USE OF MICRO CHP PLANTS TO SUPPORT THE LOCAL OPERATION OF ELECTRIC HEAT PUMPS

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ABSTRACT

There is a common assumption that to decarbonise the heat market in the UK a large number of households will need to switch from fossil fuel heating to heating with low carbon electricity. Electric heat pumps are the most energy efficient way of using electricity for space heating so it would appear logical to promote their use. Domestic electricity demand is highly stochastic and distribution supply transformers are sized to take advantage of load aggregation. This results in the transformers having capabilities between 1.4 and 9.8 KW per house depending on the number of houses connected to a specific transformer. Heat pumps are typically rated 3 to 6 kW and operate at a steady load for appreciable lengths of time. Consequently they should not be considered as stochastic loads. If these are installed in a high proportion of houses that previously used gas heating there is a real possibility that the local supply transformer would be overloaded. One alternative to replacing the transformers is to provide local generation. An obvious candidate for this is local combined heat and power units (CHP) as these are likely to be required to run at the same times of the year as the heat pumps. This paper examines the running characteristics of the two heating systems and looks at the running restrictions that would be required to produce complementary operation. The reduction in CO_2 emissions of the resulting network will be compared with those produced by a similar sized network of houses using condensing boilers.

Keywords: heat pumps, micro CHP, distribution transformer loading, limiting net local load

INTRODUCTION

Domestic heat pumps typically use 3 to 6 kW of electricity. In many cases this is more than the capacity per property of the 11 kV/415 V distribution transformer supplying them. Consequently the wide spread introduction of them would have consequences for the distribution system.

Micro combined heat and power units (μCHP) feed power into the 415 V system and hence reduce the load on the distribution transformer. In the early morning it is likely that the μCHP units will be running but the total domestic load on the transformer will be low; on these occasions they will export power through the transformer. This should not matter providing:

- the export does not thermally overload the transformer,
- the transformer is not fitted with an automatic tap changer,
- the transformer is not fitted with directional over-current
- there is sufficient load on the local 11 kV system to absorb the generation

.

There could also be power quality issues and a need for power factor correction with some equipment.

The possible synergy between heat pumps and μCHP system was discussed by Hawkes [1]. As both heat pumps and μCHP units will be operating to supply heat demands in the same neighborhood it is tempting to think that there must be a ratio of μCHP units to heat pumps where the CHP units power the heat pumps. At one level this would appear a trivial calculation, however the running characteristics of the two technologies are different and the energy consumption of similar properties can vary considerably [2]. Consequently it is necessary to model the heat demands for a range of properties with different heating systems to see if they can operate together and avoid overloading the local supply transformer. It was decided to consider a mixed housing development of 128 dwellings, supplied by a 200 kVA transformer. This is slightly less than the maximum number of houses that could be fed from the transformer as it was felt that in a real installation spare capacity would be allowed to supply future infill development.

BACKGROUND

Nature of domestic electricity demand

Domestic electricity demand is made up of a number of steady loads like lighting and consumer electronics and a number of high short duration loads that result from the use of domestic appliances. For distribution systems the extent of these peaks can be estimated using the Velander Formula [3]

$$P = k_1 W + k_2 \sqrt{W} \quad (1)$$

Where
P is the peak load in kW
W the annual consumption in MWh,
k1 and *k2* are empirical constants

For domestic consumers k_1 is 0.29 and k_2 is 2.5. For a typical domestic consumer who uses 4 MWh a^{-1} this would give a peak load of 6.2 kW compared to a 24 h average load of 0.46 kW. The Velander Formula was developed for sizing transformers and cables that feed groups of similar consumers rather than for individual households. Newborough [4] carried out a detail monitoring program of 30 households and found that the peak recorded power varied between 0.6 and 15 kW although most were between 4 and 7 kW (which is consistent with the Velander formula) with daily load factors of 8 - 15%.

Distribution transformers are required to supply the peak power demand for the properties connected to them, but as the individual peaks are only for a few minutes it is unlikely that they will occur at the same time in a group of houses. In practice the maximum coincidental load that is seen on a system is known as the maximum diversified demand. This is frequently normalized by the number of households to produce the "After Diversity Maximum Demand" (ADMD).

The ADMD was measured by Richardson [5] for 22 house and the results are reproduced in Table 1 together with the value of ADMD used by Central Networks a major distribution company taken from their "Network Design Manual" [6] for houses with mains gas. Distribution transformers come in a number of standard sizes Central Networks predominantly use 200, 315 and 500 kVA transformers which can feed a maximum of 136, 219 and 351 houses respectively. At this level of load aggregation the load is no longer considered to be stochastic so the ADMD is only applicable to the 415 V system.

Table 1: ADMD for a number of houses

Number of houses	Reported	Central Network
1	11	9.8
3	6	4.2
6	4	2.8
11	3	2.16
22	2	1.78

Emission benefits of using heat pumps

Heat pumps are thermal engines that take heat from a low temperature source and deliver it to a high temperature sink. They require energy to do this. The ratio of the energy they use to the energy they deliver is called the coefficient of performance (COP). For them to achieve a reduction in emissions the emissions associated with the electricity they use must be less than those associated with the heating system they replace. i.e. they must satisfy the following condition:

$$\frac{(heatout)(CI_E)}{(COP)} < \frac{heatout}{\eta_T}(CI_T)$$

$$COP > \frac{\eta_T(CI_E)}{(CI_T)} \quad (2)$$

where

heatout is the thermal output of the heating system,
η_T is the primary energy efficiency of the heating system around 85% for a condensing boiler.
CI_E is the carbon intensity of the grid
CI_T is the carbon intensity of the heating system

The grid uses a mixture of coal, gas, nuclear and renewable energy power stations. If the grid is considered as a whole it had an average carbon intensity (CI_E) of around 0.6 $kgCO_{2e}$/kWh for the years 2000 - 2009 [6]. The carbon intensity of natural gas is 0.20 $kgCO_{2e}$/kWh [7]. This means that a heat pump with a COP>2.6

will produce a carbon saving when compared to a gas fired condensing boiler.

There are plans to decommission 17 GW of obsolete power plant by 2015. This is largely being replaced by gas fire plant and wind turbines. Consequently it is reasonable to expect that the grid carbon intensity is likely to fall further so heat pumps can make a real contribution to decarbonising the heat market.

The COP is a function of the amount of work that the heat pump has to do to raise the working fluid to the sink temperature. It follows that the lower the sink temperature the higher the COP. The sink temperature is the temperature of the heating system in the building. In order to optimise the COP it is desirable to keep this as low as possible consistent with supplying the heat demand for the building. This can be achieved by running the heat pump all of the time and modulating its output temperature, as such they are not stochastic loads.

Emission benefits from using micro CHP

The use of waste heat from power stations for district heating is an obvious way of reducing emissions. At a large city scale scheme heat can be extracted from a steam cycle (which will reduce the cycle efficiency of the electricity generation). But at a community or individual house level waste heat can be recovered from a reciprocating gas engine. The amount of useful heat delivered to the consumer will depend on the percentage of waste heat recovered from the engine and the losses in the heat distribution system between the engine and the customer. For a gas fired CHP scheme to have an emission benefit it must use less gas than would be used to supply the same amount of electricity and heat generated separately by a combined cycle gas turbine (CCGT) power station and local gas condensing boiler. If:

- G_{CCGT} is the gas used by the CCGT,
- G_b is the gas used by the condensing boiler, G_{CHP} is the gas used by the CHP unit,
- $Power$ is the electricity generated by the CHP unit,
- η_{echp} the electrical efficiency of the CHP unit , η_{eccgt} the electrical LHV efficiency of the CCGT power plant electricity by an average gas fire CCGT typically 48% (after transmission and distribution loss) ,
- Q the useful heat supplied by the CHP unit, η_T,
- The heating efficiency of the condensing boiler typically 83%,
- rr the waste heat recovery ratio and,
- D_{loss} the fraction of heat lost from the distribution network.

$$Saving = \frac{(G_{CCGT}+G_b-G_{CHP})}{(G_{CCGT}+G_b)} \qquad (3)$$

where

$$G_{CHP} = \frac{Power}{\eta_{echp}} \qquad (4)$$

$$G_{CCGT} = \frac{Power}{\eta_{eccgt}} \qquad (5)$$

$$G_b = \frac{Q}{\eta_T} \qquad (6)$$

$$Q = rr(1-D_{loss})(1-\eta_{echp})G_{CHP} \qquad (7)$$

The savings for a range of CHP plant electrical efficiencies for installations with different levels of heat recovery and distribution losses are shown in Figure 1.

It is noticeable that the effect of higher distribution losses and lower heat recovery is more significant for lower efficiency CHP engines. This simply reflects the relatively higher heat outputs of these engines when compared with the engines with higher electrical generation efficiency.

As a general rule larger engines are more efficient but they need bigger heat loads which in suburban areas mean that they need bigger heat distributions networks which will have higher losses. µCHP engines tend to be less efficient but have low distribution losses as they only supply a few buildings; consequently they can achieve similar fuel savings to larger schemes.

µCHP have the added advantage in that they are simpler to implement than district heating schemes and could use existing consumer utility interfaces. µCHP systems either use Stirling Engines or internal combustion (IC) engines.

Stirling engines only produce electricity when they are up to temperature; IC engines only produce useful heat once they are up to temperature so it is normally advised that both of these technologies are used with thermal stores [2,9-11] to avoid short runs. Consequently they can be considered as constant generators.

METHOD

Technologies compared

To investigate the potential synergies in the operation of Air Source Heat Pumps (ASHP) and µCHP units, various combinations of them have been simulated for a three month period (92 days) covering the heating season, recording parameters such as the peak net power demand. It was decided to look at mixed installations of the following equipment:

- ASHP: Heliotherm HP10L - a commercially available high performance air source heat pump rated as 10.3 kW thermal and 2.34 kW electrical load.
- SE µCHP: Whispergen mk5 - a Stirling Engine micro CHP unit designed for use by a single household rated at 7 kW thermal and 1 kW electrical output.
- Small thermal output IC µCHP: Ecopower - an IC engine that can run with fixed or modulating output that is designed for use by a single household. 3.8-11.4 kW thermal 2-4.7 kW electrical output
- Large thermal output IC µCHP: Senertec Dachs - a fixed output IC engine for use in large houses or with multiple households. These were installed on the basis of two households sharing one engine. 12 kW thermal 5 kW electrical.

This was considered to cover the variety of µCHP technology that is commercially available. The units considered had all been studied under the Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme [11] who have published their performance characteristics.

A ground source heat pump was not included as it is likely to have a similar operating characteristic to an air source one.

Although fuel cell µCHP systems offer the potential for improved performance when compared to gas engines [1] they are not yet competitive economically and so have not been considered in this study. However they may be an interesting option for replanting µCHP installations as the gas engines wear out.

A benchmark run of ASHP and boilers was also conducted to see how many could be supplied by the existing transformer.

Overall modelling approach

A modelling approach with finite time-steps of one minute has been taken for this study. In order to model the transient power flows associated with the operation of the heating units and other electrical demands, it is necessary to have sufficiently detailed models of the units, the conditions they will operate in and the additional electrical demands which need to be satisfied. Because of the significance of diversity in this context, it would not be sufficient to take average load profiles and multiply them by the number of dwellings to derive the total electrical demand profiles.

A model was constructed with these interactions being considered, a development of that used previously [13, 14]. 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.

Heating systems

The four heating systems take the "two-lumped capacitances model" suggested by IEA ECBCS Annex 42 [14], see the heating system diagram in Figure 2**Error! Reference source not found.**. The group's final report [12] contains values for the thermal characteristics of the SE µCHP unit and large IC µCHP unit and sufficient data to infer their values for the small IC µCHP unit. The corresponding values for the ASHP unit have been estimated from the physical characteristics of the device and the performance of similar devices. These will not be as accurate but given the modulating nature of the ASHP unit's operation, its overall performance is relatively insensitive to them.

The nominal steady-state thermal efficiencies of the units (relative to higher heating value of fuel, gross of thermal losses inherent to unit) are provided in Table 2. The electrical efficiency of the SE µCHP unit varies as a function of its engine temperature. The Small IC µCHP unit is capable of continuously varying its output but its electrical efficiency varies by about 4%. So it was decided to run this unit at the load where its efficiency is highest.

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 [15].

Table 2: Steady state nominal unit performance.

UNIT	**COP**	
ASHP	4.20	
UNIT	ELECTRICAL EFFICIENCY	THERMAL EFFICIENCY
SE-µCHP	8.4%	87%
Small ICE-µCHP	22.3%	61%
Large ICE-µCHP	24.3%	63%

Control of heating systems

Three heating system configurations were considered to reflect the different operating modes of the heat sources:

1. Indirect - the boilers and mCHP units are run on an on / off basis to heat a thermal buffer tank (300 kg water, increased to 600 kg water for large ICE-μCHP unit) at 55°C (with a deadband of +/-5°C). The radiator system is run on an on / off basis to heat the dwelling.
2. Direct - The modulating ASHP unit feeds the radiator system directly and have their output temperatures modulated by a proportional controller to reduce the temperature difference between the room and a 20°C set point.
3. Indirect ASHP – the ASHP is operated with the 300 kg thermal buffer tank but maintaining it at a temperature determined by the outside air temperature, this effectively de-rates the system on warmer days.

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.

A constant programme room temperature of 20°C was used in all the scenarios simulated apart from one in which the programme temperature was set-back to 16°C between 22:00 and 06:00

Domestic Hot Water (DHW) demands are assumed to follow the pattern of active occupancy, scaled to match estimates of daily consumption [17]. 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 considered for this study. 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) as illustrated by Figure 2.

The neighbourhood is assumed to consist of four building types:

- 64 semi-detached houses half of which have improved insulation all of which have 4 occupants,
- 32 terrace houses with 3 occupants,
- 32 flats with 2 occupants.

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 [18] and data from these models has been used to calibrate the parameters of the simplified models used in this study. This calibration resulted in a RMS temperature difference of less than 0.5°C between the model used and the established ESP-r model.

Test reference year climate data for London Heathrow has been used to supply outside air temperature and solar radiation data [19]. Occupant gains have been calculated using the CREST active occupancy model [5], assuming 60 W per active occupant and 30 W 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 [5] has been used to model the power demands from lighting and appliance use in the dwellings. 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 as these duties would be covered by the heating systems being modelled.

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 a typical January 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 selected profile had a maximum total appliance load of 202 kW and a total appliance demand of an average of 15.7 kWh / dwelling / day.(after seasonal adjustment this would correspond to 4,600 kWh a year). Example demand profiles for the appliances and lighting are shown Figure 3.

RESULTS AND DISCUSSION

It was found that if more than 16 of the 128 houses had heat pumps the transformer would suffer overload. The operation configurations of the heat pumps have a dramatic impact on their average electrical load and their peak rating as shown in Table 3. The direct configuration has a clear performance advantage for heat pumps.

Table 3: Additional Electrical system demands imposed by 16 heat pumps

Configuration	**Peak demand kW**	**Average daily winter demand kWh**	**COP**
indirect constant room T	33.8	18.9	3.16
direct	30.9	16.0	3.84
direct night-time set-back	32.9	14.1	3.95

The direct mode configurations would appear to use less power than the indirect one. This can be explained by considering the work done by the heat pump. This is a function of the heat transferred and the difference between the source and sink temperatures, an elevation of the output temperature will increase the work required from the heat pump. The indirect heating configuration has an additional heat exchanger between the heat pump and the storage tank. This will typically require the transfer fluid to be operating at 10°C higher than the tank temperature for it to work. The tank temperature set point is determined such that the water will be hot enough for the radiator system to feed the maximum credible load with the given exterior temperature. In practice there will be other sources of heat in the dwelling (solar gain, appliances and metabolic) which will provide some heating consequently even with a reduced capacity the radiator system will still be able to deliver more heat than is required. Consequently the delivery temperature of the heat pump will be considerably higher than that required to supply the net heat loss from the building. By modulating the output temperature of the heat pump such that the radiator will just supply the shortfall in the heat demand the output temperature will be lower.

This study looked at mid-winter conditions as these will induce the maximum load on the electrical system.

It is reasonable to expect that the night time set-back (reduction in set point temperature overnight) should cause a reduction in energy demand as the night time loss will be lower. However the increased flow temperature required when the heating system is raising the temperature of the dwelling up to the daytime temperature causes an increase in the peak demand.

It is possible to overload the transformer by importing or exporting electricity through it. Table 4 shows the combinations of equipment which were close to the limit of overloading the transformer along with the percentage CO_2 saved over the 128 houses when compared to a similar development using gas condensing boilers and 2009 grid electricity [7].

Table 4 maximum numbers of low carbon heating systems that can be installed

	CHP	**Boiler**	**ASHP**	**CO_2 saving**
ASHP indirect		112	16	2.6%
ASHP direct		112	16	5.7%
SE µCHP	128			-12%
SE µCHP & ASHP	48		80	6.1%
Small IC µCHP	40	84		14.4%
Small IC µCHP & ASHP	48		80	38.6%
Large IC µCHP	28	72		19.9%
Large IC µCHP & ASHP	24		80	38.1%

The performance of the 128 SE µCHP units needs some explanation. The µCHP systems are being compared with condensing boilers. As none of the µCHP engines were fitted with condensing heat exchangers they will have much higher exhaust gas heat loss than the condensing boilers. This inherent disadvantage is offset by the emissions saved resulting from lower imports of grid electricity to. Stirling Engines do not generate electricity until they are up to temperature so their electrical efficiency in operation can be considerable lower than the steady state value [2]. This means that they may not be able to generate sufficient electricity to overcome their inherent disadvantage when compared to condensing boilers. The situation can be improved by increasing the size of the thermal store to reduce the number of starts on the engine [9].

Given the relatively poor performance of the Stirling Engine µCHP and the ASHP operating in indirect mode it was decided to exclude them from further consideration.

From the equipment rating one may expect to need one large IC µCHP units for 2 ASHPs. Table 4 shows that this simple calculation would result in an oversupply of CHP engines. One possible reason for this can be seen in Figure 4. It would appear that the peak heat pump demand lags the peak appliance demand consequently in practice the transformer has more usable spare capacity than would be implied from the peak load data.

The CO_2 savings in Table 4 have been calculated using the carbon intensity for the grid in 2009. Figure 4 shows the savings using the following different grid carbon intensities:

- low carbon 200 $kgCO_2/MWh$
- gas based 432 $kgCO_2/MWh$
- 2009 average 594 $kgCO_2/MWh$
- 1990 average 858 $kgCO_2/MWh$

Figure 4 highlights some interesting points:

The carbon savings of ASHP increase with decreasing carbon intensity but the transformer limitations means that this will have limited impact on the emissions of the whole group of households.

The µCHP boiler combination give high savings if the grid intensity is high but becomes a liability as the grid is decarbonised.

The difference in carbon savings between the large and small IC µCHP units is the result of the difference in their electrical output. The total electrical output of the large units is more than the demand imposed by the heat pumps where the total generation of the small units is less than the total heat pump demand. The higher electrical production will give a higher carbon saving with a high carbon grid but becomes a liability if the grid becomes decarbonised.

Combinations of ASHP and CHP produce the highest emission savings even with a low carbon grid.

CONCLUSION

The rating of existing distribution transformers will restrict the number of heat pumps or µCHP that can be installed on the UK electricity system.

The operating mode of heat pumps effect the peak demand they impose on the system and hence the number that can be supplied by a single transformer.

The optimum mode is for the heat pump to supply the heat distribution system without using a buffer tank with the outlet temperature modulated using proportional control to keep a steady room temperature.

Heat pumps have the potential to produce CO_2 savings but only if the grid carbon intensity continues to fall. Gas fired µCHP systems have potential to save CO_2 emissions but only if the grid uses a reasonable amount of coal.

Combinations of heat pumps and internal combustion based µCHP engines can remove the constraint imposed by the existing transformer rating.

Combinations of heat pumps and internal combustion based µCHP engines produce appreciable CO_2 savings with a high or low carbon grid without the need to upgrade the grid transformers.

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NOMENCLATURE

CI_E	carbon intensity of the electricity grid
CI_T	is the carbon intensity of the heating system
D_{loss}	fraction of heat lost from the distribution network
G_b	gas used by the condensing boiler,
G_{CCGT}	gas used by the CCGT,
G_{CHP}	gas used by the CHP unit,
P	peak load in kW
$Power$	electricity generated by the CHP unit,
Q	useful heat supplied by the CHP unit,
$k1$ and $k2$	empirical constants
W	annual consumption in MWh

η_{eccgt} electrical LHV efficiency of the CCGT

η_{echp} electrical LHV efficiency of the CHP unit

η_T primary LHV energy efficiency of the heating system,

rr waste heat recovery ratio,

REFERENCES

[1] Hawkes A D,Brett D J L, and Brandon N P, Role of fuel cell based micro-cogeneration in low carbon heating, Proc. IMechE Vol. 225 Part A: J. Power and Energy, 2011

[2] Carbon Trust, Micro-CHP Accelerator Interim report November, 2007, Carbon Trust report CTC726,2007

[3] E. Lakervi, E.J. Holmes, Electrical distribution network design, 2nd Edition, IEE Power Engineering Series 21, Peter Peregrinus ltd ISBN 0 86341 308 0, 2003.

[4] M. Newborough,P. Augood, Demand-side management opportunities for the UK domestic sector, IEE Proceedings of Generation Transmission and Distribution 146 (3) (1999) 283–293.

[5] I. Richardson , M. Thomson , D. Infield, C Clifford, Domestic electricity use: A high-resolution energy demand model. Energy and Buildings ,42 (10), p1878-1887, 2010

[6] T Haggi, Network Design Manual v7.7, Central Network, downloaded from www.eon-uk.com/downloads/Network-Design-Mannual.pdf, 2006.

[7] AEA,2011 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. 2011downloaded from http://www.defra.gov.uk/environment/economy/business-efficiency/reporting

[8] Whispergen Tech ltd, Whispergen Mk 5 System design manual, Part No. WP-5037-025-00 UK, 2006

[9] Haeseldonckx D, Peeters L, Helsen L, D'haeseleer W, The impact of thermal storage on the operational behavior of residential CHP facilities and the overall CO2 emissions, Renewable and Sustainable Energy Reviews 11(2007),1227–1243,

[10] Beyer D, Kelly, Nick N, Modeling the behavior of domestic micro-cogeneration under different operating regimes and with variable thermal buffering. In: Micro-Cogen 2008,1st International Conference on Micro-Cogeneration Technologies and Applications, 29 April -01 May 2008, Ottawa, Canada. available from http://eprints.cdlr.strath.ac.uk/6416/

[11] SenerTec, Instructions for Installation, assembly, commissioning and assembly of Dachs, Art No 07/4798.232.102

[12] I. Beausoleil-Morrison, Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Sys- tems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007, p. 255.

[13] S. J. G. Cooper, G. P. Hammond, and M. C. McManus, "Thermodynamic efficiency of low-carbon domestic heating systems: heat pumps and micro-cogeneration," Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Oct. 2012.

[14] S. J. G. Cooper, J. Dowsett, G. P. Hammond, M. C. Mcmanus, and J. G. Rogers, "Performance implications of heat pumps participating in demand side management," in Proceedings of SDEWES 2012, Ohrid, Macedonia, 1 - 7 July 2012, 2012.

[15] N. J. Kelly, J. A. Clarke, A. Ferguson, and G. M. Burt, "Developing and testing a generic micro-combined heat and power model for simulations of dwellings and highly distributed power systems," Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 222, no. 7, pp. 685–695, Nov. 2008.

[16] Warmepumpen-Testzentrum, 2010. Air to water heat pump at A7/W35-25, Development of COP. Interstaatliche Hochschule für Technik NTB, Buchs, Switzerland.

[17] The Energy Saving Trust, Measurement of domestic hot water consumption in Dwellings, 2008 available from

http://www.decc.gov.uk/publications

[18] J. Hong, C. Johnstone, N. J. Kelly, M. C. McManus, and C. N. Jardine, "Identifying characteristic building types for use in the modelling of highly distributed power systems performance." 2010.

[19] M. Eames, T. Kershaw, and D. Coley, "On the creation of future probabilistic design weather years from UKCP09," Building Services Engineering Research and Technology, Oct. 2010

FIGURES

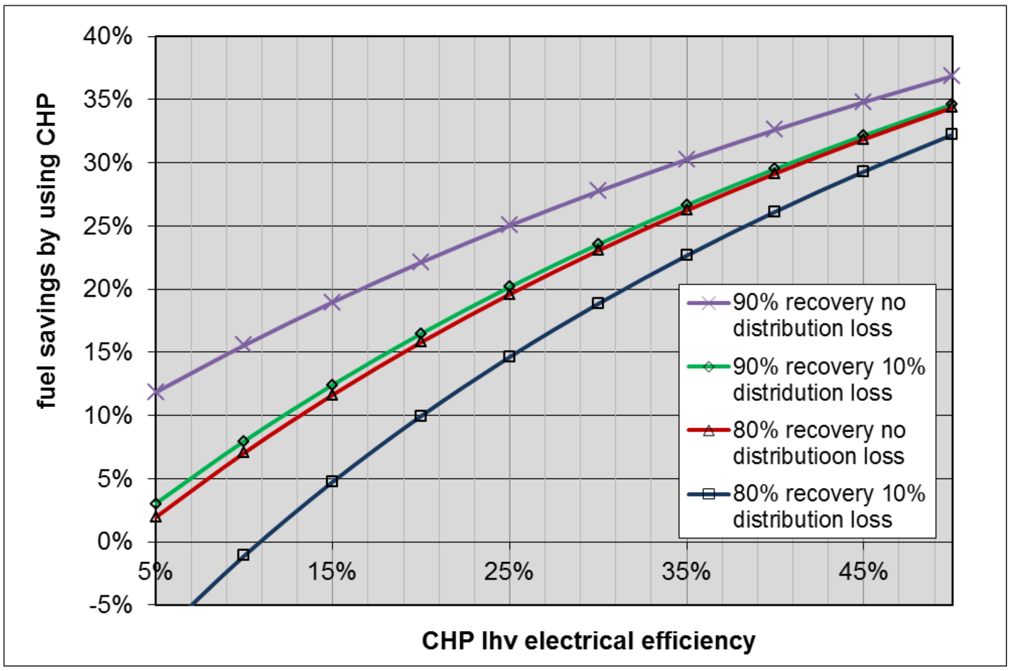

Figure 1: Potential fuel saving for gas CHP plant

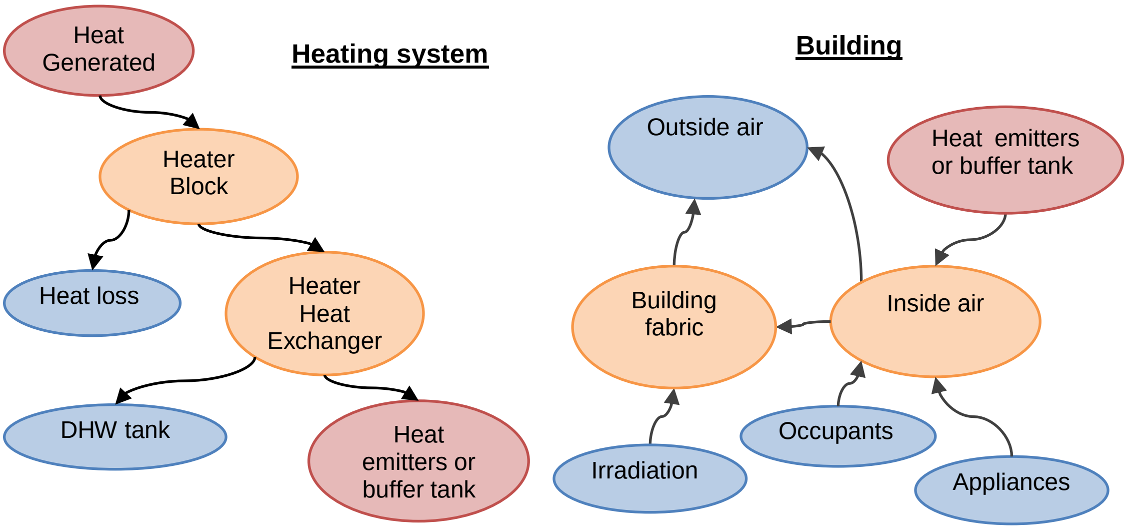

Figure 2: thermal model diagrams

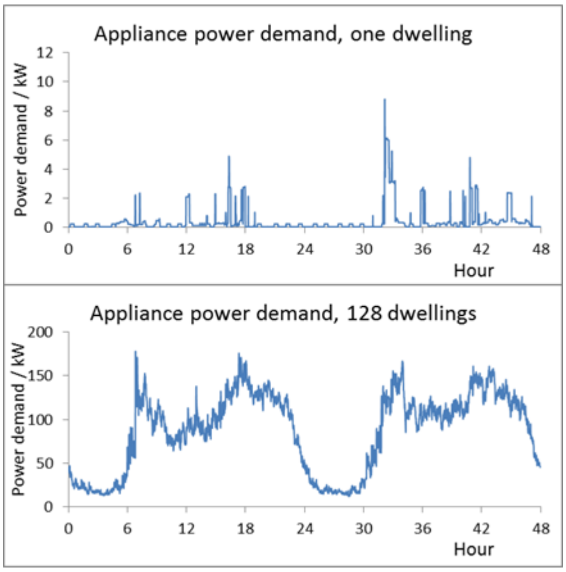

Figure 3: Examples of appliance and lighting demand profiles

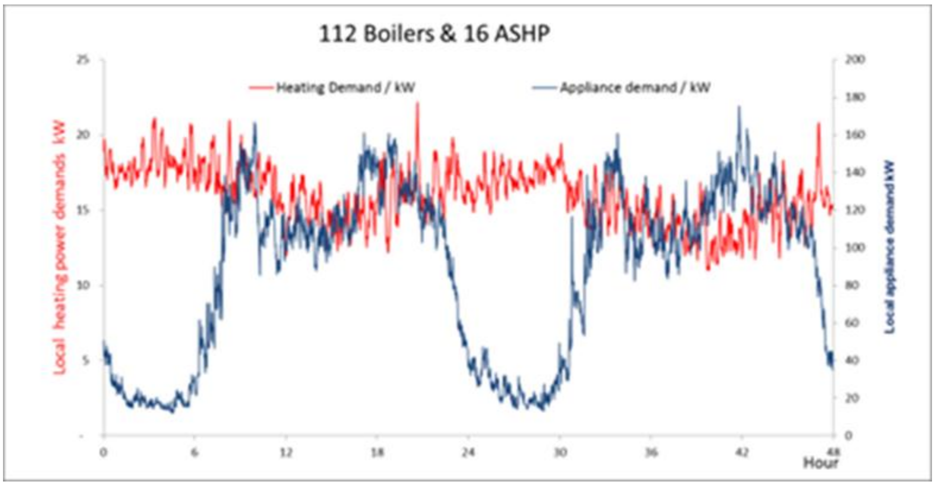

Figure 4: ASHP and appliances electrical loads

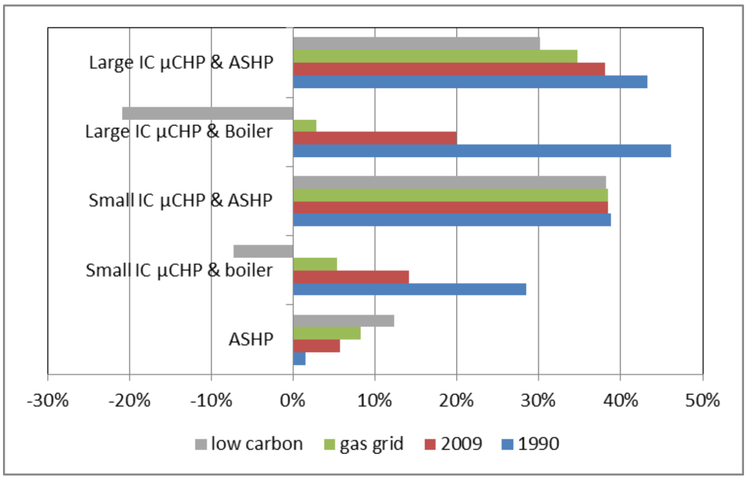

Figure 5: CO_2 savings for different electricity grid carbon intensities