Impact of solar PV and heat pump installations on residential distribution networks.

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ABSTRACT

This paper focuses on the network impact of two key low carbon technologies being promoted by UK policy in domestic premises, namely heat pumps (HP) and photo-voltaic solar panels (PV).

These technologies present opposing challenges to the distribution network: with HPs, the additional load at times of peak demand may cause thermal and voltage limits of infrastructure to be reached; with PV there is the potential for over-voltage and 'back-feeding' when local electricity demand is low, but PV generation is high.
Using high resolution bottom up modelling, the effects of different levels of HP and PV penetration are evaluated on a representative London LV network.

INTRODUCTION

The UK's renewable heat incentive (RHI) scheme came in to effect on the 9th April 2014[1]. This scheme promotes a range of 'low carbon technologies', including HPs, for use in the residential sector. In parallel the government promotes renewable electricity generation, including PV, through the Feed in Tariff (FiT) scheme [2]. Of the 2.41GW of solar PV capacity in the UK, 70% is at domestic level.

If adopted in large numbers heat pumps will present a challenge to the distribution network, as their demand is likely to be highest when electricity demand is already high and distributions systems are already under stress. Conversely on a residential network PVs generate electricity when demand is at its lowest, with consumers often being at work or on holiday, and this presents the risk of over voltage when supply outweighs demand.

Scenario modelling

The power flow simulation data to follow was achieved using a bottom up modelling framework developed at Imperial College, London as part of a doctoral thesis [3].
In essence it uses data driven rules to activate physical models of appliances, including gas, water, and electricity demand, and heat transfer modelling. For a more detailed introduction to this refer to our 2013 CIRED paper 'Network benefits of energy efficient lighting' [4]. Before the scenarios can be simulated, baseline demand behaviour is modelled, using UK system balancing data as a target for after diversity profiles [5]. For the purpose of this paper weekdays for both winter (blue trend) and summer weekdays (red trend) are approximated.

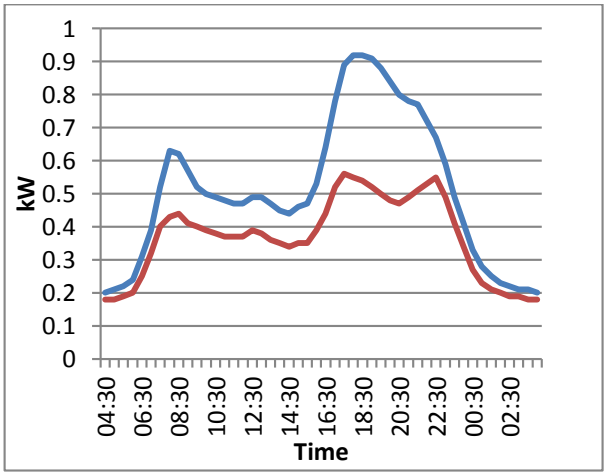

Figure 1, UK non-electrically heated average residential demand profiles for summer and winter weekdays.

The model homes and consumers are then used to populate a selected prototypical London low voltage (LV) network. The LV network under Merton substation 6601 (Love Lane) was selected due to it being connected to 339, mainly residential customers.

The network data was made available by UK Power Networks as part of the Low Carbon London (LCL) programme. Household appliance ownership characteristics used to populate the bottom up model were established through a significant household survey conducted with EDF Energy again as part of LCL.

Heat Pumps

Heat pumps provide heating services by extracting heat from an external source and typically heating water, which in turn may be used to raise internal temperatures. The efficiency of a heat pump is described by its coefficient of performance (COP), this is the amount of heat energy extracted for the electrical energy input. The heat-pump is

able to 'produce' heat through a process known as the Carnot cycle and this effect poses physical limits upon the performance a heat pump. While theoretically a heat pump can have a COP in the region of 10, in practice manufacturers of air source heat pumps claim a COP of 4-5, but these are often stated for optimal conditions.
In practice, field trials of heat pumps have reported COPs in the range of 1.2 to 3.6 [6], but these values relate to the whole system performance not just the heat pump itself.

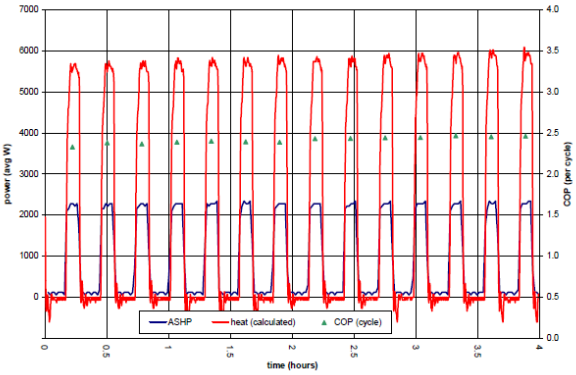

Figure 2, typical cycling behaviour of an ASHP.

Figure 2 shows the cyclic behaviour of an air source heat pump (ASHP) under relatively favourable outdoor temperature conditions [7]. In this example we see the relationship between input power (blue) and heat transferred (red). What this charts does not show is that the COP performance drops with lower outside temperatures, or more accurately, with an increase in the differential between the source and output temperatures (for example radiators).
Figure 3 gives an example of the relationship between source temperature and COP for ASHP feeder radiators at 50 degrees. This shows a significant reduction in performance as temperatures drop. The resulting effect of this is that at lower temperatures the HP will in effect operate in steady state if it is not able to achieve the desired target room temperature.
Operating at higher COPs of around 3 and above, heat pump technology becomes competitive with a gas boiler in terms of fuel costs with electricity prices being around 3 times gas prices. In terms of carbon dioxide, at a COP of 3, heat pumps have roughly the same emissions of a modern condensing gas boiler, with grid electricity giving 0.45 Kg/kWh compared to gas at 0.184Kg/kWh [8].

With the additional benefit of the FiT, in economic terms, the heat pumps become an attractive alternative to the gas boiler. However there are a range of issues associated with heat-pump deployment that are distinct from gas heating systems.

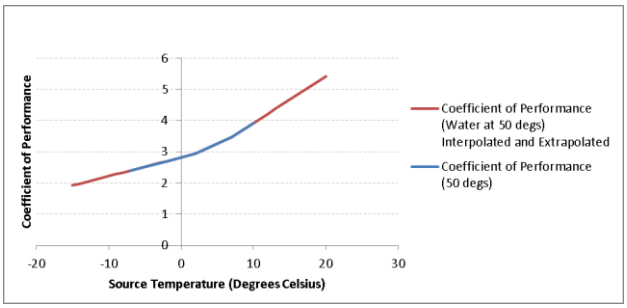

Figure 3, heat pump efficiency versus temperature differential [9]

From the householder's perspective, there is a limit to how much heat energy a given heat pump can produce and as the COP diminishes with external temperature, they may not achieve desired temperatures in poorly insulated homes on a cold day. In this situation, there will be coincidence of such loads as thermostat cycling ceases to operate.
From the DNOs perspective this is problematic since, firstly decreasing diversity will lead to increased load, but in extremis there may be additional use of auxiliary heating such as fan heaters exacerbating system stress.
The following analysis examines the likely impact of varying heat pump penetration levels upon a typical London residential distribution network. The selected network is simulated with different levels of heat pump penetration and under different weather scenarios.

Heat-pump modelling

In order to understand the effects of heat pumps on an LV network there are a number of parameters that need to be established: weather data is required to provide realistic outside temperatures; target temperatures are required for the residence to be modelled; typical home insulation values; heat pump power; and heat pump COP behaviour.

Whilst all of these parameters could be varied and sensitivities established, there is a need to manage the number of simulation executions.

Firstly for the weather data, a single day temperature profile was modified to produce four separate temperature profiles. A 'high' temperature profile reflects the last 10 years winter average temperatures at 6.7 degrees. Three additional profiles are then produced from this to model more demanding weather conditions, at 4, 0 and -4 degrees centigrade.
DECC reports average internal temperatures, over the last 10 years the average is 17.9 [10]. In the simulation houses are seeded with a value between 16.9 and 18.9. Whilst in practice some houses will use timers to modulate the internal temperature, this was deemed problematic to model in the absence of data about heating timer usage.
Home energy loss values are estimated by DECC in terms of watts per centigrade of temperature differential. To model energy demand at the national level then a single

figure could be used. In a model with individually modelled homes we require some heterogeneity to avoid homes exhibiting the same behaviour. To this end, a heat loss parameter is randomised to be between 250 and 350 W/°C.

As described earlier heat pumps have varying efficiency depending on source and output temperature differentials. In the simulations to follow a universal heat pump is modelled with a COP calculated to be 8.0 minus 0.1 for every degree of source output temperature differential. This provides an approximate linear fit to the relationship seen in Figure 3.

Solar PV modelling

In practice solar panels will differ in their orientation and hence the profile of their power output, and this will in a sense provide some diversity to the PV generation for a given feeder. Whilst this is perhaps worth considering in more detail, there are also natural effects such as clouds which on typical British days will contribute to both a reduction of output as well as peaks and troughs in output. To understand the effects of these peaks and troughs in insolation would require significant simulation time. However given that the DNO is interested primarily in work case conditions, for the purposes of this paper the output profile for all panels in the model is a scaled up version of a real panel output profile from a clear day (near to a half sinusoid). This is scaled up to produce a typical 3.6kW maximum system output.

RESULTS

Heat pumps

Figure 4 shows Merton secondary (06601) transformer loadings for four different penetration levels: 5%, 10%, 15% and 20%, for weather scenario 1. In terms of planning, this is the weather scenario that is of most relevance. With a capacity of 500kVA and 315 consumers, Merton could just support the highest penetration of 20% of homes using heat pumps for space heating. Figure 5, showing transformer loadings for weather scenario 4 (average temperature 7°C), shows that at 20% penetration daily peak transformer loading is increased by 15% over the baseline. For 20% penetration the increase in peak load at an average outdoor temperature of -4°C is 72%: at 7°C it has fallen to a fifth of this.

Summary

For an average temperature of -4^{0}C and a penetration level of 20% of household owning heat pumps, the peak daily load increases by 72% above baseline, almost reaching the capacity of the substation transformer. As most heat pumps in the network will be working at full capacity in weather this cold, diversity will be greatly reduced. In addition heat pumps work at reduced efficiency in low temperature conditions. These two factors are responsible for the large increase in peak load. In contrast, at 7^{0}C the corresponding peak load increase is just 15%. Here diversity is increased and heat pump efficiency improved. Reducing penetration levels from 20% (to 15%, 10% and 5%), show approximately proportional reductions in peak loading increase. See Table 1 for all HP scenario results. It is also worth noting that under-voltage did not occur in any of the HP scenarios examined.

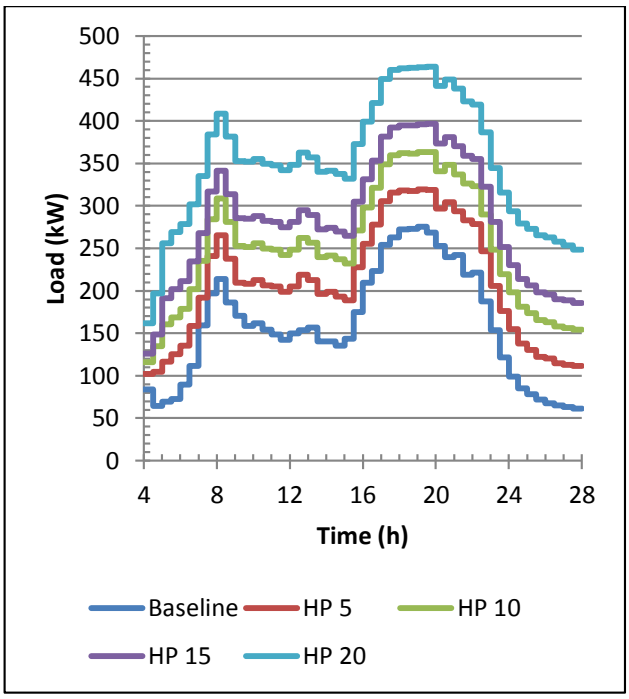

Figure 4, Transformer loading under weather scenario 1 conditions (av. temperature, -4°C).

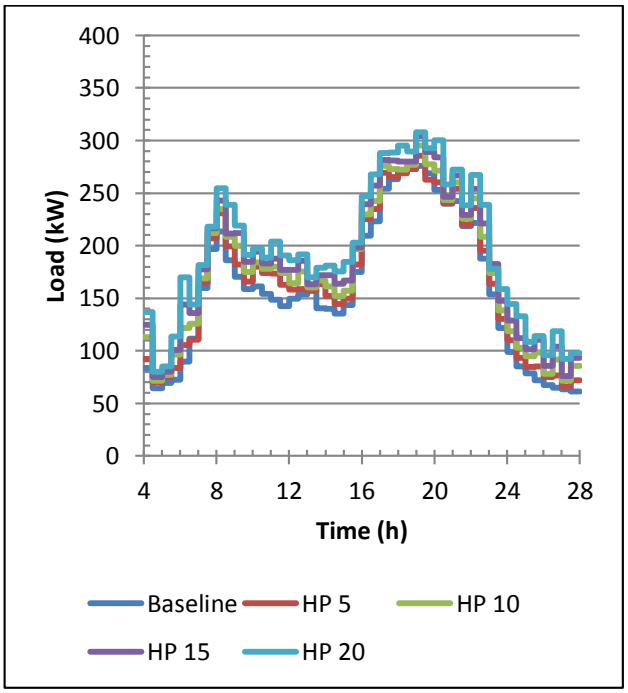

Figure 5, Transformer loading under weather scenario 4 (av. temperature 7°C).

Table 1: Heat pump scenario summary

Scen-ario	Percentage peak daily load increase over baseline at:			
	5% penetration	10% penetration	15% penetration	20% penetration
1 (-4°C ave)	19%	33%	48%	72%
2 (0°C ave)	9%	18%	32%	39%
3 (4°C ave)	9%	14%	18%	25%
4 (7° C ave)	5%	7%	11%	15%

Solar PV

10% Solar PV penetration

Since we know that residential demand is on average around 300 – 400W in the middle of the day (see Figure 1), we might expect 10% solar penetration to reduce demand to near zero during this period.

At 10% penetration this does occur in the model, see Figure 6, we see a small amount of reverse power flow from late morning to late afternoon.

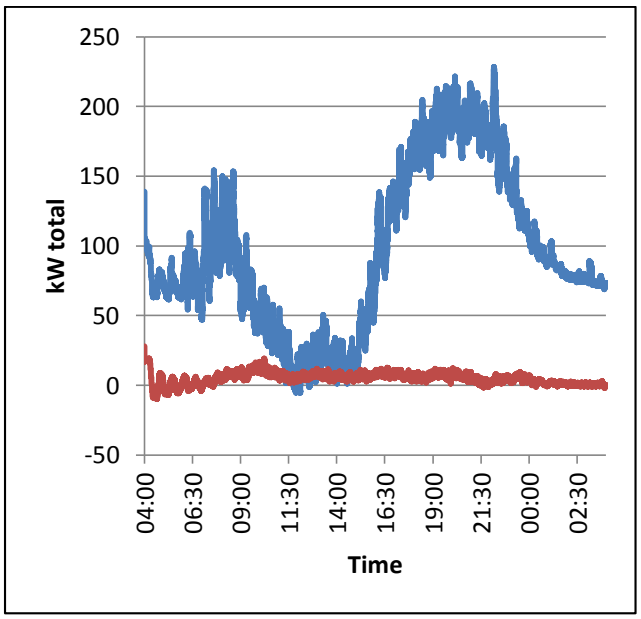

Figure 6, Merton 06601 Love Lane substation power flow on clear sunny day in June.

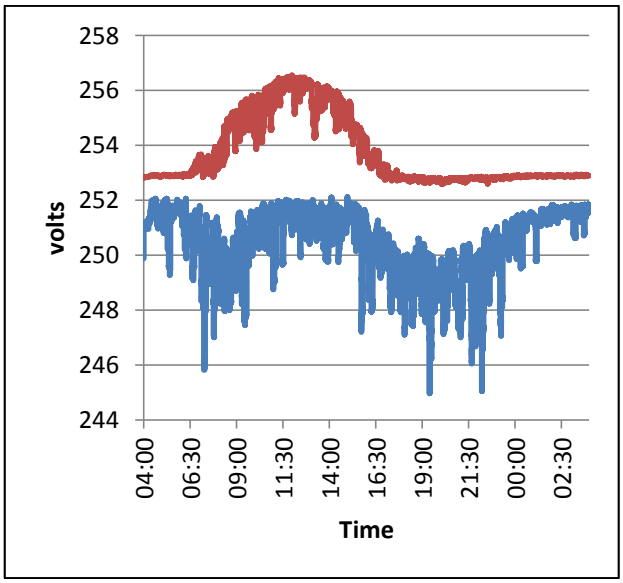

Figure 7, voltage minima and maxima on network.

Figure 7 shows the voltage and minima and maxima throughout the day. The maximum is the maximum voltage seen by any of the 339 customers on the network in that period; and the minimum is the minimum voltage seen by any of the customers in that period. This demonstrates that even with minimal back-feeding voltage rise is likely to occur. This warranted investigation into even lower levels of penetration. Moreover it warrants investigation into higher penetrations since very large over-voltage may occur.

At 5% penetration the demand curve for the substation remained clearly positive throughout the day. Perhaps surprisingly, this situation still gives rise to over-voltage albeit by 2 V. Due to phase imbalance we observed that the second phase is closer to zero and is the likely source of the voltage rise.

At 25% penetration voltage is approaching the G83 PV cut-out limit of 262V [11], thus finally we increase penetration to 30% to establish if we can identify the likely penetration to cause cut-out losses.

At 30% penetration we observed significant back-feeding, with a profile that is approaching zero net energy demand. In other words the mid-day reverse power flow approaches the inverse of the evening demand peak. This causes significant voltage rise and exceeds the G83 limit. This situation would not arise if the inverter cut-out is activated.

Summary

Table 2 summarises the findings from PV modelling. Higher penetration levels cause significant levels of back-feeding at the substation. At 30% penetration the result is almost zero net energy demand. Over-voltage is then a clear problem.

Table 2, Solar PV Summary

	Penetration level:			
	5%	10%	25%	30%
Over-voltage	**2V**	**3V**	**4.3V**	**14V**
Reverse power flow level	None	Low	High	High

Even a small penetration of PV's is found to produce an over-voltage of 2V. Whilst uptake at higher levels is not currently foreseen, it is interesting to examine the nature of the relationship between penetration and instances of over-voltage at higher uptake levels. At 25% penetration the over-voltage more than doubles to 4.3V, but from here onwards it rises steeply to 14V at a 30% penetration level. In practice, inverter cut-outs should prevent over-voltages of more than 9V.

CONCLUSIONS

The two technologies examined in this report, heat pumps and solar panels, pose very different and potentially contradictory problems for the distribution network.

For heat-pumps, on the modelled network, the primary concern was transformer capacity. The 6601 transformer was well below capacity at 370kW/500kW. This supported 25% heat-pump penetration with no under-voltage. However, in the cold scenario all homes will not achieve their target temperature, and the system is at risk of auxiliary heating being used. From these early indications it would appear that considerable additional transformer headroom is required to account for cold conditions and the collapse in COP. These issues would not arise to the same extent in a population of well insulated homes.
The issues surrounding Solar PV are, on the other-hand, voltage related. Voltage rise happens well before the onset of back feeding to the high voltage network. A modest 5% population of PVs can cause over-voltage, albeit by only a few volts. However, as PV penetration increases, then voltage maxima increase considerably. For the network as modelled the threshold at which G83 devices will trip-out (262V) due to over voltage lies somewhere between a PV penetration of 25% and 30%.

Given the above, it is likely that there are sites within London which may already be subjected to significant over voltage. G83 protection is not designed to keep voltages within limits, rather it is a last ditch measure to avoid dangerous over-voltage. If tripping does occur, then this is wasted energy which is also undesirable.

ACKNOWLEDGEMENTS

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