatures (below 18°C) or low hot water supply temperatures (below 40°C).

6.1 Existing Housing Stock

The initial simulations looked at the scope for manipulation of the heat pump operating times in a detached house and flat, insulated to levels typically found in the current UK housing stock and when relying only on the intrinsic thermal inertia of the building fabric and heating system. The results indicated that limited time shifts of between 1-2 hours were achievable. From the perspective of the operation of electricity distribution networks, the ability to shift the heat pump operating time only within a time window of 60-to 120-minutes would not permit sufficient flexibility to flatten the characteristic peaks for electricity seen in housing during the morning and evening periods. It would however, permit a local network operator to stagger the operation of the heat pumps within their area. This would be a useful in preventing concurrent heat pump morning or evening start-ups, perhaps negating the need for investment in local low voltage network reinforcement in areas with significant penetration of heat pumps.

Various strategies were the employed in an attempt to increase the achievable time shift. Boosting the heat pump's hot water and space heating control set points towards their operational limits (50°C and 23°C, respectively) was of little benefit. Further, boosting storage tank temperatures to 60°C employing an auxiliary electric heating coil proved successful only where lower space heating loads prevailed; this was at the expense of very significantly increased energy consumption.

Adding thermal buffering to the heating system met with mixed success, only the addition of 500L of thermal buffering proved effective at seriously improving flexibility, and then only in summer where time shifts of 3 and 6-hours were achieved for the detached house and flat respectively. In winter and the transition seasons, with a larger space heating load, the time shifts achieved were more modest.

6.2 Future Housing Stock

Turning to the simulations of the future house types, insulated to passive house standards, it was apparent that improving insulation levels alone had almost no effect on the potential to shift the operational times of the heat pump due to the fact that hot water rather than space temperatures were the limiting factor. However, as would be expected, the overall energy demand of the heat pump was dramatically reduced.

Again, boosting the heating set points towards the limits of the heat pump's operational range proved largely unsuccessful, increasing the range of potential operating times by only 30-minutes at the expense of significantly more heat pump electricity use.

Adding an auxiliary heating coil to the hot water storage tank, boosting water temperatures to 60^oC enabled the maximum time shift of 6-hours to be achieved at the expense of a very significant increase in energy consumption.

The combination of improved insulation and additional 300L or 500L thermal buffering tanks proved to be the most successful mechanism to improve operational flexibility enabling time time-shifting of 5-6 hours in all seasons.

To conclude, the simulations undertaken for this paper have demonstrated that substantial time shifts of up to 6-hours were achievable in the operating times of heat pumps serving dwellings without seriously affecting either dry resultant or hot water temperatures. However, such shifts were only achievable if insulation levels were dramatically improved and substantial levels of thermal buffering (300L or 500L) were added into the heating system.

7. FURTHER WORK

This paper was predicated on the assumption that the manipulation of the heat pump operating time should not adversely affect the end-user through low dry resultant temperatures or low hot water temperatures. However, the definition of low temperatures is open to interpretation and is context dependent. For example, an 18^oC dry resultant temperature, whilst regarded as at the lower end of the comfort scale in the literature may be unacceptable for certain vulnerable user groups such as the elderly. Conversely, an enthusiastic early adopter of responsive heat pump control may be perfectly willing to accept low dry resultant and water temperatures for a short period of time, perhaps with the added financial incentive of a tariff reduction. Given that the temperature limits selected will have a pronounced effect on the achievable time shift for microgeneration, the willingness of consumers to accept slightly reduced temperatures and the point at which these become discernible in a domestic environment deserves serious investigation. .

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