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Residential air source heat pump deployment at scale and UK electricity substation limits during critical cold event

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Abstract: This study analyses the potential impact of future widespread UK heat pump (HP) adoption on electricity distribution networks across four scenarios: (1) monthly peak demand analysis, (2) critical cold event analysis, (3) monthly peak demand analysis with thermally upgraded homes, and (4) critical cold event analysis with thermally upgraded homes. The Totton substation near Southampton was taken as the case study. The results indicate that the Totton substation would experience monthly peak-time overload at 20% HP penetration. Thermally upgrading houses can raise this limit to 25%. During critical cold event, switching HPs to continual 24-hour operation mode significantly enhances the hosting capacity of HPs at Totton substation by smoothing peak load demand, which would be increased from 20%-60%. Thermally upgrading houses can further improve this to 70%. The paper highlights the potential importance of demand-side management of HPs when are deployed at scale to support the electricity network.

Keywords: electricity distribution networks, heat pump, overload, peak-time, substations

1. Introduction

To combat climate change, UK has committed to net-zero emissions by 2050 and to achieve this ambitious target, residential heating needs to be decarbonised as it accounts for nearly a quarter of the UK's total emissions (GOV.UK, 2021). In response, the UK government has set a target of reaching an annual installation rate of at least 600,000 units by 2028 (GOV.UK, 2023). By that time, HPs may become a scalable low-carbon heating system in the UK. However, the large-scale deployment of HPs is expected to pose significant challenges to the UK's power system, primarily due to a sharp increase in electricity demand.

Previous studies have assessed the impact of air source heat pumps (ASHPs) on the UK residential electricity distribution network. They focused on a variety of impact issues. Navarro-Espinosa and Mancarella performed simulation analyses based on a UK suburban low-voltage (LV) case study network to find that thermal overloading in the distribution network begins to occur when the penetration of the air source heat pump (ASHP) reaches 40%. In more extreme weather conditions, thermal overloading occurs at 15% penetration with poorly insulated home (Navarro-Espinosa and Mancarella, 2014). Insulation and thermal capacity of a house, and weather conditions are all potentially important variables. Similarly, Mancarella et al. conducted a case study of LV network in urban and rural areas of the UK, with consideration of different building types. They observed that substations in urban networks would overload when HP penetration is at 30%. At a penetration of 50%, the peak load of the network could increase by approximately 50%. The thermal overload issue is less pronounced in rural areas (Mancarella et al., 2011). Considering the true distribution of building types at a larger network scale may more accurately reflect the impact of future HP deployments at substation. Moreover, Akmal et al.'s case study of a UK test network carrying capacity for HP does not exceed 20% HP penetration, and the authors also explain the limitations of this result occurring only in very cold weather (Akmal et al., 2014). Therefore, there is also a need to explore the impact of heat pumps on the distribution network during peak times, as well as the need to pay particular attention to the impact during very cold weather conditions.

In this study, the potential impact of different HP penetration rates on substations within residential electricity distribution networks was examined through data-based modelling. A modelling approach was developed to estimate the overload issues that widespread adoption of residential HPs may cause at case study substations, with a particular focus on the risks during peak winter periods and the constraints that could arise during a critical cold event. The modelling results could be used to inform potential future capacity upgrades and adjustments to dispatch strategies at the case study substations, highlighting the potential importance of demand side management for HPs in supporting the electricity grid during large scale deployment.

2. Methodology

2.1 Baseline Data Collection and processing

The baseline data used in this paper contains the following types: capacity of substation, load profiles of distribution network area, weather conditions, heating degree days (HDDs), space heating and domestic hot water (DHW) demand, and HP coefficient of performance (COP) curves.

Substation capacity was collected from the networks maps of the network operator (SSEN, 2024a) and load thresholds (minimum and maximum loads) were obtained, and half-hourly aggregated smart meter data from homes and businesses was gathered from the data portal of (SSEN, 2024b). The smart meter data was sorted by date, with each file containing energy consumption data for all substations. According to the substation ID, the energy consumption data of each substation can be screened from each file. However, since not all customers in an area have smart meters, the resulting electricity consumption data is incomplete. This data can be converted to power units and scaled to the actual level according to the thresholds after missing values and outliers (greater than the maximum load) are removed.

Weather conditions use actual meteorological year (AMY) weather data for 2018, which provides a more accurate reflection of the peak heating demand brought by HPs to buildings under extreme weather conditions, and that year due to 'The Beast from the East' hit the UK from February to March 2018, resulting in exceptionally low temperatures. HDDs measure the heating demand required to maintain comfortable indoor temperatures in a region during a given period. It is calculated based on the difference between the daily average temperature and the base temperature, which is generally 15.5 °C for buildings in the UK.

Space heating and DHW demand was obtained from an Energy Performance Certificate (EPC) survey of dwellings within the distribution network area. Due to the large number of users, a stratified sample based on different dwelling types was used to obtain an average, with the sample size established at 95% confidence level and 5% margin of error.

Assuming constant HP condenser outlet temperatures of 35 °C (for space heating) and 50 °C (for DHW supply). The HP COP curves were fitted to the air-water heat pump COP data obtained from (Haller et al., 2014) experiments at this setup to account for the effect of ambient temperature on the HP COP.

2.2 Scenario Setting

Four scenarios based on HP penetration, building EPC rating and HP operation mode were developed to assess the impact of HP penetration on substations under different possible future external conditions. All scenarios involve HP penetration from 10% to 100% in 10% increments and are all based on 2018.

S1. Monthly peak demand analysis: HPs run at a setpoint for 8h, Building EPC D.
S2. Monthly peak demand analysis with thermally upgraded homes: HPs run at a setpoint for 8h, Building EPC C.
S3. Critical cold event analysis: HPs run continuously 24h, Building EPC D.
S4. Critical cold event analysis with thermally upgraded homes: HPs run continuously 24h, Building EPC C.

2.3 Sensitivity Analysis

The sensitivity analysis in this paper is set to analyse the impact of different HP heating temperature settings on the substation. This is because the initial setting of 35 °C space heating temperature is a low-temperature HP system, which has the advantage of a high COP. However, this can present a challenge in the retrofit market as it requires the installation of underfloor heating or oversized radiators to ensure effective heat dissipation. In contrast, a 45 °C distribution temperature may be more suitable for existing pipework and in practice some users may prefer a higher temperature system. Therefore, space heating temperatures of 45 °C and 55 °C were also added as sensitivity variables.

3. Case Study and Results

Totton Substation serves a total of 8,736 customers, 7,461 domestic and 1,275 non-domestic customers (SSEN, 2024c), was taken as a case study. It has a 24.5 MVA substation transformer that converts 33 kV to 11 kV, and the lowest load recorded for the substation is 4.55 MW and the highest is 15.59 MW. According to the report of (SSEN, 2024d), the power factor of Totton substation can be set at 0.95 and losses at 5 %. Therefore, the actual maximum load that can be carried by the substation is about 22.1 MW. The recorded smart meter heating season (12 February-30 April 2024) data for Totton substation was read from the SSEN data portal and processed to obtain the half hourly load profile (Fig. 1a). It can be observed that the peak load occurs between 18:00 and 19:00. The weak linear correlation between Totton electricity demand at 18:00 and ambient temperature between February and March 2024 suggests that the current level of electrical heating around the substation is relatively low (Fig. 1b).

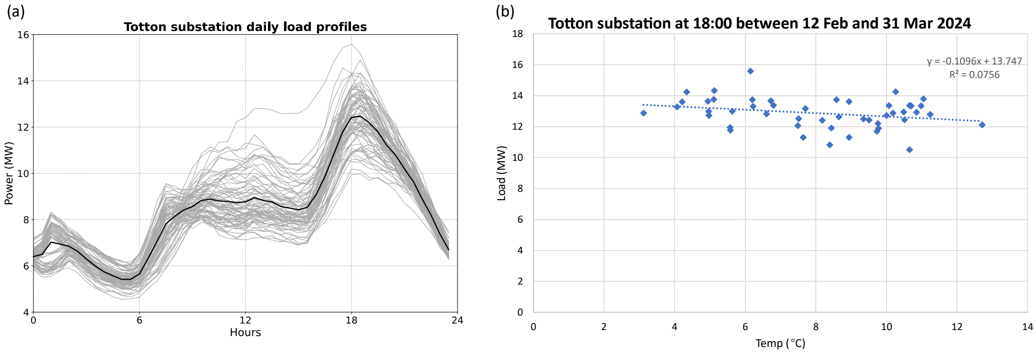

Figure 1. Daily load profile of Totton substation from 12 February to 30 April 2024, correlation between Totton substation electricity demand at 18:00 and ambient temperature between February and March 2024.

Calculated daily HDDs based on 2018 AMY weather data provided by Southampton Weather Station, Southampton, England, are shown in Figure 2. 2018 had 1,856 HDD compared to 1,769, HDD baseline 2001-2020 median for Southampton (MetOffice, 2024). It can be observed that there was a prolonged and extreme period of HDDs from 21 February to 3 March. This indicates a very high and sustained residential heating demand during this period. As a result, critical cold event scenarios are modelled during this period.

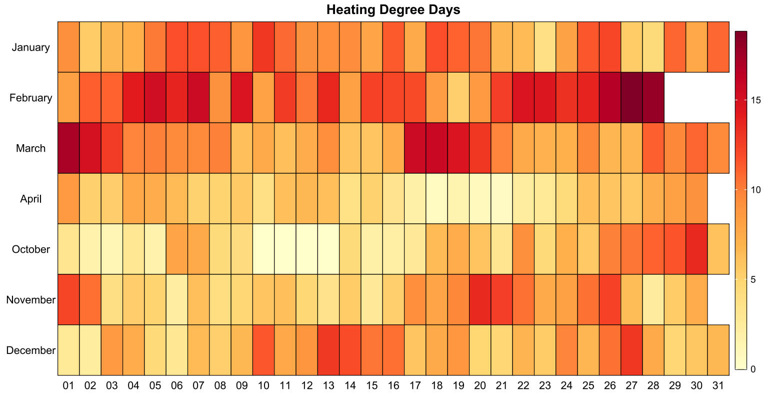

Figure 2. Daily HDDs for Totton from January to April and October to December in 2018.

The sampling results for dwelling EPC certificates are shown in Figure 3. The average electricity demand for HPs in the baseline model for individual dwellings was determined by considering the average heating and DHW demand for each dwelling type, as well as the proportion of each dwelling type.

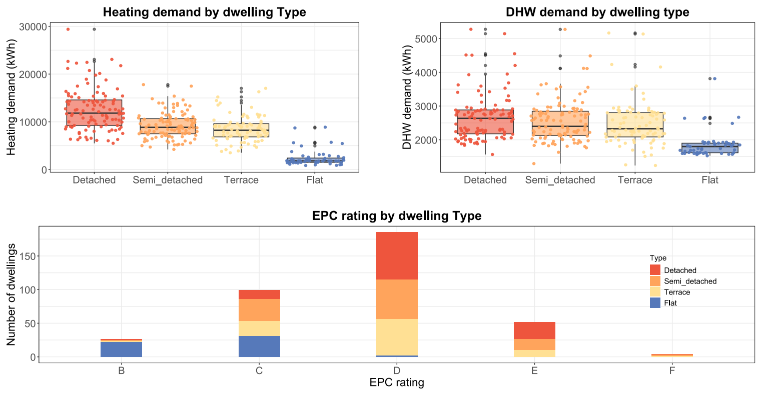

Figure 3. The summary of sample dwellings in Totton.

The modelling results for the scenario 1 and scenario 2 are shown in Figure 4.

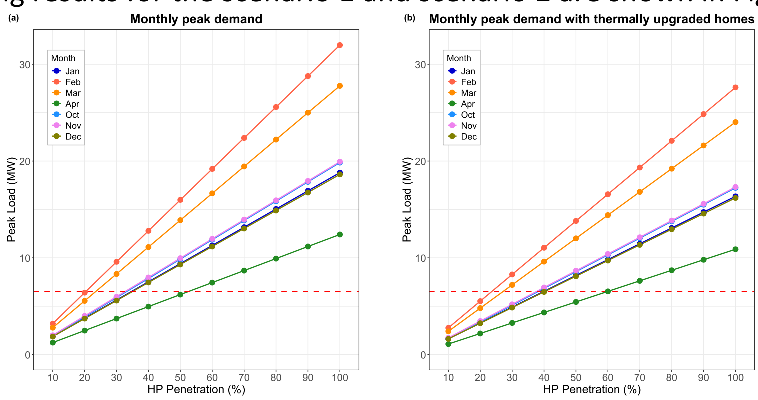

Figure 4. The monthly peak demand for heat pumps at Totton substation.

In scenario 1, the monthly peak demand at the Totton substation is close to the substation's maximum capacity when HP penetration is only 20%. When HP penetration exceeds 50%, the monthly peak demand throughout the heating season surpasses the substation's capacity, especially in February, when heating demand is at its highest, the peak demand caused by the HPs is more than twice as high as the substation's margins. At 100% heat pump penetration, the substation will be severely overloaded, with 200% ~ 500% overload at peak moments. HP penetration could be increased by about 5% through thermally retrofitting the houses to reduce demand. At 100% HP penetration, the maximum overload of the substation transformer with retrofitted houses is reduced from 500% to about 400%.

Figure 5 (a) shows the time series of substation loads for scenario 2. It is interesting to note that the substation would support at least 60% HP penetration during very cold weather when the HPs are running at 24h flat schedule. Even if the penetration increases to 70%, only minor overloads occur on specific days and at specific moments. However, when HP penetration increases to over 80%, the substation begins to experience extensive overloads. At 100% HP penetration, the substation is predicted to occur overload on 8 out of those 11 days, and continuously for 9 hours starting on 27 February 2018 at 11:30am. Nonetheless, the maximum overload level of 118% is significantly lower compared to the conventional 8h HP operation. Similarly, as in the scenario involving the thermally upgraded homes shown in Figure 5 (b), the substation was able to handle an additional 10% of HP penetration under the same conditions. At 100% penetration, the maximum overload duration of the substation is reduced to 3.5 hours, with a 6% reduction in the maximum overload level.

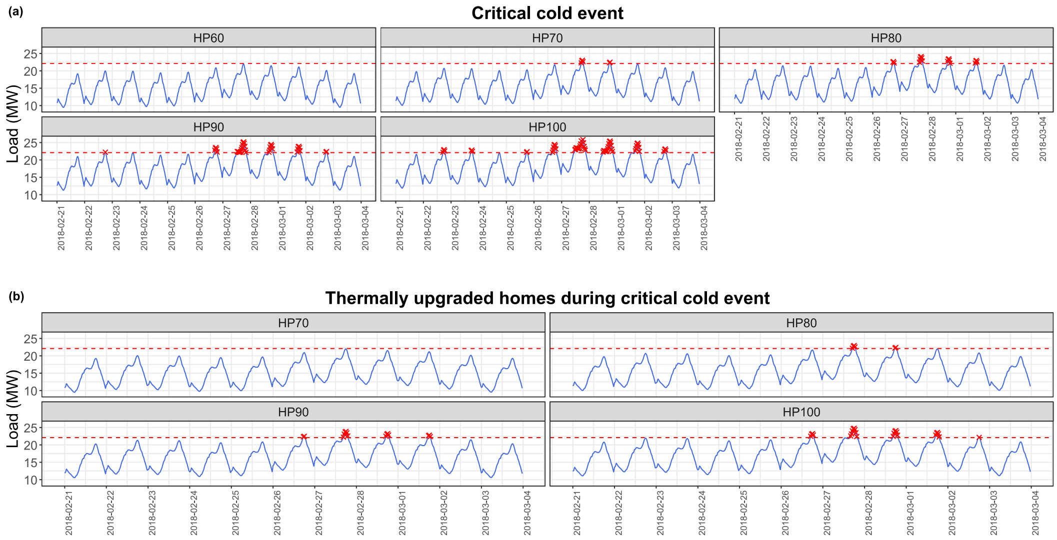

Figure 5. The load of Totton substation during critical cold event. The red X represents the moment when electricity demand exceeds substation capacity. HP60 (HP 60% penetration).

Finally, sensitivity analysis was performed by implementing different heat pump space heating temperatures. The results show that high-temperature HP systems pose a more severe challenge to the distribution network. In scenario 1, the HP penetration is reduced by 1% and 4% for 45°C and 55°C heating temperature settings, and 1% and 10% during critical cold event, as well as a reduction in the gain of the thermally upgraded house, as shown in Table 1.

Table 1. Sensitivity analyses results of different space heating temperature settings

Variables	S1	S2	S3	S4
Space heating temp	Max. HP penetration			
35°C	20%	25%	60%	70%
45°C	19%	23%	59%	68%
55°C	16%	19%	50%	58%

4. Discussion and Conclusions

This study quantifies the impact of future HP scale deployments on residential distribution network substations, focussing on peak moments and extreme weather. The paper modelled and assessed the carrying capacity of the Totton substation near Southampton for HP and found that the substation can accommodate approximately 20% of the heat pump penetration when the heat pumps are running on a regular 8-hour schedule, whereas thermally upgraded homes can increase the limit to 25%. During a critical cold event, if the HPs are run continuously for 24 hours, the HP penetration that the substation can handle increases to more than 60%, and the thermally upgraded homes are able to further increase the limit to 70%. In addition, the results of the sensitivity analysis showed HP temperatures for 45°C and 55°C space heating reduced penetration by 1-10 percentage points and the benefit of the thermally upgraded house was reduced.

This study highlighted the benefit of varying HP demand patterns to smooth peak load demand emphasising the potential importance of demand side management of HPs when deployed at scale to support the grid. It also suggests that demand-side management strategies to mitigate the stress on the distribution network may be needed. For example, incorporating innovative tariff designs (e.g. time-of-use tariffs) to reduce peak impacts through load shifting, which can enable flexible and cost-effective HP systems, coupled with high government adoption subsidies to further entice customer investment. In addition, as more and more low-carbon technologies such as photovoltaics and electric vehicles become commonplace in the possible future, their coupling and co-ordination with HPs deserves further investigation.

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