PERFORMANCE IMPLICATIONS OF HEAT PUMPS AND MICRO-COGENERATORS PARTICIPATING IN DEMAND SIDE MANAGEMENT

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ABSTRACT

This work considers the potential impact of participating in demand side management on the performance of air source heat pumps and micro-cogenerators. As significant consumers and generators of electricity at the distribution level, large numbers of heat pumps and micro-cogenerators would provide considerable scope for participation in demand-side management systems. However, it is possible that operating regimes which are optimised for grid considerations will not achieve the maximum performance that is possible from these units.

Modelling has been conducted to investigate the significance of this effect, considering the case where local distribution constraints are the main driver for demand side interventions. A model of domestic electrical demand has been adapted to consider a neighbourhood of 128 dwellings in order to identify when interventions are necessary. This has been combined with dynamic models of two micro-cogenerators (derived by IEA ECBCS Annex 42 and based on Stirling engine and internal combustion engine prime movers) and a similar model of an air source heat pump. A simple thermal model of each building is combined with a range of user preferences in order to determine the preferred operating profiles of the heating units.

The efficiency of the air source heat pump units is generally found to suffer by about 5% but additional heat losses bring the total increase in primary energy required by the air source heat pumps to 10% to 25%. Although the performance of the micro-combined heat and power units is observed to vary with the operating conditions, this variation is not specifically an effect of demand side management. The effects are not as significant as the observed variations in performance due to differences in installation and operation of the units but are large enough to warrant consideration when assessing the benefits and costs of a similar scheme.

Keywords: Demand side management; micro-cogenerator; heat pump; micro-combined heat and power; efficiency

INTRODUCTION

Participating in demand side management (DSM) is likely to increase the primary energy consumption of air source heat pumps (ASHPs) and may have other impacts on the use of micro-combined heat and power (mCHP) units. These trade-offs should be considered when assessing the relative merits of subjecting them to a DSM system.

ASHP and mCHP units have both been suggested as technologies capable of reducing the carbon emissions associated with domestic space heating demands [1–4]. Both types of unit have significant electrical power flows associated with them; ASHP units are a relatively large load and mCHP units generate electricity which can sometimes result in net electrical export from a dwelling. Successful integration of large numbers of these units will require careful consideration of these power flows, especially in the context of local distribution infrastructure that was not designed to cope with them [5, 6].

DSM is the management of electrical loads to better match demand and supply; for example by adjusting or moving loads away from peak times [7]. In this way, the use of DSM provides the potential to increase the number of ASHP or mCHP units which can be connected to the local distribution infrastructure without exceeding its capacity.

Although other microgeneration devices also have the potential to save energy [8], ASHP and mCHP units have the capacity for greater interaction with DSM schemes. The technical

feasibility of using ASHPs as flexible load has been considered [9, 10]. However, both ASHP and mCHP units perform most efficiently when operated as evenly as possible. Stirling Engine mCHP (SE-mCHP) units have reduced electrical efficiency as they warm up, internal combustion engine mCHP (ICE-mCHP) units have some thermal lag and ASHP performance is improved when they supply heat at the minimum temperature possible (which is lower if heat is supplied continuously).

It is likely that the adjustment of the operation of the heating units associated with DSM will result in less even operation. This study uses modelling of the systems to consider the extent to which this is likely to adversely affect their performance. For ASHP units, the modelled efficiency is reduced by around 5% while the performance drop is minimal for adequately buffered mCHP units.

For this study, the DSM considered is the interventions appropriate to maintaining power flows within the limits of local distribution infrastructure. This limit is taken to be 200kW (representing the capacity of a small 415V distribution transformer). It is possible that additional objectives (e.g. maximising the utilisation of intermittent renewables) will apply to actual implementations of future DSM systems, but they are likely to have a comparable effect [11].

METHOD

Scenarios compared

To investigate the effect of this use of DSM on the performance of ASHP and mCHP units, 18 scenarios have been simulated and the average performance of the units operating in them are then compared. The 18 scenarios consist of three levels of DSM intervention with six different mixes of heating systems supplying heat to 128 dwellings, as given in Table 1.

The simulations were all run for a three month period (92 days) covering the heating season. Outside of this period the interventions associated with the DSM objectives are minimal as all demands are lower.

Heating demand is sensitive to the difference in temperature between the air inside and outside each dwelling [12] and the performance of the heating units has been observed to depend upon this [13], so it is important to compare energy demands on a like for like basis. To achieve this, additional, “control” simulation runs were performed without any DSM intervention but with the heating control coefficients relaxed to give a comparable level of thermal comfort.

Table 1: Main permutations considered

Permutation	DSM level	Dwellings with boilers	Dwellings with ASHP	Dwellings with SE-mCHP	Dwellings with ICE-mCHP	Buffering
1	1	80	48			No thermal buffering
2	1		64	64		
3	1		92		36	
4	2	72	56			
5	2		72	56		
6	2		96		32	
7	3	64	64			
8	3		80	48		
9	3		100		28	
10	1	80	48			300kg buffer tank
11	1		64	64		
12	1		88		40	
13	2	72	56			
14	2		72	56		
15	2		96		32	
16	3	64	64			
17	3		80	48		
18	3		100		28	

Modelling approach

A modelling approach with finite time-steps of one minute has been taken for this study. In order to model the effect of the DSM on the performance of the ASHP and mCHP units, it is necessary to have sufficiently detailed models of the units, the conditions they will operate in and the nature of the DSM interventions that will be applied to them. Because each of these elements will interact throughout the simulation period, it is not sufficient to use separate models and simply feed the results from one to the next. In particular, a DSM system which is attempting to limit total power demand will need to be aware of the net power demands of each of the dwellings under consideration and each of these net power demands will, in turn, depend to some extent on the nature of the DSM being applied at that time.

A model was constructed with these interactions being considered, a development of that used previously [11, 14]. A fuller description of the modelling assumptions and parameters is given in [15]. Although the authors are not aware of any similar integrated model, models of each of the individual elements have been published and these were used wherever possible.

DSM control signal

An "indirect" DSM control signal is assumed. That is, for each time-step, a signal is generated which represents the extent to which the DSM control system is attempting to discourage net power demand. The control system for each ASHP and mCHP unit will then take this signal into account when determining the heat generation it demands from the unit. This is in contrast to a "direct" control signal in which the power consumption or generation of each device is determined directly by the DSM control system.

Using the indirect control system approach allows the DSM control system to function without being aware of the characteristics of each of the heating units or the conditions and constraints they are operating within. However, it does require iteration within each time-step. The DSM system in this study starts to send a signal to discourage power demand when the distribution system is delivering 75% of its capacity and then progressively increases the signal as demand rises above this. The iteration refines the signal strength given the change of demand which it causes (see Figure 1).

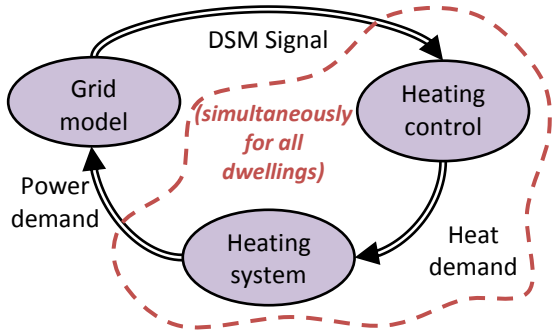

Figure 1: DSM control system iterations

It is assumed that the control system of each heating unit adjusts the programme temperature it is aiming for as a function of the DSM control signal. Three different levels of responsiveness have been characterised by the maximum acceptable adjustment from the programme temperature, (taken to be 20°C), see Table 2. Within each of the 18 scenarios, it is assumed that all residents will accept the same level of DSM intervention. This simplification is adopted on a pragmatic basis in order to make the effect of increasing the level of DSM intervention clear. However, it is likely that actual residents will have a range of different responses to proposals to implement some measure of DSM influence over their electrical systems [16].

Table 2: DSM levels

DSM level	Maximum temperature programme adjustment
1	-1°C
2	-2°C
3	-3°C

With an adjusted programme temperature, the control system of each heating unit determines the desired heat generation from that unit (see below). The heating unit then consumes or generates power according to its characteristics and either the iteration repeats or the time-step increments on as appropriate.

Heating system control

The ASHP and ICE-mCHP units are capable of modulating between an upper and lower limit. In the cases where a thermal buffer is not used, the control algorithm for these units makes a heat demand proportional to the temperature difference between the DSM-adjusted programme temperature and the inside air temperature. The SE-mCHP unit is not capable of modulated control and so the control algorithm for it uses a step on-off function, based upon the DSM-adjusted programme temperature and the inside air temperature with a 2°C dead-band.

For the cases where a thermal buffer is used, heat is supplied to the building's heat emitters based on an on-off function representing a thermostat, again with a 2°C dead-band. Similar control algorithms are used to maintain the buffer tank temperature at 55°C, adjusted in the same way by the DSM signal. A proportional controller is used with the ASHP and ICE-mCHP systems. An on-off controller with a dead-band of 8°C is used with the SE-mCHP systems.

Heating systems

The three heating systems take the "two-lumped capacitances model" suggested by IEA ECBCS Annex 42, see Figure 2 [17]. The group's final report [18] contains values for the thermal characteristics of the SE-mCHP unit, and sufficient data to approximate their values for the ICE-mCHP unit considered here (see [15]). The corresponding values for the ASHP unit have been estimated from the physical characteristics of the device and the performance of similar devices.

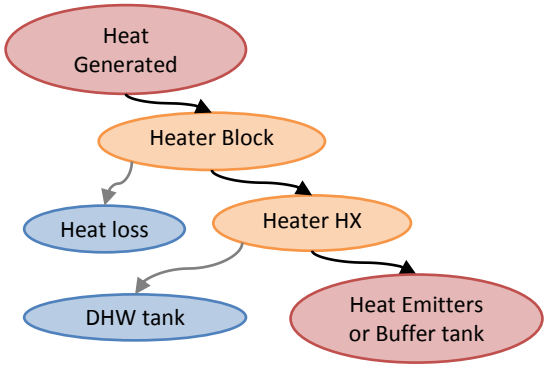

Figure 2: Heat flows modeled in heating system

The nominal steady state efficiencies of the units are provided in Table 3.

The electrical efficiency of the SE-mCHP unit varies as a function of its engine temperature [18]. The ICE-mCHP unit is capable of continuously varying its output and its electrical efficiency varies by about 4% with this; it is calculated by linear interpolation between the nearest test output conditions. The coefficient of performance (COP) of the ASHP is a function of the temperatures of its heat source and heat sink. It is therefore calculated as the weighted average of its exergy efficiency at the nearest test conditions [19]. The heat which is actually generated by each heating unit will depend upon the demand from its control algorithm but also its maximum and minimum heat generation levels.

Table 3: Steady state nominal unit performance.

UNIT	**COP (A2 / W35)**	
ASHP	4.20	
	ELECTRICAL EFFICIENCY	**THERMAL EFFICIENCY**
SE-mCHP	8.4%	87%
ICE-mCHP	22.3%	61%

Domestic Hot Water demands are assumed to follow the pattern of active occupancy, scaled to match estimates of daily consumption [20]. Heat is transferred to the DHW tank in parallel with the space heating system. If the DHW tank temperature drops outside tolerance, heat transfer to the space heating is suspended so that the heating unit's heat exchanger temperature rises and more heat is transferred to the DHW tank.

Buildings

A neighbourhood of 128 dwellings is modelled for this study, these are described below. As the approach taken requires a thermal model for each of these buildings to be run simultaneously, the thermal models have been simplified to consist of lumped thermal capacitances for the inside air and for the building fabric and heat transfers due to convection from the building fabric, air infiltration, solar gains and internal gains (occupants and appliances), see Figure 3.

The neighbourhood is assumed to consist of four building types (i.e. 32 of each). Building types representative of the UK housing stock have been modelled in detail using ESP-r by Dr. N. Kelly and Dr. J. Hong of ESRU, University of Strathclyde [21] and data from these models has been used to calibrate the parameters of the simplified models, resulting in a good fit between the temperature profiles (average air temperature difference of less than 0.5°C, see Figure 4).

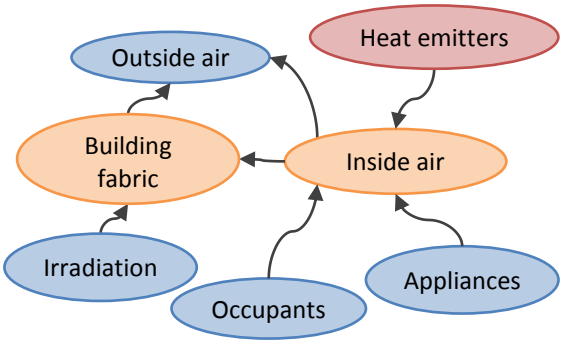

Figure 3: Building thermal model

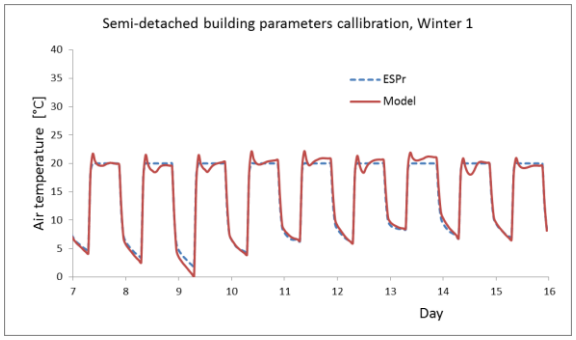

Figure 4: Example of fit between temperature profile from simplified model and detail model

Test reference year climate data for London Heathrow has been used to supply outside air temperature and solar radiation data [22] Occupant gains have been calculated using the "CREST active occupancy model" [23], assuming 60W per active occupant and 30W per dormant occupant.

Heat emitters are sized such that a flow temperature of 45°C is required to balance the heat losses from each dwelling when the outside temperature is 0°C.

Appliance and lighting use

The CREST domestic lighting and appliance model has been used to model the power demands from lighting and appliance use in the dwellings [23]. Half of the dwellings were assigned four residents, a quarter were assigned three residents and the remaining quarter were assigned two.

The model was adapted slightly to provide a continuous profile of demand data rather than modelling individual 24-hour periods separately. Additionally, power demands associated with electric showers and electric storage heating were excluded.

The CREST model uses a set of transition probability matrices to simulate the changes of power demands in each dwelling. The modelled demand profile changes every time the model is run but its parameters have been calibrated to provide the same stochastic characteristics as measured data sets. However, to ensure fair comparison across the different scenarios in this study, the model was run several times and an average profile selected to be used with each of the scenarios. That is, the appliance and lighting demands were not dynamically simulated during each run of the model.

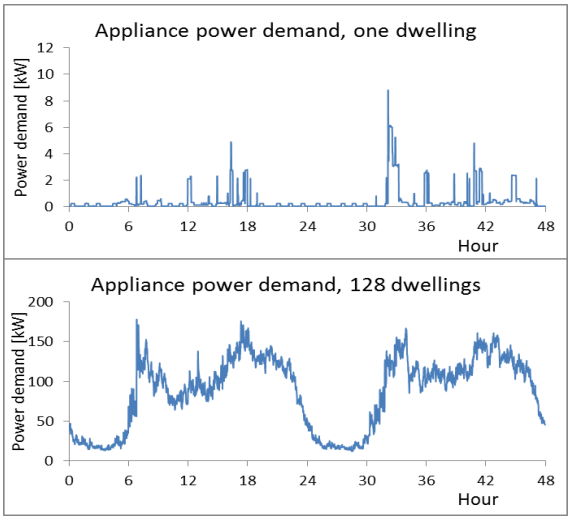

Figure 5: Examples of appliance and lighting demand profiles

RESULTS & DISCUSSION

Operating characteristics

Representative power flow and temperature profiles derived from the modelling are provided in Figure 6. Each profile covers the same 48 hour simulation period (in early January). The six scenarios shown are those with the middle level of DSM intervention (i.e. deviations in programme temperature of up to -2°C). Power flow profiles (total and appliances only) are on the left side, relating to all 128 dwellings. Temperature profiles (programme and actual air temperatures) on the right relate to one dwelling; the selected dwelling is equipped with either an ASHP, SE-mCHP or ICE-mCHP unit, depending upon the scenario it relates to.

The total power demand profiles are similar to each other but are generally smoother in the scenarios with buffering.

The temperature profiles, on the other hand, show some significant differences. The sharp down spikes in the scenarios without the 300kg thermal buffers are a combination of the real effect of heat being diverted to the DHW tank and the modelling limitation of no additional heat capacities. They are therefore not an inherent part of this study. The rapid fluctuation in heat flows (manifest by temperature fluctuation) in the case of the buffered SE-mCHP unit are those from the buffer tank (flow is regulated with a thermostat on-off function) rather than from the heating unit itself.

The variation in programme temperature due to DSM intervention has a more continuous profile in the scenarios without mCHP units (top two profiles) than in the scenarios with mCHP (in which case it tends to flip between the nominal temperature and a lower temperature). This is an interesting effect. Because the objective of the DSM system in this study is to prevent the total net power demand from exceeding the distribution limits, it only has a significant effect at times of high demand. At these times, the effect is to decrease the programme temperature for the dwellings with ASHP units but to increase it for dwellings with mCHP units. As the heating control systems are set up (in this study) to vary the programme temperature between the nominal temperature and a minimum, (i.e. not to *increase* the programme temperature above the nominal temperature) the mCHP units' scope for contributing at these times of high power demand is reduced.

If a system with a similar design to the one described here were to be implemented it is of course likely that the programme temperature would be allowed to increase above the nominal programme temperature. This would probably increase the system's ability to respond to high power demand and allow a higher ratio of ASHP to mCHP units to be successfully operated. It has not been done here as the aim of the study is to compare the performance and energy requirements of the systems; the increase in heating demand which is likely to occur would be of similar magnitude to the effects being studied and would make the comparison invalid.

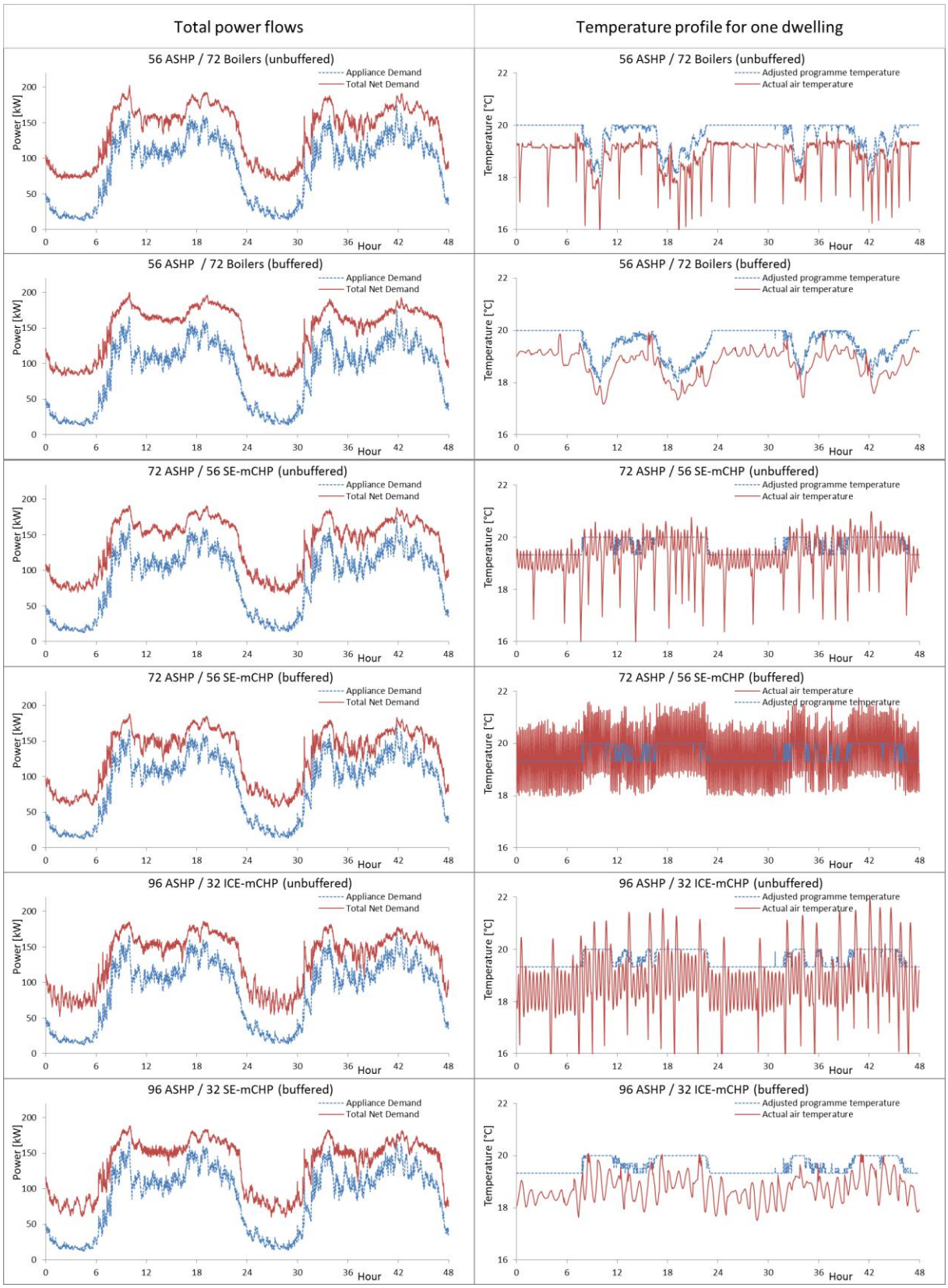

Figure 6: Power and temperature profiles for 48hr for the six "middle DSM" scenarios

Unit performance without consideration of thermal comfort

The average COP of the ASHPs without the thermal buffer varied from 3.84 to 3.86 as the level of DSM was varied; i.e. there was no significant change in performance. With the 300kg thermal buffer, the COP varied from 3.16 to 3.18.

The efficiencies of both mCHP units were also seemingly unaffected by the level of DSM intervention. Without the thermal buffer, the SE-mCHP unit achieved an average electrical efficiency of 3.2% to 3.3% and a thermal efficiency of 62.3% to 62.8% (all efficiencies here are considered relative to HHV of fuel). With the thermal buffer, the electrical efficiency was increased to 6.9% and the thermal efficiency decreased slightly from 58% to 57.5%.

The ICE-mCHP unit achieved an average electrical efficiency of 20.8% to 21% and a thermal efficiency of 53.0% to 54.1%. The thermal buffer had no significant effect.

The decrease in performance when buffering is used by the ASHP systems can be attributed to the higher flow temperature which is required; heat must be supplied at a temperature higher than the thermal buffer. The systems with thermal buffering also provide a more consistent inside air temperature, as notionally apparent from Figure 6 but also in more quantitative metrics (see below).

The increase in electrical efficiency observed as a thermal buffer is used with the SE-mCHP unit has been noted elsewhere [23, 24] and is associated with the reduced number of operating cycles (with reduced losses at the start and end of the cycles). Because of the size of the effect, it is considered in more detail below. The slight decrease in thermal efficiency is probably due to losses from the buffer tank.

The ICE-mCHP is less affected by the presence of the thermal buffer as its efficiencies are relatively unaffected by flow temperatures and only vary slightly as it modulates its output from minimum to maximum.

Consideration of thermal comfort & energy consumption

Although the performance of the units has been noted to be apparently insensitive to the DSM interventions, these do incur a penalty in terms of the extent to which the inside air temperature deviates from the programme temperature which the occupants request. Given the large effect that building temperature has on heating demand, this effect should not be ignored if fair comparison is to be made between the units.

In order to assess the extent to which the inside air deviates from the programme temperature, the cube of the deviations below 18°C (i.e. 2°C less than nominal programme temperature) are integrated with respect to time for each simulation. Although far from perfect as a proxy for thermal comfort, it does provide a metric against which the systems can be compared.

As expected, the deviation from programme temperature is higher in the scenarios involving more DSM intervention. Additional control simulations without DSM but with the heating system control gains relaxed to achieve similar levels of temperature deviation have therefore been run. The average COP of the ASHP units under these conditions is compared to their performance when DSM is used in Figure 7:

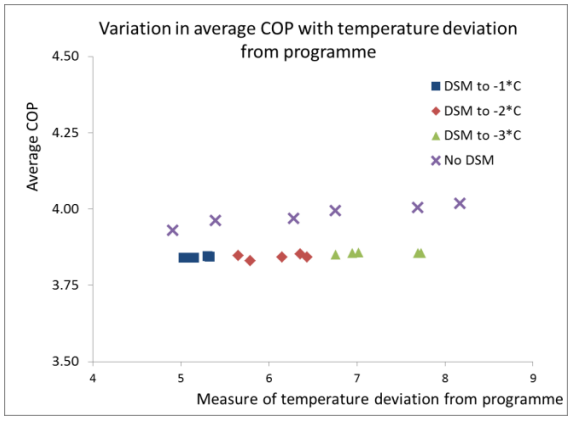

Figure 7: ASHP performance

This shows that although the performance of the ASHP units is not adversely affected by an increase in DSM intervention, the COP which could have be achieved with a similar level of thermal comfort is around 5% higher. That is, the COP when DSM is used is 5% lower than it could be with a similar level of thermal comfort.

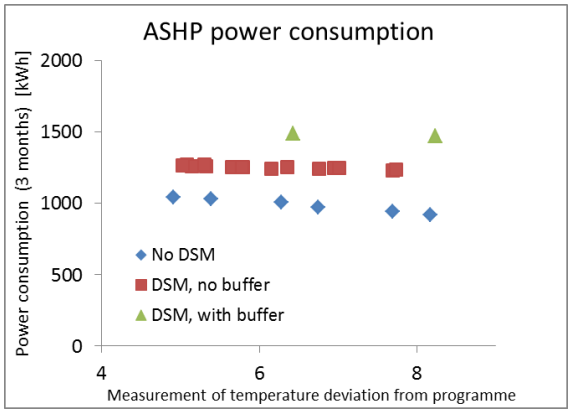

Figure 8: ASHP power consumption

This effect is more marked if the total power consumption (rather than performance) of the units is considered, Figure 8. Reductions in

power consumption in the order of 20% to 25% are possible compared to the same thermal comfort with DSM intervention.

The electrical efficiency of the SE-mCHP unit is highly dependent upon adequate load or buffer size to reduce the number of start-stop cycles that take place. This is illustrated for units without DSM (taking averages across the building permutations) in Figure 9 for a wider range of buffer sizes.

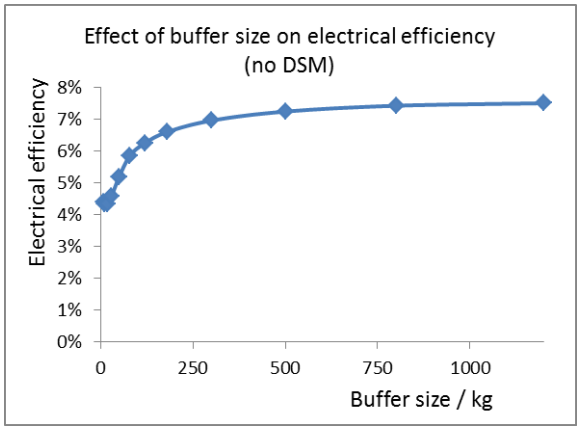

Figure 9: Effect of buffer size on SE-mCHP electrical efficiency

Because of the significance of the buffer size, the performance has been considered under a wider range of parameters. The effect of buffer size on unit fuel consumption is compared to the effect of the heating system control coefficients in Figure 10. Buffer sizes from 12kg (effectively no buffer) to 1200kg are considered for each of the levels of DSM intervention (first four data sets, almost vertical groupings). The buffer size has a clear effect on the fuel consumption of the unit but little effect on the thermal comfort within each dwelling. This is because the control system determining the heat delivered to each dwelling and this is largely independent of the buffer size. Less fuel is required as the DSM intervention is increased; this can be explained by the resulting reduction in the heating demand associated with the lower average inside air temperatures. Relaxing the control coefficients of the control systems without DSM has a similar effect of increasing the temperature deviations and reducing the fuel consumption of the units (here, this is shown for four buffer sizes). In fact the effects are not discernable from each other; the same reduction in fuel consumption associated with lower inside air temperatures occurs whether the temperature change is caused by DSM interventions or by relaxed control coefficients.

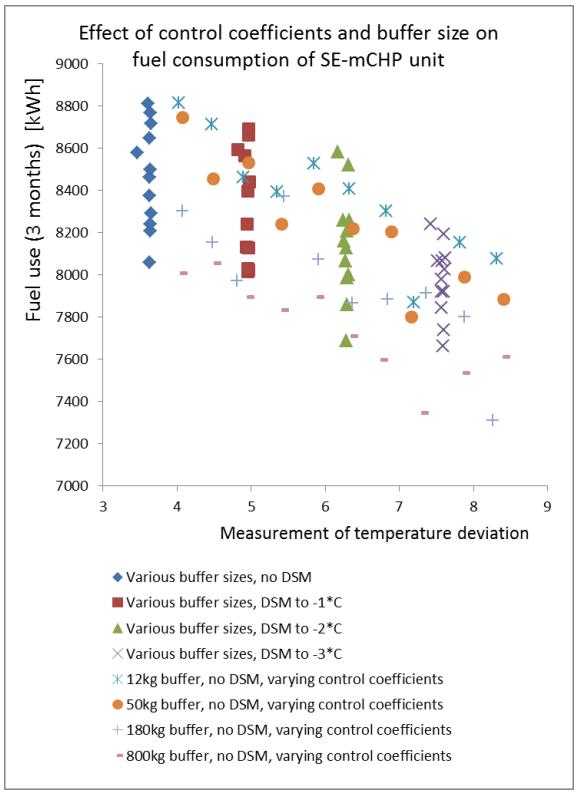

Figure 10: SE-mCHP fuel consumption

Similar but less marked relationships are observed for the electrical efficiency of the SE-mCHP units. The relationship illustrated in Figure 9 is repeated for cases with DSM intervention but with very small decreases in electrical efficiency as the intervention increases. However, the same small decreases in electrical efficiency are observed when a relaxed control system is used, implying that they are caused by the reduced run characteristics and are not specific to the DSM.

It is suggested that with a greater level of DSM intervention there is a larger set of times when mCHP operation could be interrupted (which would decrease average run-times, all things being equal). However, more heat is required to raise the inside air temperature back to its original temperature so overall there is some cancellation of this effect and average run-times are not affected as much as originally suggested

The efficiency of the ICE-mCHP units is not significantly affected by the relaxed control gains or the DSM intervention. However, less heating is required when the temperature is allowed to fall (Figure 11). A distinction can be seen between the cases with thermal buffering and those without; fuel consumption increases of around 5% result from not using a thermal buffer.

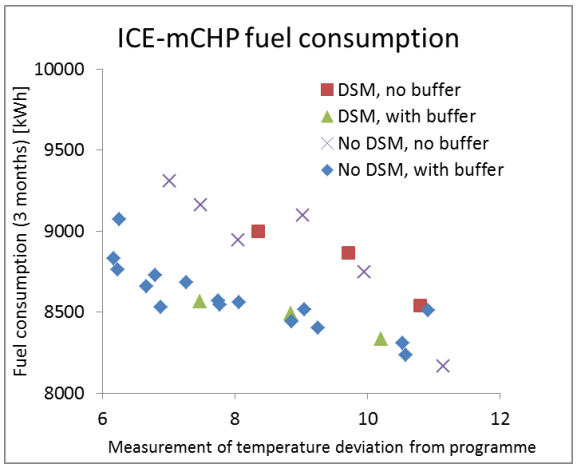

Figure 11: ICE-mCHP fuel consumption

CONCLUSIONS

A model has been created to study the performance and energy flows associated with micro-cogeneration and air source heat pumps at the neighbourhood level, with or without demand side management.

The model has been used to consider the effect of introducing demand side management on the performance of these units. It indicates that there is a performance penalty associated with the use of demand side management in conjunction with air source heat pumps. This performance penalty and the altered heat demand profile potentially result in a 10% to 25% increase in the power consumed by the heat pumps.

The effect on mCHP units with suitable thermal buffering is less significant. However, it is likely that a more extensive demand side management strategy for the heating systems would have implications. It is important that these implications are understood when assessing the relative benefits of such a scheme.

ACKNOWLEDGMENTS

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) [Grant number EP/G031681/1] as part of the SUPERGEN Highly Distributed Energy Futures (HiDEF) consortium. The authors gratefully acknowledge the interchange made possible under this programme. In particular, the help of Dr. N. Kelly and Dr. J. Hong (ESRU, University of Strathclyde) and Dr. M Thompson and Dr. I. Richardson (CREST, Loughbourgh University) in developing and calibrating the models is gratefully acknowledged. The authors are grateful to the anonymous reviewer for their helpful comments. Authors' names appear alphabetically.

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