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Impact on energy requirements and emissions of heat pumps and micro-cogenerators participating in demand side management

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Abstract

The potential impacts of participating in demand side management (DSM) on the performance of air source heat pumps (ASHP) and micro-combined heat and power (mCHP) units are considered by this study. 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 DSM systems. However, it is possible that operating regimes which are optimised for grid considerations will not achieve the maximum performance that is possible from the 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 combustion engine micro-cogenerators, a solid oxide fuel cell micro-cogenerator and two ASHPs. 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 DSM scheme analysed here is likely to have minimal impact on the emissions and energy requirements associated with each heating unit. Its effect is similar to that which occurs without DSM if the control system gain is relaxed such that equivalent thermal comfort is achieved. DSM can reduce the peak electrical demand of the neighbourhood. However, in the scenarios investigated, it is unlikely that the peaks can be reduced sufficiently such that they do not exceed the capacity of the local distribution transformer if ASHPs are used in all dwellings. By using a combination of mCHP units with ASHPs, it is possible to supply heating to all dwellings without exceeding this capacity. In this case, the use of DSM can increase the ratio of ASHPs used. In the context of a low carbon grid electricity supply, this will reduce the average carbon emissions associated with the neighbourhood.

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

Abbreviations

ASHP	Air Source Heat Pump
COP	Coefficient of Performance
DSM	Demand Side Management
ICE	Internal Combustion Engine
mCHP	micro-Combined Heat and Power
PER	(non-renewable) Primary Energy Requirement
SE	Stirling Engine
SOFC	Solid Oxide Fuel Cell

1. 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 (Cockroft and Kelly 2006; Dorer and Weber 2009; Peacock and Newborough 2005; Roselli et al. 2011). 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 (Sulka and Jenkins 2008).

DSM is the management of electrical loads to better match demand and supply; for example by adjusting or moving loads away from peak times (Strbac 2008). Some aspects of the use of mCHP and ASHP units with DSM have been explored (e.g. Peacock and Newborough 2007; Hong et al. 2012). However, both ASHP and mCHP units perform most efficiently when operated as evenly as possible. Typically, Stirling Engine mCHP (SE-mCHP) units only achieve full electrical efficiency after reaching their operating temperature, internal combustion engine mCHP (ICE-mCHP) units demonstrate some thermal lag and ASHP performance is improved when they supply heat continuously to minimise the heat distribution temperatures (Cooper et al. 2013b; Kelly and Hawkes 2013). The low ramp-rate which is currently achieved by solid oxide fuel cell mCHP (SOFC-mCHP) units, may limit their direct involvement in DSM but it is possible that their operation will have implications for the way in which other units are operated. It is important that these interactions are understood and that the potential implications for the performance of the units are explored.

For this study, the DSM considered is the interventions appropriate to maintaining the net power flows for a neighbourhood of 128 dwellings 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 use of electricity generated with a low marginal carbon emissions factor) will apply to actual implementations of future DSM systems, but they are likely to have a comparable effect (Cooper et al. 2013a).

The DSM schemes analysed here are likely to have minimal impact on the emissions and energy requirements associated with each heating unit. Their effect is similar to that which occurs without DSM if the control system gain is relaxed such that equivalent thermal comfort is achieved. DSM can reduce the peak electrical demand of the neighbourhood. However, in the scenarios investigated, it is unlikely that the peaks can be reduced sufficiently such that they do not exceed the capacity of the local distribution transformer if ASHPs are used in all dwellings. By using a combination of mCHP units with ASHPs, it is possible to supply heating to all dwellings without exceeding this capacity (Rogers et al. 2013). In this case, the use of DSM can increase the ratio of ASHPs used. In the context of a low carbon grid electricity supply, this will reduce the average carbon emissions associated with the neighbourhood.

2. Method

2.1 Scenarios investigated

To investigate the effect of this use of DSM on the performance of ASHP and mCHP units, 40 unique scenarios were simulated (with an additional seven variations on two of them) and the average performance of the units operating in them compared (see Table 1). The scenarios consist of different levels of DSM intervention and different combinations of six heating systems across the dwellings of a 128 property neighbourhood.

Table 1: Scenarios considered

DSM scheme	Heating systems in use						Notes
	ASHP A	ASHP B	Boiler	SOFC-mCHP	SE-mCHP	ICE-mCHP	
-	128						Standard semi-detached
-		128					
-			128				
-				128			
-					128		
-						128	
-	128						Improved dwellings
-		128					
-			128				
-				128			
-					128		
-						128	
A	128						
B	128						
C	128						
D	128						
E	128						
F	128						
A	128						Buffer
B	128						Buffer
C	128						Buffer
A						128	
B						128	
C						128	
D						128	
E						128	
F						128	
-	24		104				
B	40		88				
-	84			44			
A	104			24			
B	104			24			
A	96			32			
-	56				72		
A	64				64		
B	64				64		
C	64				64		
A	64				64		Buffer
B	64				64		Buffer
C	64				64		Buffer

N.B. All SOFC-mCHP units are also buffered

The six heating systems considered were two ASHP units (ASHP “A” and ASHP “B”, corresponding to state-of-the-art and mid-range ASHPs which are currently available), a SE-mCHP unit, an ICE-mCHP unit, a SOFC-mCHP unit and a condensing gas boiler for comparison. The units are described in more detail in section 2.4.

In the first set of 12 scenarios, the power flows associated with using the same heating system in every dwelling were simulated to illustrate the characteristics of the power demands and the extent of the overloading which would need to be addressed. DSM was not used. Six scenarios used neighbourhoods consisting of 128 standard semi-detached houses (with each of the six heating systems) and the other six scenarios used neighbourhoods consisting of 128 semi-detached houses with improved insulation levels and upgraded heat emitter systems. The building characteristics are given in section 2.6.

A second set of nine scenarios used ASHP A with different levels of DSM. These scenarios were used to illustrate the effect of the DSM on the performance of the ASHP units but also indicated that the capacity of the local distribution transformer would be exceeded in each case. The semi-detached houses with improved insulation and heat-emitters were used for these scenarios. Carbon dioxide (CO_2) emissions and non-renewable primary energy requirements (PER) associated with each of these scenario were calculated in the context of a future generation grid hypothesised for 2035 by the Transition Pathways project (Hammond and Pearson 2013), described in section 2.5.

A third set of six scenarios considered a similar neighbourhood but with all dwellings equipped with the ICE-mCHP unit instead of ASHP A. Different levels of DSM were used but no buffer tanks were installed.

A final set of 13 scenarios were modelled such that they would not cause the capacity of the local distribution transformer to be exceeded. Combinations of the different heating systems were used in the 128 dwellings (e.g. 64

dwellings with ASHP A and 64 dwellings with SE-mCHP units).

As the DSM schemes employed in this study resulted in some reductions in inside air temperature, achieving a fair comparison required that a metric for thermal comfort was recorded for each scenario. An additional fourteen simulations were performed, modelling variations of the scenarios in set two and three (i.e. with all dwellings were supplied by either ASHP A or the ICE-mCHP), without DSM but with relaxed control systems such that equivalent levels of thermal comfort were achieved.

2.2 Overview of modelling approach

A modelling approach with finite time-steps of one minute was taken for this study. In order to model the effect of the DSM on the performance of the ASHP and mCHP units, it was 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 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 the total power demand must 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 by Cooper et al. (2012); (2013b). A fuller description of the modelling assumptions and parameters is provided by Cooper (2013). Although the authors are not aware of any similar integrated model, models of many of the individual elements have been published by other researchers and these were used wherever possible.

Each simulation covered a one month period (31 days) typical of the heating season. During warmer periods of the year, the interventions associated with the DSM objectives are reduced as all demands are lower and so the peak heating demands observed in winter do not occur. If DSM with alternative objectives (e.g. increasing the temporal coincidence of wind generation and heat pump operation) were adopted then it would be appropriate to include simulations representative of other seasons in which there is potentially more flexibility available to the DSM system. However, the objective considered here (reducing the peak net electrical demand of the neighbourhood) relates primarily to the extreme case and so it is unlikely that this DSM system would have a discernible effect in other seasons.

2.3 Control systems

Four diurnal temperature programmes were used, with a quarter of dwellings using each programme (Fig. 1). A random delay of up to one hour was applied to the programme for each dwelling, to ensure a reasonable level of diversity between them.

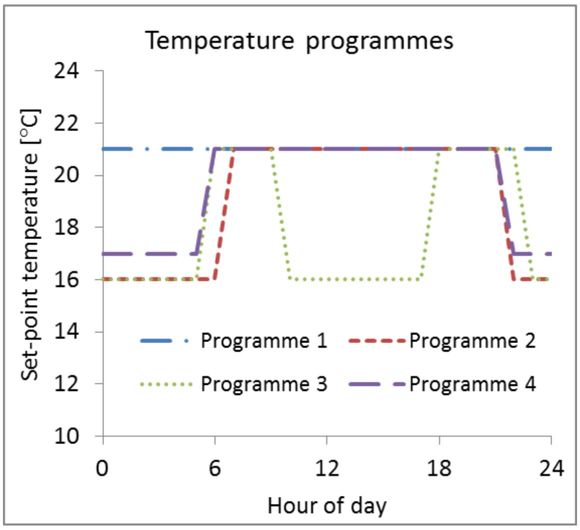

Fig 1: Temperature programmes

Indirect DSM control was assumed. That is, for each time-step, a signal was generated which represents the extent to which the DSM control system is attempting to influence net power flows. The control system for each ASHP and mCHP unit took 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.

It was assumed that the control system of each heating unit adjusts the set-point temperature it is aiming for as a function of the DSM control signal. DSM schemes with different levels of responsiveness were characterised by the maximum adjustment from the programme temperature which was permitted with them. Within each scenario, it was assumed that all residents in the neighbourhood would accept the same level of DSM intervention. This simplification was adopted on a pragmatic basis in order to make the effect of increasing the level of DSM intervention clear. The temperature ranges assumed for each scheme are given in Table 2.

Table 2: Temperature deviations used by DSM systems

DSM scheme	Maximum temperature increase [°C]	Maximum temperature decrease [°C]
A	+2	-2
B	+1	-3
C	+0	-3
D	+0	-2
E	+1	-2
F	+1	-1

Each of the heating system which was considered is capable of modulating its heat output between an upper and lower limit (see Tables 3 and 4). In the cases where a thermal buffer was not used, the control algorithm for these units requested heat generation proportional to the temperature difference between the DSM-adjusted set-point temperature and the inside air temperature. For the cases where a thermal buffer was used, heat was supplied to the building's heat emitters based on an on-off function representing a thermostat with a 2°C dead-band. Similar control algorithms were used to maintain the buffer tank temperature at 55°C, adjusted in the same way by the DSM signal.

Because of the SOFC-mCHP unit's low ramp-rate, a different control approach was used. The unit was limited to operate within a narrow band near its maximum electrical efficiency and an auxiliary gas boiler was used to supply any additional heat demand, following the same algorithm as the other systems. As such, the SOFC-mCHP systems did not respond to the DSM signal.

In order to control for the variation in internal temperature which may result from the different DSM interventions, a pseudo- Predicted Mean Vote (a standardised measure of thermal comfort, defined by ISO (2005)) was calculated for each dwelling, each time-step and the average of the negative values (i.e. corresponding to cool temperatures) was calculated. The term "pseudo-predicted mean vote" is used as the calculation method was simplified by assuming a fixed relationship between air temperature and effective radiant temperature; the metric will provide a relative measurement which is consistent between scenarios but will not necessarily represent the exact predicted mean vote which would be experienced.

Fourteen additional simulations were performed in order to provide comparisons which considered this metric of thermal comfort. Seven of these simulations were performed with all dwellings using ASHP A and seven with all dwellings using the ICE-mCHP. In each case, DSM was not used but the gain coefficient for the proportional control system was progressively reduced from 95% to 65% of its original value. In this way, the effect of reduced thermal comfort on the heating demands and impacts could be assessed, enabling a fairer comparison of the extent to which the effects of DSM schemes were inherent to the schemes or a result of the reduction in internal air temperature which might have occurred.

2.4 Heating systems

The heating system models use a "two-lumped capacitances model", similar to that suggested by Kelly et al. (2008), see Fig. 2. Beausoleil-Morrison et al. (2007) provide sufficient data to approximate the characteristic parameters for the

ICE-mCHP unit considered here. Data from Lipp (2012) and Magri et al. (2012) was used to estimate parameters for the SE-mCHP unit. Performance data for the SOFC-mCHP unit was taken from Payne et al. (2009). The corresponding parameters for the ASHP unit were estimated from the physical characteristics of the device and the performance of similar devices detailed by Mitsubishi Electric Europe (2008). More detail on the characteristics of the units is provided by Cooper (2013). The nominal steady state efficiencies of the units are provided in Tables 3 and 4. A fixed efficiency of 90% (to higher heating value) was assumed for the gas boiler.

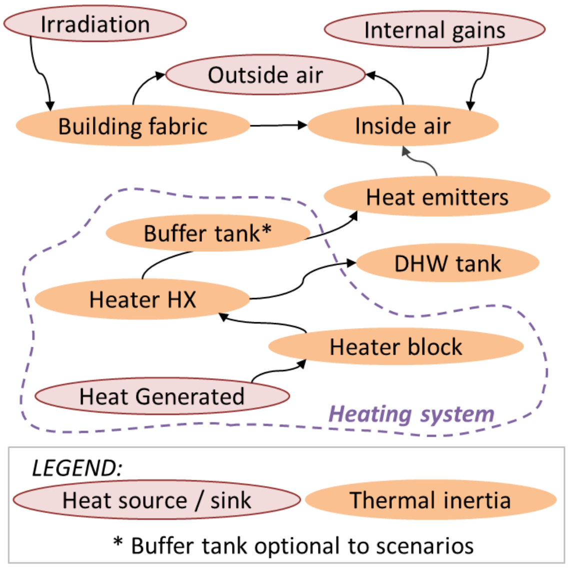

Fig. 2: Thermal model

Table 3: mCHP unit characteristics. Data from Beausoleil-Morrison et al. 2007; Magri et al. 2012; Payne et al. 2009

	Electrical efficiency [%]	Thermal efficiency [%]	Maximum electrical output [kW]	Minimum electrical output [kW]
SOFC-mCHP	54	21	1.5*	1.5*
SE-mCHP	12	80	0.15	0.9
ICE-mCHP	21	61	4.3	1.0

Efficiencies relative to higher heating value of fuel
*restriction imposed in this study, unit is capable of greater range

Table 4: ASHP unit characteristics. Data from Butler and Hyde 2007; Mitsubishi Electric Europe 2008; Warmepumpen-Testzentrum 2013.

	Coefficient of Performance	Maximum thermal output [kW]	Minimum thermal output [kW]
ASHP A	4.2	10	2.0*
ASHP B	3.0	8.5	2.5

Data relates to standard (“A2/W35”) test conditions.
*Estimate.

The steady-state thermal and electrical efficiencies of the mCHP units vary with their output and so they were calculated by linear interpolation between the nearest test output conditions. The coefficients of performance (COPs) of ASHP units is a function of the temperatures of the heat source and heat sink which are used. These were calculated for the ASHPs by using the weighted average of their exergy efficiencies at the nearest test conditions, calculated using data from Warmepumpen-Testzentrum (2013) and Butler and Hyde (2007). The heat which is actually generated by each heating unit depended upon its maximum and minimum heat generation limits as well as the demand from the control algorithm.

2.5 Electrical grid

The CREST domestic lighting and appliance model created by Richardson et al. (2008) was used to model the power demands from lighting and appliance use in the dwellings. It was assumed that each dwelling had three residents. Power demands associated with electric showers and electric storage heating were excluded. The demand profile generated by the CREST model changes each time it 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 a typical 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.

The impacts of the operation of the heating systems (emissions and energy requirements) are assessed in the context of a future electrical grid as it is hoped that this will be more representative of the period in which such DSM systems may be employed. The “Transition Pathways, Market Rules 2035” context was selected. Hammond and Pearson (2013) and associated works discuss the development of the pathways in more detail but this particular context consists of approximately a quarter of electricity supplied by gas power stations with slightly smaller proportions supplied by wind, nuclear, other renewables, and coal, respectively. Mean carbon emissions and primary energy factors of 97g_{CO2e}/kWh and 2.02kWh/kWh apply. For the results of the present study, it is these factors rather than the details of how they are achieved which is pertinent.

It should be noted that a context with a relatively clean, efficient grid was selected for the present study in order to provide a relatively uncomplicated case in which emissions can be reduced by using DSM to maximise the proportion of dwellings using heat pumps. This enables the study to consider any additional potential performance penalty which this might then incur. The specific results (in terms of carbon emissions and PER) are clearly sensitive to the assumed context but the study will provide insights into the performance implications of DSM systems that are not.

2.6 Buildings

As the simulation approach taken required a thermal model for each of these buildings to be run simultaneously, the thermal models were 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 Fig. 2. This is similar to the approach taken by Sulka and Jenkins (2008) and by Ramallo-González et al. (2013). Its use is justified on the basis that the key result of interest to this study is the relative effect on the performance of the heating units rather than an exact value for the heat demand associated with the dwellings (which is highly sensitive to other assumptions such as occupant behaviour, irrespective of the modelling approach adopted). A semi-detached house, typical of the UK housing stock, has been modelled in detail using ESP-r by Dr. N. Kelly and Dr. J. Hong of ESRU, University of Strathclyde and the temperature profiles which were generated were used to calibrate the parameters of the simplified model, resulting in a good fit between the temperature profiles (root mean square air temperature difference of less than 0.5°C). In the case of the “improved insulation” house, the air infiltration rate was halved and the effective heat transfer rate from the outer skin reduced by 40%.

Heat emitters were sized such that flow temperatures of 50°C or 35°C were required (in the case of standard or enhanced heat emitters, respectively) to balance the heat losses when the outside temperature is -1°C. Buoyancy-driven convection was assumed for the heat transfer from the heat emitters to the inside air (Incropera and DeWitt 1985).

Test reference year climate data for London Heathrow, generated by Eames et al. (2010) was used to supply outside air temperature and solar radiation data Occupant gains were calculated using CREST active occupancy model (Richardson et al. 2008), assuming 147W for active occupants and 84W for dormant occupants, equivalent to 1.4 met and 0.8 met respectively (see ISO 2005). Domestic hot water requirements were distributed according to the active occupancy, scaled to match daily consumption figures provided by the Energy Saving Trust (2008). Heat was transferred to a hot water tank in parallel with the space heating system; when the hot water tank temperature dropped outside tolerance, heat transfer to the space heating was suspended so that the temperature of the heating unit's heat exchanger could rise.

3. Results & Discussion

3.1 Effect of unconstrained systems on electrical demands

This sub-section considers the 12 scenarios in which all houses in a neighbourhood are fitted with the same type of heating systems in order to illustrate the challenges which may be faced without the use of DSM. Fig. 3 and 4 summarise the net power flows if all of the dwellings in the neighbourhood are standard semi-detached houses. The results relate to the month of January.

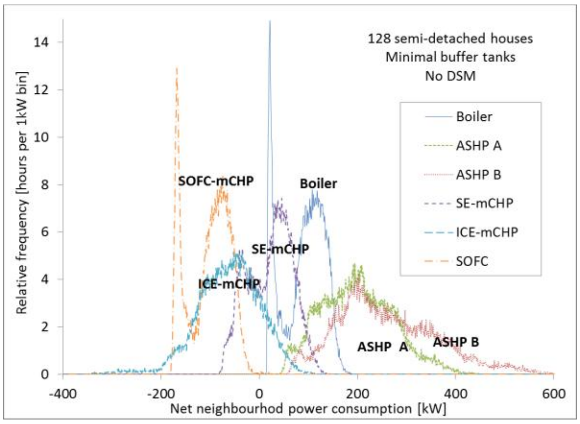

Fig. 3: Occurrence of power flows

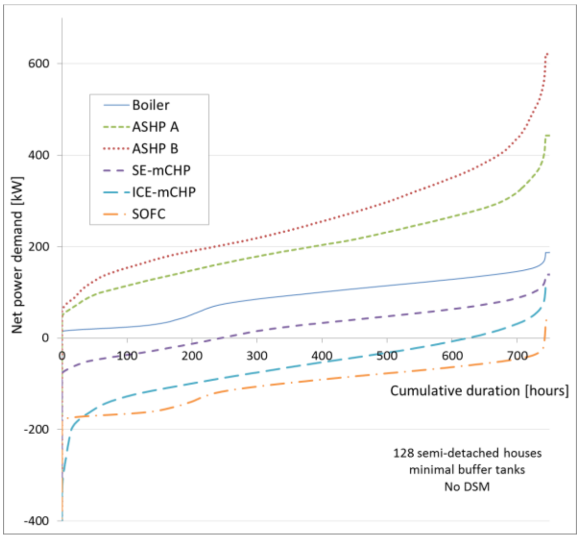

Fig. 4: Cumulative demand curves for neighbourhood

In the case of gas boilers, the data is effectively the same as the appliance consumption for that period. There is a high occurrence of demands around 20kW, corresponding to periods such as the night when active occupancy is low. A second distribution with a modal average at around 110kW corresponds to periods of active occupancy and exhibits a peak power demand of around 190kW. In the neighbourhoods with ASHPs, net electrical demand is significantly increased and the extended periods of low demand disappear. Using the more efficient ASHP "A" results in demands which exceed 200kW for around half of the month and which peak at around 440kW under these conditions. Using the less efficient, ASHP "B" increases the peak demand to over 600kW and results in demand which exceeds 200kW for around 65% of the month. By using the SE-mCHP units, the neighbourhood is likely to export electricity for around 30% of the month with peak net exports approaching 100kW and peak net imports reduced to around 140kW. Using the ICE-mCHP units increases electrical generation resulting in higher exports but also a proportionally larger range of power flows. Peak net imports are not decreased significantly relative to the case with SE-mCHP units (to around 110kW) but peak net exports are increased to over 300kW. Electricity is exported for around 85% of the month. Because the SOFC units are operated continuously, generating around 1.5kW each, the net demand profile for this neighbourhood is similar to that for the neighbourhood with gas boilers but with net demand decreased by around 190kW; the neighbourhood is exporting electricity for almost all of the month but peak exports do not exceed 190kW.

Improving the insulation and heat emitter systems of the houses reduces the effect of most of the heating systems on the net electrical flows associated with the neighbourhood (Fig. 5). The electrical demands of the boiler and SOFC systems are not affected because of the low electrical demands of the gas boilers and the constant operation of the SOFC systems. The total electrical consumption and peak demands associated with the neighbourhoods with ASHPs are significantly reduced but still significantly exceed 200kW for 15% or 40% of the month and peaking at 320kW or 400kW (for ASHP A or ASHP B, respectively). Exports of up to 50kW occur for around 15% of the month when the SE-mCHP units are used. Using the ICE-mCHP units still results in electrical exports for around half of the month. Although these exceed 50kW for only 15% of the month, the peak exports still exceed 250kW.

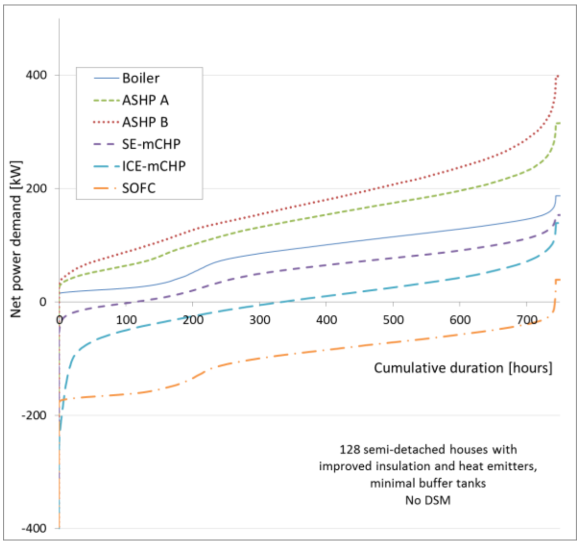

Fig. 5: Cumulative demand curves with improved dwellings

3.2 Performance of ASHPs with DSM

Fig. 6 shows the net demand duration curves for neighbourhoods with improved housing, heated in each case by ASHP A. In each case, the maximum net power demand exceeds 200kW.

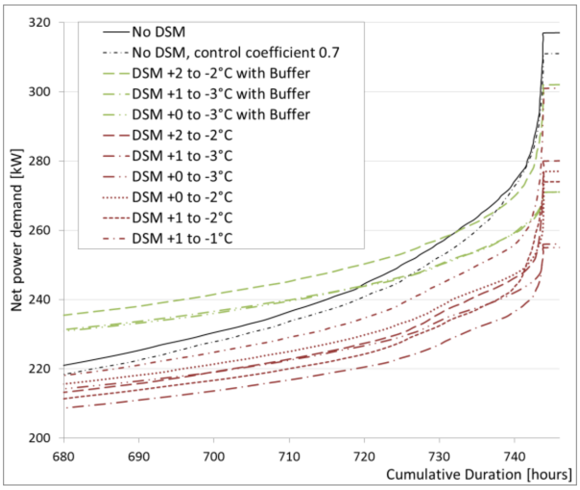

Fig. 6: Cumulative demand curves for ASHP A scenarios

Data is only shown for the 3840 minutes (64 hours) of the month during which net imports were greatest. The plot for the system in which DSM is not used is the same as that for ASHP A in Fig. 5. Although the simulated DSM scheme reduced the peak demand by up to 60kW, this still resulted in a peak demand of almost 260kW. It was not possible to reduce peak demand below 200kW. The three scenarios in which buffer tanks were used with variable-temperature (i.e. “weather compensated”) control tended to exhibit higher overall electrical consumption but similar peak demands due to the flexibility achieved through the use of the buffer tanks. Relaxing the control coefficient to 70% of its nominal value, without using DSM, resulted in a minimal reduction in the peak electrical demand despite the relative thermal comfort being slightly lower than in the scenarios using DSM (Fig 7).

The average CO_2 emissions and PER incurred by ASHPs in the scenarios without buffer tanks are shown in Fig. 7. A reduction in CO_2 emissions and PER can be associated with a slight reduction in the average inside air temperature and thermal comfort which occurs. However, the effect on all of these parameters is small and comparable to that observed when the control coefficients for the heating systems are relaxed without any DSM intervention. Although the change in the thermal comfort appears relatively large (an increase of over 50% between the extremes), the absolute values are likely to be small and so show the DSM scheme having only minimal impacts in terms of both thermal comfort and the performance of the ASHPs.

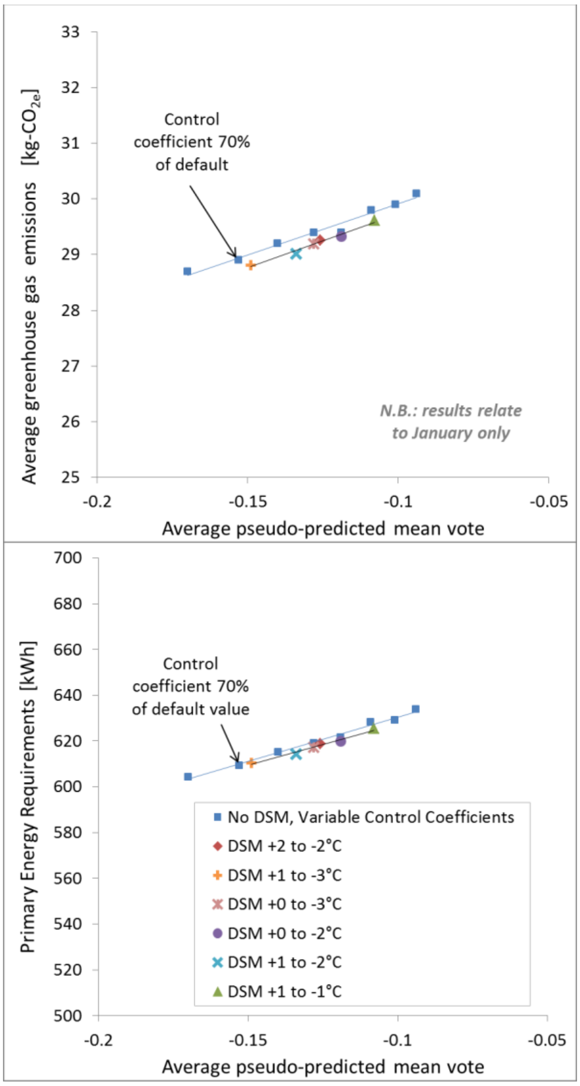

Fig. 7: Performance of ASHPs

Within these scenarios, the DSM schemes were designed to be conservative and, as such, did not increase the inside air temperature of the dwellings during periods of high electrical demand in order to increase the flexibility available to them when the electrical demands were even higher. Preliminary simulations with less conservative systems indicated that some reduction in peak demand could probably be achieved (perhaps to 250kW under the conditions considered), but with a significant impact on overall energy demand. It is possible that optimisation of such a system could improve its performance but this is considered to be beyond the scope of the present study.

It appears that the effect on emissions and energy requirements should not be considered a barrier to the use of DSM under these circumstances. However, additional measures would be required in order to ensure that the peak power demands of the ASHPs do not cause the local distribution infrastructure to be overloaded.

3.3 Performance of ICE-mCHP units with DSM

If the ICE-mCHP units are deployed across the neighbourhood then the large peak export power flows present a challenge. The neighbourhood is likely to export electricity for around a half of the month if DSM is not used; with exports peaking at more than 250kW. However, it is possible to limit the peak net power export to less than 200kW by using DSM (Fig. 8).

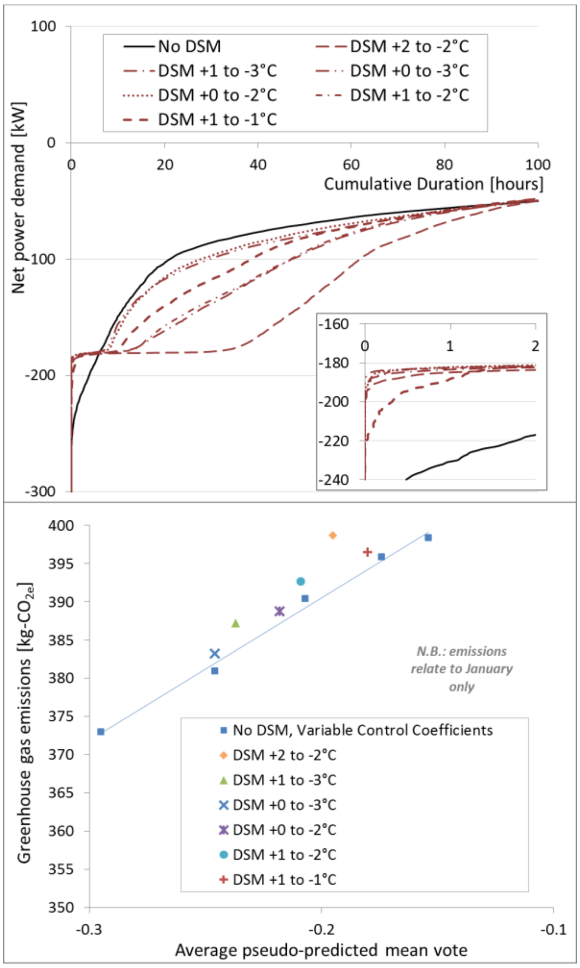

Fig. 8: Performance of ICE-mCHP units

For most of the month, the net electrical demands of the neighbourhoods do not result in any DSM intervention and so the demand curves associated with the different scenarios are similar. Because of this, the curves at the top of

Fig. 8 are drawn for only the 6000 minutes (100 hours) in which significant electrical exports occur. For the majority of the periods shown, the DSM schemes result in an increase in generation from the ICE-mCHP units; larger net exports are observed. This is due to two factors. Firstly, the systems need to restore the dwelling inside air temperatures after periods in which generation has been discouraged; this effect increases slightly as the maximum temperature fall available to the DSM systems increases (compare the central plots for DSM systems B, E and F). Secondly, it is due to the DSM schemes slightly increasing the inside air temperature of the dwellings when net power exports increase in an attempt to increase the flexibility available to them when even higher net exports are encountered. This effect increases as the maximum temperature lift available to the DSM systems increases. It can be most clearly observed for DSM scheme A (with a maximum temperature lift of +2°C available to it, see Table 2).

The effect of the DSM schemes discouraging generation from the ICE-mCHP units can be clearly observed in the demand curves when net exports exceed 180kW. However, the inset detail shows that there are around 60 minutes in the month in which the net exports are larger. DSM scheme F (maximum temperature drop of only -1°C) is not able to completely prevent the net exports from exceeding 200kW.

Comparing Fig. 7 with Fig. 8 reveals that the DSM systems appear to have a greater effect on the thermal comfort in the buildings when used with the ICE-mCHP units rather than with the ASHPs. To some extent this is due to the mismatching of the large mCHP units to the dwellings resulting in an increase in the time for which operation is constrained. It is therefore possible that the effect of the DSM systems on thermal comfort would be more comparable to that in the other scenarios if the operating conditions where changed. In both cases, the estimated drop in thermal comfort is small.

A small performance penalty is observed, associated with the use of this DSM scheme with the ICE-mCHP unit (illustrated here as an increase in CO_2 emissions). However, it is likely that other factors such as installation conditions will be far more significant in determining the overall performance of the units. It is also likely that the emissions increase could be eliminated if the times at which the mCHP units increase the inside air temperature were optimising to only occur before predicted periods of peak power exports.

3.4 Combinations of ASHPs with boilers, SE-mCHP units and SOFC-mCHP units

By combining a mixture of ASHP units with boilers, SE-mCHP units or SOFC-mCHP units it is possible to supply heating to the dwellings in a neighbourhood without the peak electrical demand of the neighbourhood exceeding 200kW. This sub-section considers the influence of DSM on the performance of thirteen possible combinations.

Fig. 9 presents the results of combining ASHP units with either SOFC-mCHP units or boilers. The slopes of the demand duration curves increase significantly in the hours with the highest demands; in each simulation there are short periods in which the net demand is relatively much higher as usually diverse demands coincide. This effect is reduced by the DSM systems, allowing a greater set of demands to be supplied but does not eliminate it completely. The ratio of units was selected such that the peak electrical demand in each case is around 200kW. As the power demands which occur in actual neighbourhoods are highly dependent on a range of uncontrolled variables, the ratios used here should only be treated as illustrative of the ratios of units which might be appropriate, such that the effect of the DSM system can be studied. The sharp rise in power demand observed for short periods also indicates that the results would be sensitive to lower temporal resolutions being employed; averaged heating demands are unsuitable for this kind of study.

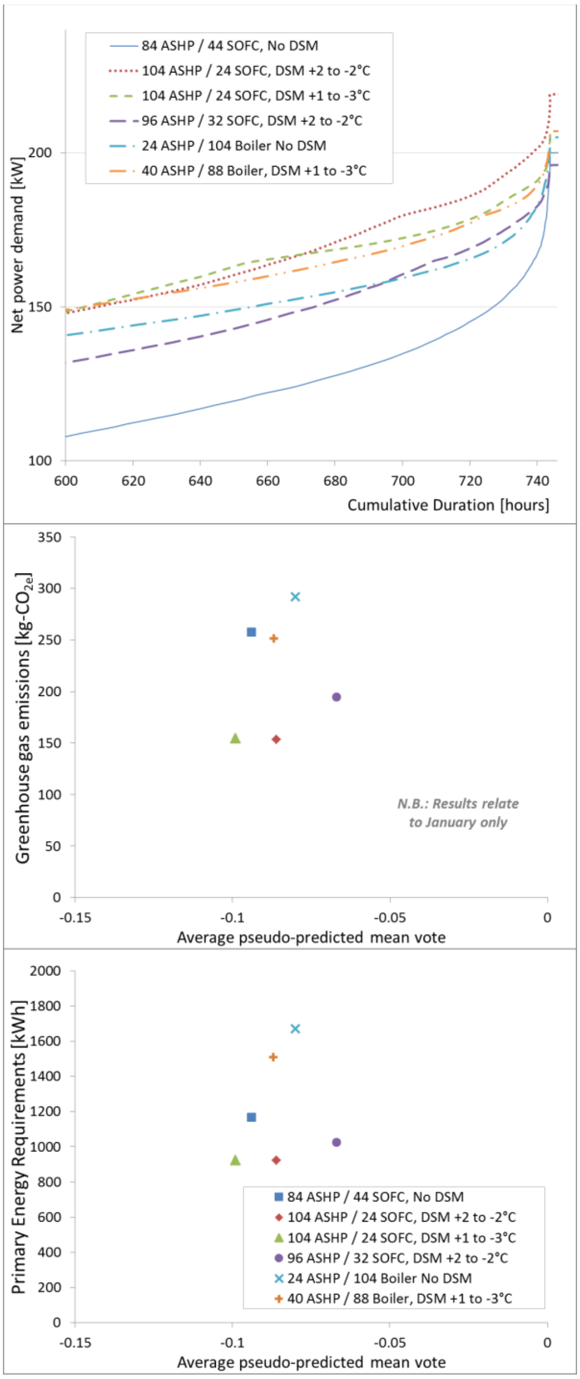

Fig. 9: Performance of SOFC-mCHP systems

There is no direct impact of the DSM signal on the performance of the SOFC-mCHP units as rapidly varying the output of the SOFC unit is inappropriate from a technical perspective. However, the application of DSM enables a higher proportion of ASHP units to be deployed. Because the context considered here (i.e. the "Transition Pathways, Market Rules 2035" scenario) has a relatively low carbon emissions factor and primary energy ratio, increasing the proportion of dwellings using ASHPs causes a significant reduction in the CO_2 emissions and PER. If the heating were to occur in a context with higher impacts associated with electrical consumption, then the benefit of increasing the number of heat pumps would decrease but this does illustrate that, under appropriate conditions, the DSM system could enable a reduction in CO_2 emissions and PER.

The results relating to the two scenarios with 104 ASHPs and 24 SOFC-mCHP units but different levels of DSM illustrate that there is a potential trade-off between the average level of thermal comfort and the peak electrical demand which is experienced. However, the differences observed under the conditions considered here are rather small.

Similar results are obtained when the ASHP units are combined with SE-mCHP units (see Fig. 10) but the ratio of ASHP units which can be achieved without exceeding 200kW peak demand is reduced. This increases the impacts associated with the heating systems of the neighbourhood. Different levels of DSM intervention have a relatively small effect on the emissions except in as much as they facilitate a higher ratio of ASHP units to be deployed in the neighbourhood.

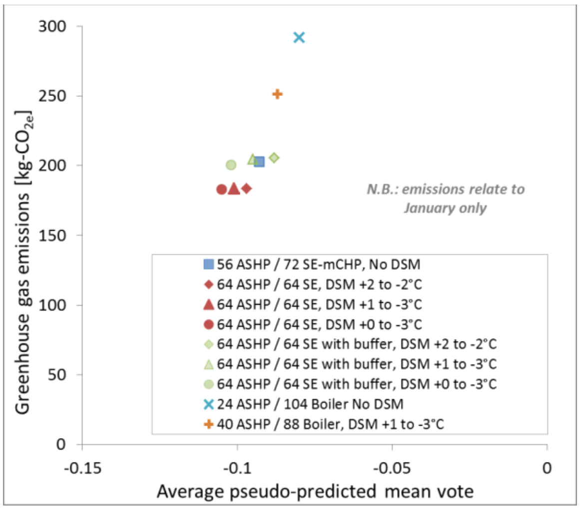

Fig. 10: Performance of SE-mCHP units

4. Concluding remarks

A model has been created to study the performance and energy flows associated with mCHP units and ASHPs at the neighbourhood level, with or without DSM.

The DSM scheme analysed here is likely to have a small impact on the emissions and energy requirements associated with each heating unit. Its effect is similar to that which occurs without DSM if the control system gain is relaxed such that equivalent thermal comfort is achieved. The effect of the DSM schemes was minimal for most of the simulations and so they had only a small impact on thermal comfort in the dwellings. However, a conservative approach in this respect is advisable as consumers may resort to additional (potentially inefficient) sources of heat in response to any inadequacies in the provision of their main system.

DSM can reduce the peak electrical demand of the neighbourhood. However, in the scenarios investigated, it is unlikely that the peaks can be reduced sufficiently such that they do not exceed the capacity of the local distribution transformer if ASHPs are used in all dwellings.

By using a combination of mCHP units with ASHPs, it is possible to supply heating to all dwellings without exceeding this capacity. In this case, the use of DSM can increase the ratio of ASHPs used. In the context of a low carbon grid electricity supply, this will reduce the average carbon emissions associated with the neighbourhood.

It is possible that DSM schemes with alternative objectives may be adopted and these may have different effects. Additionally, if the DSM objectives do not correspond entirely to peak demands, their effect may be more apparent in other seasons. Although the effect of DSM on the performance of individual units has been shown to be minimal under the conditions of this study, it does have system impacts and it is important that the full implications of its use are understood when assessing its relative merits.

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