ELECTRICAL LOAD CHARACTERISTICS OF DOMESTIC HEAT PUMPS AND SCOPE FOR DEMAND SIDE MANAGEMENT

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ABSTRACT

Domestic heat pumps are a key part of the UK Government's decarbonisation strategy and are expected to form a substantial part of national electrical demand by 2050. This paper reports on the practical performance and electrical load characteristics of a group of ten heat pumps over an annual cycle. The variation of electrical load with ambient temperature and domestic hot water usage is explored and useful opportunities for demand side management are identified.

INTRODUCTION

Policy Background

Heat Pumps are likely to form a significant part of the UK strategy for meeting carbon emission targets, via initiatives such as the strategy for Household Energy Management [1] and the Community Energy Saving Programme [2]. Furthermore, as an eligible technology for the proposed Renewable Heat Incentive programme, uptake is likely to increase rapidly following its introduction in June 2011. The programme is expected to assist in achieving a target of 12% renewable heat by 2020, and offers fixed payments based on an estimate of the amount of renewable heat generated [3]. A rapid increase in heat pump adoption may offer opportunities for energy suppliers to improve demand-side management via tariff-setting, thermal storage or other methods, provided load profile characteristics are sufficiently well understood.

The present work has been undertaken as part of the Carbon, Control and Comfort (CCC) project. CCC is a cross-disciplinary project aimed at developing techniques for reducing carbon emissions while maintaining desired comfort levels, using action research and user-centred design approaches to assess the effects of both improved control technology and social issues surrounding control systems. Detailed monitoring of energy consumption, and other relevant parameters, of 10 IVT ground-source heat pump (GSHP) systems has taken place over a period of one full year.

Building and Heat Pump Characteristics

The monitored systems (IVT Greenline HT Plus C6s) were all retro-fitted to rurally located one- or two-bedroom bungalows, built between 1967 and 1980, and let by Harrogate Borough Council as social housing for the elderly. All the dwellings were upgraded with cavity-wall insulation, double-glazing and additional loft insulation before installation of the GSHPs during the winter of 2007-2008, almost two years before monitoring commenced.
The systems were connected to a conventional wet central heating system with radiators oversized by around 30% by comparison with normal UK practice for gas fired boiler installations. Space-heating and domestic hot water (DHW) were both supplied by the heat pump, with the assistance of a 3 or 6 kW inbuilt electric resistance heater, which is brought incrementally online only as a supplement where necessary, typically during the weekly hot water pasteurisation cycle.

Monitoring

Electrical consumption of the heat pumps was measured at 10-minute intervals, with separate measurements for the total consumption, and that of the electric cassette and the hot-side and ground-loop pumps. The resolution of all electrical measurements was 1 Wh. Heat output from the condenser was also monitored, together with heat delivered to the space-heating circuit, thus enabling calculation of Coefficients of Performance (CoPs –ratios of heat output to energy input) and annual Seasonal Performance Factors (SPF – the ratio of total heat output to total energy input over an annual period). Other parameters such as fluid temperatures, DHW usage, and dwelling temperatures and humidity levels were also monitored in order to place the heat pump performance into context and assist in the detection and resolution of any performance issues.
External conditions were monitored via a weather station with integral logger. Data from all meters and sensors was transmitted wirelessly via Eltek Gen II transmitters to loggers (Eltek Squirrel RX250) at ten minute intervals. This data was then downloaded remotely at regular intervals via GSM modem.

RESULTS

Fig 1 shows the month-by-month average performance factor of the 10 heat pump systems. The average seasonal performance factor given by

$$SPF = Q_{out}(\text{annual total}) / E_{in}(\text{annual total})$$

is also shown on this graph. All SPF values shown in Fig 1 exclude the contribution of the hot-side (distribution) pump.

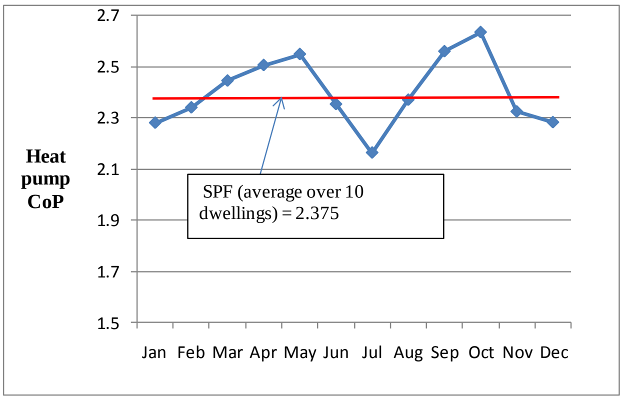

Figure 1. SPF and variation in heat pump performance by months through 2010

Four periods of 14 days each were studied in detail with respect to daily patterns of consumption. The four periods were distributed over different seasons during 2010 as follows:

1. March 18th – 31st
2. July 11th – 24th
3. October 10th – 23rd
4. December 1st – 14th

Fig 2 gives the daily average demand of the heat pumps expressed in half-hourly intervals. In all four seasons two maxima can clearly be seen, at around midnight and around 8-9 a.m. The midnight maximum is an artefact of the fact that these heat pumps operate a weekly pasteurisation cycle, using the direct electric cassette, which always takes place at midnight, (though it may be on different days of the week). The early morning maximum is more significant and can be attributed to a peak in domestic hot water (DHW) usage at this time of day (see Fig 3).

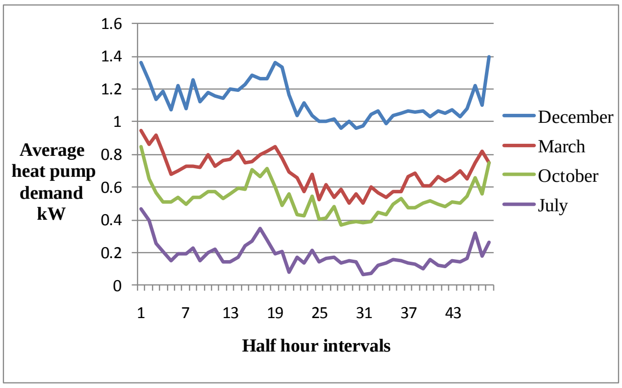

Figure 2. Daily profile of heat pump electricity demand by seasons

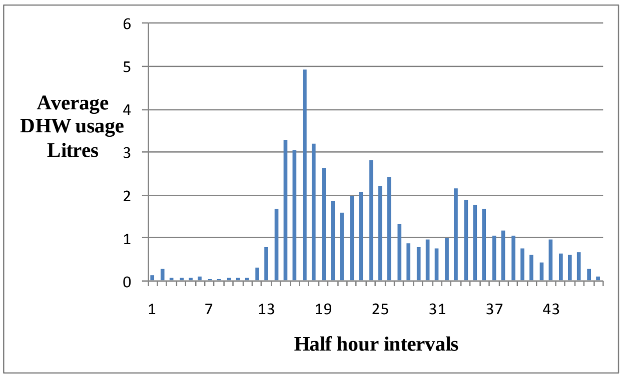

Figure 3. Distribution of domestic hot water (DHW) use

Fig 4 shows the variation in electrical consumption with external weather conditions (expressed as degree-days) for the four periods studied. In Fig 5 the whole-house electrical consumption is broken down into space-heating (heat pump), DHW (heat pump) and residual (lights, appliances and electric showers). The total consumption of the heat pump was metered, and the electricity used for DHW heating was estimated from the intercept of the kWh/degree-day plot for that period, since at zero degree-days, no additional space-heating should be required. The fact that this intercept varied considerably throughout the year was attributed to a combination of variable hot-water tank losses (most of the pump/tank systems were located in un-heated outhouses), ground-loop conditions, and possibly also some variations in usage patterns.

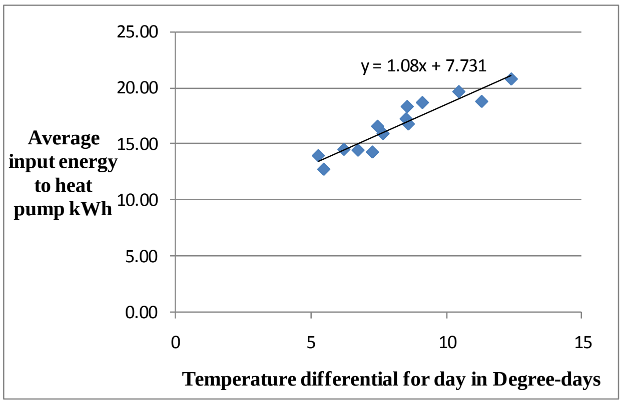

Figure 4. Dependency of daily heat pump demand on heating load for March 18-31st 2010

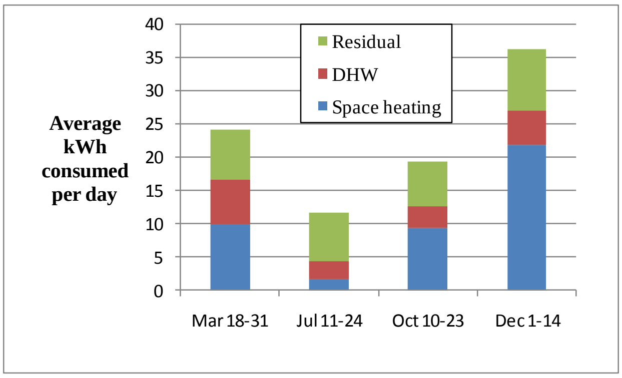

Figure 5. Seasonal breakdown of electricity consumption

PREDICTION OF HEAT PUMP DEMAND

The shape of the daily profile visible in Figure 2 is essentially driven by two factors, the external ambient temperature and the times when heating of domestic hot water (DHW) takes place. Heat pump manufacturers and installers generally recommend that space heating should operate continuously, with a control mechanism that seeks to maintain a constant room temperature by varying the temperature of the circulating water in the radiator system so that the heat transfer from the radiators to the rooms matches the losses to the external environment. This leads to an electrical load proportional to the difference between room and external ambient temperatures. The empirical relationship is linear as shown in Figure 4 despite the underlying non linearity of heat pump efficiency arising from its dependency on the Carnot Ratio.

The times when DHW heating takes place are determined partly by the usage pattern and partly by the configured policy for DHW pasteurisation. The average usage pattern for this user group in October is shown in Figure 3. The prominent peak at 08:30 results in a corresponding peak in electrical demand at 09:00. The strong correlation in DHW use is of course a function of the demographics of this user group, and a more mixed community might produce a flatter distribution and a second evening peak. In the present case the peak in electrical demand at midnight seen in Figure 1 arises from a feature of the heat pump control system that heats the storage tank to 60°C at this time once every 7 days to eliminate any risk of legionella. There is no reason in principle why this pasteurisation heating should not be performed at some other time.

The aggregate daily demand shown in Figure 2 can therefore be predicted from the function shown in Figure with a y-intercept value that varies seasonally representing the electricity demand for DHW. This has a strong dependency on ground temperature since that impacts both the temperature of the cold water input and the CoP of the heat pump. A complete model of the electrical demand for DHW is the subject of further study but a sinusoidal annual cycle of the form $demand = a + bcos\omega t$ is expected [4] where $t = 0$ occurs in late January or early February when soil temperature is at a minimum.

MANAGEMENT OF HEAT PUMP DEMAND

The increase in national electricity demand by a factor of 2.3 in the UK's decarbonisation strategy to 2050 [5] implies that the distribution infrastructure will have to be exploited as efficiently as possible. Currently about 1.5M UK homes are electrically heated using storage radiators whose demand is managed dynamically using the Economy 7 tariff scheme and the Radio Teleswitch system [6]. The migration of these homes to more efficient heat pumps will represent a loss of vital demand response capability unless an alternative scheme can be devised. The question considered here is whether heat pumps could respond to a dynamic real-time price signal delivered via the smart meter network, for example as proposed by Roscoe and Ault [7].

The heat pumps studied have a DHW storage volume of 190 litres which offers an opportunity for demand management. Their cooling rate (determined by practical measurement in an unoccupied house) is about 2.5W / °C of temperature difference between the water temperature and surroundings. For a worst case temperature difference of 40 °C this implies losses of 100W which at the reduced CoP achieved for DHW heating can be recovered with an electrical input of 50W. So the cost of heating the tank even 10 hours before the hot water is needed will be no more than 0.5kWh which is about 10% of the daily usage shown in Figure 2. As long as the user is rewarded with a tariff reduction of better than 10%, and hot water is available when needed, then there is ample scope for the electrical demand for DHW to be placed any time during the day as determined by a suitable control system.

Time shifting of space heating demand is a more challenging problem unless a buffer tank is fitted giving similar opportunities to DHW. The cost and space requirements for this make it unattractive for most homes, and it is possible to gain demand response without one because of the improved level of building insulation that normally accompanies a heat pump installation. When combined with the high thermal mass typical of UK homes the result is a very long thermal time constant. The dwellings in this study have heat loss rates as perceived in the core of the building of about 100W / °C and thermal capacity of about 7kWh / °C giving a thermal time constant of 70 hours. The effect is that it takes about 3.5 hours for room temperature to fall by 1 °C when outside temperature is 0 °C, given a starting temperature of 20 °C and no heat input.

So in principle it should be possible to maintain an acceptable room temperature through a cessation of heating of say 2 hours given a suitable starting temperature. This would allow heat pump demand to be dropped for intervals of this length, for example during the early evening demand peak which is generally the time at which electricity cost (and carbon emissions from generation by peaking plant) are highest. Conversely, it should be possible for periods when low cost electricity is available to be used to "charge" the thermal capacity of the dwelling. However, this capability will be constrained by the preferences and tolerance of the users – some do not like their heat pump to operate overnight because of the noise generated, and many prefer a cooler room temperature at night. Both of these preferences would limit exploitation of low overnight tariffs as currently offered by Economy 7.

Thus any system exploiting these opportunities must acquire information concerning the user's hot water usage patterns and thermal comfort preferences, and then determine a heat pump operating schedule that meets these requirements and is optimum with respect to the real-time pricing signal. Work on automation of domestic heating control [8] and optimisation methods [9], indicates that this capability can be realised.

SUMMARY

The default daily profile of electricity demand observed from the heat pumps represented in this study comprises a baseload proportional to the difference between room and external temperatures, overlaid with a peaky pattern related to domestic hot water production. This profile is amenable to being shaped for demand management purposes in response to a real-time electricity pricing signal by using thermal storage in the hot water tanks and in the building fabric of well-insulated dwellings with a long thermal time constant.

Acknowledgments

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