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The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial

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HIGHLIGHTS

- An aggregated load profile is constructed using data from 696 heat pumps in GB.
- It contains a morning and evening peak, falling to 40% of its peak value overnight.
- After diversity maximum demand is calculated as 1.7 kWe per heat pump.
- A first order approximation of the impact of 20% uptake of heat pumps is presented.
- This is shown to lead to the GB national grid evening peak increasing by 14%.

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ABSTRACT

Previous studies on the effect of mass uptake of heat pumps on the capability of local or national electricity grids have relied on modelling or small datasets to create the aggregated heat pump load profile. This article uses the UK Renewable Heat Premium Payment dataset, which records the electricity consumption of nearly 700 domestic heat pump installations every 2 minutes, to create an aggregated load profile using an order of magnitude more sites than previously available. The aggregated profile is presented on cold and medium winter weekdays and weekends and is shown to contain two peaks per day, dropping overnight to around 40% of its peak. After Diversity Maximum Demand (ADMD) for the population of heat pumps is calculated as 1.7 kW per site; this occurs in the morning, whereas the peak national grid demand occurs in the evening. Analysis is carried out on how heat pump ADMD varies with number of heat pumps in the sample. A simple upscaling exercise is presented to give a first order approximation of the increase in GB peak electricity demand with mass deployment of heat pumps. It is found that peak grid demand increases by 7.5 GW (14%) with 20% of households using heat pumps. The effect of the same heat pump uptake on grid ramp rate is also discussed; this effect is found to be minor. Finally, a comparison of heat pump and gas boiler operation is given, discussing day and night time operation and mean and peak power at different external temperatures.

1. Introduction

As the UK moves to a low fossil fuel future, heating of its 27 million dwellings needs to shift from the current predominance of CO_2-intensive, individual gas boilers [1]. One option is a significant increase of electrification of heating (coupled with the decarbonisation of electricity), of which the most energy efficient option is heat pumps [2,3] at either a dwelling or community scale. In most

Abbreviations: ADMD, After Diversity Maximum Demand; ASHP, Air Source Heat Pump; CLNR, Customer Led Network Revolution; DNO, Distribution Network Operator; EDRP, Energy Demand Research Project; GSHP, Ground Source Heat Pump; RHPP, Renewable Heat Premium Payment; SAP, Standard Assessment Procedure; TSO, Transmission System Operator.

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areas, heat demand density is not high enough to allow heat networks to be cost-effective [4] so individual heat pumps are likely to be a key technology [5].

During winter periods heating energy demand can reach around 5 times the magnitude of electricity demand in UK dwellings [1]. As such it is anticipated that a high uptake of individual heat pumps will have a significant effect on electric power demand and therefore the requirements of the local and national electricity grid at certain times of day and year [6].

Four potential grid problems arising from mass deployment of heat pumps arise, at either a national level (under the Transmission System Operator, or TSO) or substation level (under the Distribution Network Operator, or DNO).

The national scale problems are *peak demand increase* and *ramp rate increase*. Peak demand reflects the greatest demands on both the capacity of the transmission network and the generation infrastructure, in terms of both real and reactive power. Increases in peak demand are therefore likely to lead to investment in both new transmission capacity, and new generation capacity, if security of supply is to be maintained. Ramp rate reflects the need for electricity demand and supply to match on the grid, at a sub-minutely timescale. Currently the most rapid increase in demand over the day occurs between 06:00 and 07:00 in the morning, requiring supply to increase within this time too. If that morning ramp-up in demand were to coincide with heat pumps turning on, then further flexible plant would be required to provide the extra ramp up.

At the DNO scale, dwellings in areas that are connected to the gas network will generally have distribution network capacities designed for very little electric heating. The problems associated with connecting large number of heat pumps are excessive v*oltage drop* beyond allowed limits [7] and insufficient *thermal capacity* of the Low Voltage feeder and transformer leading to overheating of these elements unless they are reinforced [8,9].

This article will focus primarily on the national level, due to the availability of data from the national grid. It will however refer to substation level studies and metrics where relevant. Furthermore, the scope of the article will be real power (Watts) only, as opposed to apparent power (var), again due to the nature of the data available.

The relevant metrics for the impact of heat pumps on the national grid are national half-hourly averaged peak electricity demand (GW) and maximum ramp rate (GW/half hour). The half hour timestep is used for averaging here since this is the trading period of the national grid. The relevant metric to use to construct an aggregated heat pump load profile is After Diversity Maximum Demand, which is now described.

It is known that for networks where demand is aggregated over a number of customers N, the magnitude of peak power demand is less than the simple addition of peak power per customer over all customers. This is due to the phenomenon of diversity: the notion that as the number of customers increases, the maximum time-coincident demand per customer falls [10]. The metric to be used to describe peak power is therefore known as the After Diversity Maximum Demand (ADMD) [11]. To calculate ADMD, demand per consumer is summed at each timestep, then the maximum of the resulting timeseries is found. This is shown in Eq. (1).

$$ADMD = \max_t \left(\sum_{n=1}^{n=N} demand_n(t) \right) \tag{1}$$

where t = time, n = customer, N = all customers

ADMD accounts for the coincident peak load a network is likely to experience over its lifetime [10]. This is typically defined for a local network. If households form all of the load on the network, then dividing ADMD by N customers gives an *ADMD per customer*. Relating this specifically to heat pumps, *ADMD per heat pump* is taken to be the per-house ADMD of solely the aggregated heat pump demand, without the rest of the household electricity use. In this article, we define all ADMD using half hourly averaged data in accordance with Barteczko-Hibbert [10] and also to be consistent with the national metrics of grid peak demand and ramp rate given above, although it could underestimate effects on distribution networks [12].

Given these metrics, three questions can now be posed as follows. If large scale deployment of heat pumps occurs, what is the resulting peak demand of the national grid, what is the resulting ramp rate, and are either of these two outcomes then likely to be problematic? Answering these requires knowledge of not just the ADMD per heat pump, but the timing of the heat pumps' peak aggregated demand compared to the grid peak demand on a national scale.

2. Literature and previous datasets

We now describe the data and methods used in previous literature to construct aggregated heat pump load profiles and evaluate its potential effects on local or national electricity grids.

Most studies investigate aggregation of heat pump load profiles using modelled (synthetic) electricity load profiles. These in turn are based on heat demand which is either measured from conventional heating systems [13,14] or modelled. Methods of modelling heat demand include use of static or dynamic building modelling (e.g. [15–17]), simple mathematical functions [18] or assumption of flat (continuous) heating [19].

For example, acknowledging the lack of real heat pump electricity data, Navarro-Espinosa et al. [13] start with monitored heat demand profiles from conventional heating systems and infer electricity consumption, taking into account variable heat pump efficiency (although from manufacturers' datasheets as opposed to in situ data) and assuming a use profile of auxiliary heating. In a study combining heat pumps and electric vehicles, Papadaskalopoulos et al. [20] take a sample of building types from the UK building stock in different regions, derive heat and electricity demand profiles from the dynamic simulation tool Energy Plus, and add a certain number of these together according to different heat pump uptake scenarios (10–30% penetration). This methodology of aggregate load profile creation is interesting in terms of combining different building types and regions but does not fully capture the phenomenon of diversity as introduced in Section 1.

An approach to creating an aggregated load profile which does recreate diversity to some extent is found in Pudijianto et al. [21], in which data from 21 monitored systems were aggregated to create assumed heat pump profiles. However the data were derived from boiler and micro-CHP systems, as opposed to heat pumps. Another method incorporating diversity is to use 'top down' modelling [22], starting with total UK gas used for heating and dividing it by an assumed average heat pump efficiency to derive hourly and seasonal electricity demand which would be required if heat pumps replaced conventional gas boilers.

However, the heat pump demand profiles in the above studies are all based on an assumption that heat pumps are run at the same times of day as conventional heating systems (or micro CHP in the case of [21]), and thus that data derived from heating systems other than heat pumps can be used to determine the timing characteristics of heat pumps. This assumption is not verified in the literature for the UK context. The timing characteristics of heat pump operation compared to the current dominant domestic heating system – gas boilers - then becomes an additional question to be investigated in this article.

In contrast to the above, an aggregation exercise by Veldman et al. [23] focussing on the Netherlands was based on measurements from a small number of heat pumps. A large number of heat