Peak Heat WP4: Community level network modelling

Peak Heat Project

Western Power Distribution

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Executive summary

1

WP4 covered the modelling of heat flexibility solutions at the substation level. The objective was to determine how substation loads and peak demands were likely to be impacted by uptake of heat pumps, and how much these impacts could be mitigated by the use of flexibility measures such as thermal and electrical storage.

The modelling of distribution substations was primarily done in Plexos, building on the individual house modelling done in WP3. Distribution substation archetypes were created to represent the distribution substations under study across the three primary substations selected in WP1: Bath Road, Mackworth and Newport. The distribution substation archetypes were defined based on the number of customers connected to the substation and the mix of house archetypes on the substation. The distribution substation archetypes and the number of each archetype on each primary substation are listed in Table 4 on the following page.

Heat pumps were assigned to houses based on the suitability of each house archetype to having a heat pump installed. Two uptake scenarios were used up to 2030. The moderate uptake scenario sees 4-12% of homes installing heat pumps, a level that could realistically be achieved by 2030. The high uptake scenario has heat pumps in 14-30% of homes, which would be ambitious to achieve by 2030. These were chosen to align approximately with the Consumer Transformation DFES scenario for 2025 and 2030 respectively. Figure 6 on the next page shows the number and share of heat pumps on each primary substation in the modelled and DFES scenarios.

In order to simulate diversity across the network, Plexos was used to generate unique thermal and non-thermal demand profiles for each individual house based on the average for its house archetype. Commercial and other non-modelled domestic demands (such as electric immersion heating) for each substation archetype were estimated based on historical substation load data and added to the modelled substation demands.

Table 4: Number of distribution substation archetypes connected to each primary substation under study

Substation archetype code	House mix on substation	Modelled number of domestic customers on substation	Number of secondary substations of each archetype on primary		
			Bath Road	Mackworth	Newport
D-70	Mainly detached and semi-detached homes	70	14	2	0
D-120		120	8	0	0
D-200		200	1	1	0
S-70	Mainly semi-detached homes with a mix of others	70	8	5	1
S-120		120	9		2
S-200		200	14	26	6
S-350		350	1	9	1
T-70	A mix of terraced houses, semi-detached houses and flats	70	0	3	12
T-120		120	0	2	12
T-200		200	0	3	47
T-350		350	0	1	22
T-600		600	0	1	1
F-70	Mainly flats with some terraces and semi-detached homes	70	0	1	2
F-120		120	0	1	1
F-200		200	2	1	1
F-350		350	0	2	0
Total number of substations			57	58	108
Total modelled number of customers			7,330	12,130	22,300

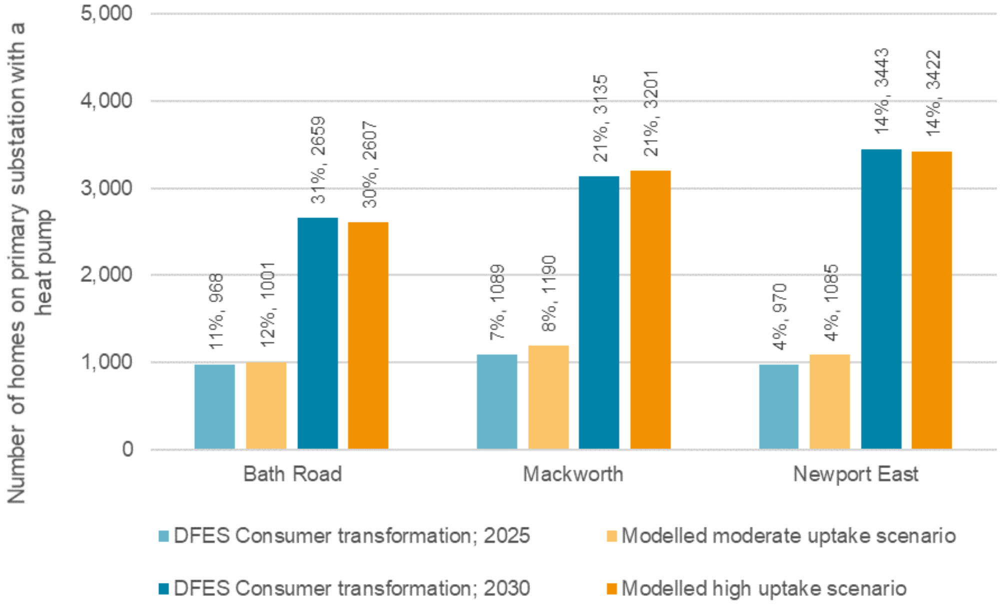

Figure 6: Number of homes on each primary substation with a heat pump installed under DFES and Peak Heat uptake scenarios; percentage share of total homes indicated above bars

Several scenarios were run in Plexos to determine the impact of different weather conditions, heat pump uptake levels and flexibility measures on substation loads. The scenarios effectively assume 100% uptake of flexibility measures, except in the case of electrical batteries which are assumed to be installed in 50% of homes with heat pumps, and should therefore be treated as illustrative rather than predictive. Example load duration curves for the S-200 substation archetype are shown in Figure 24 for different scenarios versus the present day.

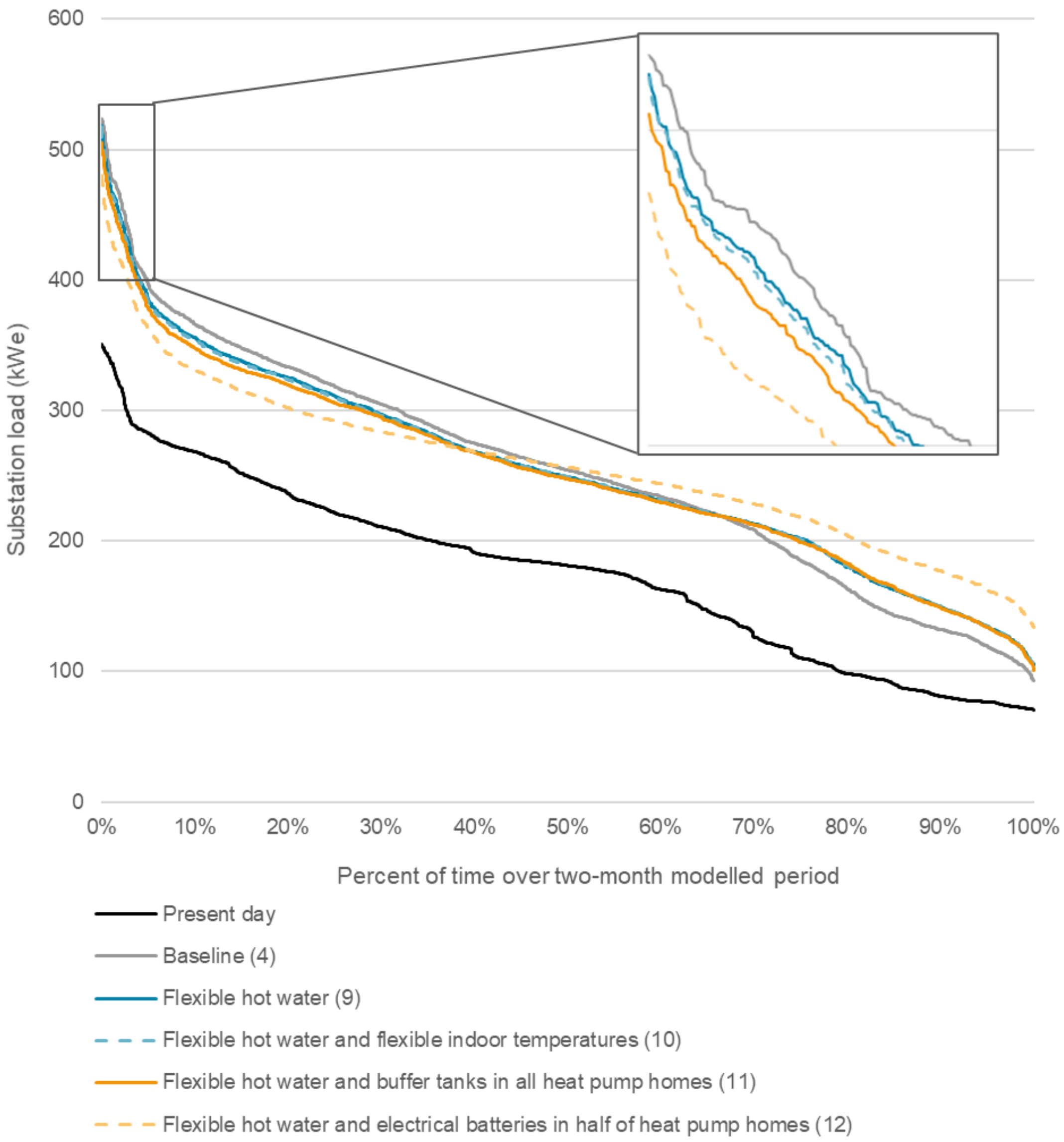

Figure 24: Load duration curves for S-200 substation archetype over two-month modelled period with cold winter conditions and high levels of heat pump uptake, with different flexibility measures applied

In general across all substation archetypes it was found that allowing flexible hot water generation in all homes with heat pumps enables roughly 1% of demand to be shifted out of peak periods. This is a small amount, but can easily be achieved by programming when heat pumps can generate hot water.

Having flexible indoor temperatures (relaxing set temperature requirements by up to 1°C and allowing pre-heating of up to 21°C in the afternoon) in all homes with heat pumps has a negligible impact (<1%) on peak demands, though this could be slightly higher if greater changes in temperature were allowed.

Use of buffer tanks in all homes with heat pumps also only reduces peaks by 1-2%, and is therefore unlikely to be a cost-effective flexibility measure. Only higher capacity thermal stores such as heat batteries can store enough heat to meaningfully reduce peak demand.

Installing electrical batteries (with capacities between 5 – 13.5 kWh depending on property size) in 50%[1] of homes with heat pumps can reduce peak demands by up to 9% in the extreme best cases, central cases will be less. For some substations, this could be enough to avoid substations being overloaded during peak periods. Because heat pumps produce 2-3 units of heat for every unit of electricity, electrical batteries are a much more space efficient form of storage than thermal stores. Electrical batteries have the added benefit of also working with other electrical technologies like solar PV panels and EV chargers to manage loads on the network.

Table 14 and Table 15 show the number of distribution substations of each archetype on each of the three primary substations, as well as how many of these substations are likely to be over their continuous load nameplate rated capacities under the different modelled scenarios.

In the moderate heat pump uptake scenarios, 44 of the 234 substations analysed across the three primaries are likely to be overloaded relative to their continuous load nameplate ratings on peak days.

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[1] Various levels of battery uptake among homes with heat pumps were tested when choosing scenarios. It was found that higher levels of uptake resulted in greater peak demand reductions, but only up to a point. The point at which additional batteries made little difference in peak demand reduction was at around 50% of homes with heat pumps.

With high levels of heat pump uptake, the number of overloaded substations increases to 94 out of 234 (including 22 overloaded during peak periods currently). Of these substations, 6 are likely to be only slightly overloaded, and so peak demands can be kept within rated capacities by shifting hot water generation out of peak periods. Installing batteries in 50% of homes with heat pumps would bring the number of overloaded substations down from 94 to 51, meaning significant cost savings on substation upgrades. Note that the value of 50% uptake of electrical batteries in homes with heat pumps has been selected as an illustrative figure. This value is substantially higher than the uptake assumptions in the DFES, but corresponds to the upper limit for the demand reductions that can be derived from batteries. The approach adopted provides consistency in the illustrative uptake assumptions for all of the flexibility measures considered. WP5 will look at how the cost of electrical batteries compares to the cost of substation upgrades to determine whether installing batteries could be cost effective.

Note that for this desktop study continuous load nameplate ratings have been applied in the reinforcement/replacement analysis of substations. In practice the reinforcement/replacement of individual transformers would consider the application of a cyclic rating, which can range from 10% to 40% larger than continuous rating, based on detailed assessment of a range of factors that could limit the capacity. This approach is more conservative and aligns with other WPD policy documentation for similar studies. Use of cyclic ratings would significantly reduce the number of distribution substations that are "overloaded" in this analysis.

Table 14: Number of distribution substations on each primary likely to have maximum demands above continuous load nameplate rating under moderate HP uptake scenario

Scenario	Total number of substations of each archetype with maximum demands above continuous load nameplate ratings							Total number of substations of each archetype connected at present
Scenario	Present day	1	3	5	6	7	8	
Weather		Average	Cold	Cold	Cold	Cold	Cold	
HP uptake		Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
Bath Road - Total	**8**	**14**	**14**	**14**	**14**	**14**	**12**	**57**
D-70	3	3	3	3	3	3	3	14
D-120	0	3	3	3	3	3	3	8
D-200	0	1	1	1	1	1	1	1
S-70	1	3	3	3	3	3	1	8
S-120	0	0	0	0	0	0	0	9
S-200	3	3	3	3	3	3	3	14
S-350	1	1	1	1	1	1	1	1
F-200	0	0	0	0	0	0	0	2
Mackworth - Total	**9**	**10**	**10**	**10**	**10**	**10**	**10**	**68**
D-70	1	1	1	1	1	1	1	2
D-200	0	1	1	1	1	1	1	1
S-70	0	0	0	0	0	0	0	5
S-120	0	0	0	0	0	0	0	11
S-200	3	3	3	3	3	3	3	26
S-350	4	4	4	4	4	4	4	9
T-70	0	0	0	0	0	0	0	3
T-120	0	0	0	0	0	0	0	2
T-200	0	0	0	0	0	0	0	3
T-350	0	0	0	0	0	0	0	1
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	1
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
F-350	0	0	0	0	0	0	0	2
Newport - Total	**5**	**20**	**20**	**20**	**20**	**20**	**20**	**108**
S-70	0	0	0	0	0	0	0	1
S-120	0	0	0	0	0	0	0	2
S-200	0	0	0	0	0	0	0	6
S-350	0	0	0	0	0	0	0	1
T-70	0	0	0	0	0	0	0	12
T-120	0	0	0	0	0	0	0	12
T-200	4	4	4	4	4	4	4	47
T-350	0	15	15	15	15	15	15	22
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	2
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
Grand Total	**22**	**44**	**44**	**44**	**44**	**44**	**42**	**234**

Table 15: Number of distribution substations on each primary likely to have maximum demands above continuous load nameplate rating under high HP uptake scenario

	Total number of substations of each archetype with maximum demands above continuous load nameplate ratings							
Scenario	**Present day**	**2**	**4**	**9**	**10**	**11**	**12**	**Total number of substations of each archetype connected at present**
Weather		**Average**	Cold	Cold	Cold	Cold	Cold	
HP uptake		High	High	High	High	High	High	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
Bath Road - Total	**8**	**18**	**34**	**30**	**30**	**30**	**18**	**57**
D-70	3	6	9	9	9	9	6	14
D-120	0	3	7	3	3	3	3	8
D-200	0	1	1	1	1	1	1	1
S-70	1	3	3	3	3	3	3	8
S-120	0	1	1	1	1	1	1	9
S-200	3	3	12	12	12	12	3	14
S-350	1	1	1	1	1	1	1	1
F-200	0	0	0	0	0	0	0	2
Mackworth - Total	**9**	**15**	**32**	**31**	**31**	**31**	**13**	**68**
D-70	1	2	2	2	2	2	2	2
D-200	0	1	1	1	1	1	1	1
S-70	0	0	0	0	0	0	0	5
S-120	0	3	3	3	3	3	1	11
S-200	3	3	19	19	19	19	3	26
S-350	4	4	5	4	4	4	4	9
T-70	0	0	0	0	0	0	0	3
T-120	0	0	0	0	0	0	0	2
T-200	0	0	0	0	0	0	0	3
T-350	0	0	0	0	0	0	0	1
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	1
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
F-350	0	1	1	1	1	1	1	2
Newport - Total	**5**	**21**	**28**	**27**	**27**	**27**	**20**	**108**
S-70	0	0	0	0	0	0	0	1
S-120	0	1	1	1	1	1	0	2
S-200	0	0	6	6	6	6	0	6
S-350	0	0	1	0	0	0	0	1
T-70	0	0	0	0	0	0	0	12
T-120	0	0	0	0	0	0	0	12
T-200	4	4	4	4	4	4	4	47
T-350	0	15	15	15	15	15	15	22
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	2
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
Grand Total	**22**	**54**	**94**	**88**	**88**	**88**	**51**	**234**

1. Work package scope, methodology and outputs

This work package covered the modelling of heat flexibility solutions at the distribution substation level. The modelling was primarily done in Plexos, building on the individual house modelling done in WP3. Distribution substation archetypes were created to represent the substations under study. Various scenarios were analysed with different flexibility measures compared. The outputs of this work package are this methodology and results report and the half hourly demand profiles for each distribution substation archetype.

1.1. Work package scope

This report details the methodology and outputs of the fourth work package of the WPD Peak Heat project. WP4 covered the modelling of heat flexibility solutions at the primary and distribution substation levels, building on the previous Peak Heat project work packages. In WP1, homes were categorised into eight house archetypes. WP2 provided an overview of the technologies and mechanisms that could be deployed by 2030 to deliver low carbon electric heating in the UK. In WP3, electrical demands were modelled for each house archetype with a heat pump installed under different weather conditions and with different flexibility measures applied. WP5 will include a cost benefit analysis comparing the costs of different flexibility measures to the cost of network upgrades.

1.2. Work package methodology

The process followed in WP4 is illustrated in Figure 1, and full details of the methodology are provided in Section 2.

The first step was creating a number of distribution substation archetypes based on an analysis of the substations in the three study areas.

The second step was assigning heat pumps to houses in the substation archetypes under different heat pump uptake scenarios. After that the third step was calculating the resultant electricity demand at the distribution substation level – this was done in Plexos using stochastic profiles based on the house archetype average load profiles created in WP3.

Additional non-modelled loads were estimated using historical data provided by WPD for the primary and distribution substations under study. These were added to the modelled demand profiles for space heating under different heat pump uptake and flexibility scenarios. Peak demands were then compared to the rated capacities for the modelled substations to determine whether they are likely to be overloaded under different conditions.

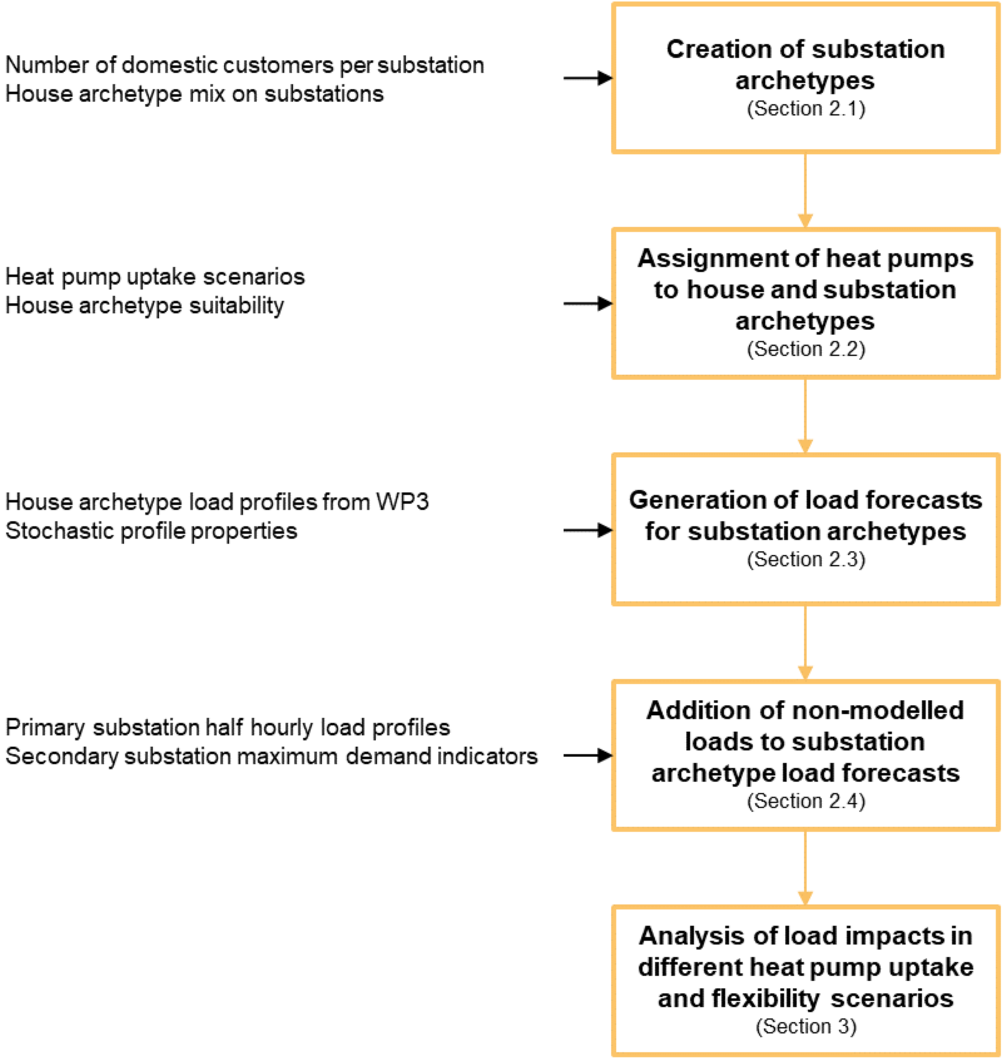

Figure 1: WP4 methodology steps and key information required; section numbers refer to sections in this report where further information is provided on that step

1.3. Work package outputs

The outputs of WP4 are:

- Half hourly input power demand profiles at the distribution and primary substation level for each study area under average and 1 in 20 weather conditions, different heat pump uptake scenarios, and with different flexibility measures applied (attached Excel spreadsheet); and
- This report detailing how these profiles were derived.

2. Methodology

This chapter describes the creation of 16 distribution substation archetypes based on the number of domestic customers and mix of house types on each substation. It also explains how heat pumps were assigned to houses to simulate moderate and high levels of heat pump uptake in line with DFES scenarios. Stochastic profiles were used to account for diversity in thermal and non-thermal demands within the house archetypes. Commercial and other non-modelled domestic demands were estimated based on historical substation load data.

2.1. Creation of distribution substation archetypes

2.1.1. Primary substations under study

Three primary substation areas were selected within the WPD area, based on differing locations, high expected heat pump uptake and constrained transformers. Details of these primaries are provided in Table 1.

Table 1: Selected primary substation areas

ESA	Licence area	DFES non-hybrid HP uptake (2030) (Consumer Transformation)	Demand headroom (MVA)	Geography
Mackworth	East Midlands	3,135	-0.7	Village / Rural
Newport East Primary	South Wales	3,443	8.8	City
Bath Road Primary	South West	2,659	5.0	Town/Rural

2.1.2. Selection of distribution substations for analysis

Details of the distribution substations connected to each of the three primaries under study were provided by WPD. Across the three primaries there are over 600 distribution substations serving more than 48,000 domestic[2] customers. As can be seen from Table 2, some of these substations have no domestic customers at all, and many have less than 50 domestic customers. Substations with few domestic customers are unlikely to be overloaded by a high proportion of homes installing heat pumps, as their rated capacity tends to be high relative to the number of customers connected. The remaining 234 substations with over 50 domestic customers (47% of all substations with domestic customers) account for 95% of all domestic customers across the three study areas. For these reasons, substations with fewer than 50 domestic customers were excluded from further analysis.

The Bath Road primary had the most substations excluded, with only 86% of customers accounted for. The impacts of this on the results are likely to be minor, but it is noted that the analysis might not pick up some smaller substations at risk of being overloaded.

Table 2: Details of distribution substations connected to the three primary substations under study

	Bath Road	Mackworth	Newport	Total
Total substations	**268**	**213**	**176**	**657**
Substations with domestic customers	190	176	133	499
Substations with >50 domestic customers	57	69	108	234
Substations with <50 domestic customers	133	107	25	265
Substations with no domestic customers	78	37	43	158
Total domestic customers	**8,654**	**15,210**	**24,536**	**48,400**
Total domestic customers on substations with >50 domestic customers	7,472	14,569	24,148	46,189
Total domestic customers on substations with <50 domestic customers	1,182	641	388	2,211
% of total domestic customers on substations with >50 domestic customers	86%	96%	98%	95%

[2] The number of domestic customers was determined based on the number of Elexon Profile Class 1 and 2 meters recorded for each substation.

2.1.3. Creation of distribution substation archetypes based on house archetypes and customer numbers

To simplify the community level network modelling, the 234 distribution substations analysed were categorised into 16 substation archetypes based on two criteria:

- The mix of house archetypes connected to the substation, e.g. mainly detached houses, mainly flats, or a mix of different types. House mix determines the **relative share** of homes on a substation that are likely to install heat pumps, as well as the amount of heat required. For example, substations with mostly poorly insulated detached or semi-detached homes will have the highest space heating demands, as houses are better suited to heat pumps than flats and will see higher levels of uptake initially, and because space heating demand is higher for larger, poorly insulated homes.
- The approximate number of houses connected, e.g. less than 100 or over 500. This determines the **absolute number** of homes on a substation that can have heat pumps installed, and hence the potential additional electrical demand for heating.

Grouping the 234 substations into archetypes was necessary to limit model run times, since calculations could only be run for up to about 1,000 homes at a time, and additional model runs were required for each of the different scenarios tested.

House archetype mix on each substation

The mix of house archetypes[3] on each substation was estimated by matching the location of the substations to the post codes from the EPC analysis done in WP1. Four typical groupings of house archetype mixes were identified, as shown in Figure 2. These groupings were determined using a K-means clustering[4] algorithm in the statistical computing software R.

The shares of house archetypes in each of the four groupings were adjusted slightly to align as closely as possible with the actual share of houses of each archetype on each of the three primary substations. A comparison of the modelled and actual shares of each house archetype determined from the EPC analysis in WP1 is shown in Figure 3. It can be seen from the comparison that the greatest absolute difference in share between the modelled and actual values for any archetype is ±3%.

For the Bath Road primary substation, the number of detached (DH) houses are slightly overestimated, whereas mid-terrace (MT) homes are slightly underestimated. This will result in a slight overestimation of non-thermal electricity demand for the Bath Road primary, as larger detached properties have higher non-thermal demands than smaller mid-terrace properties and flats. Non-thermal electricity demand might also be slightly overestimated for the Mackworth primary, for which detached (DH) and semi-detached (SH) houses are slightly overestimated and mid-terrace (MT) houses and flats are slightly underestimated.

[3] Descriptions of each house archetype can be found in Table 16, Appendix A
[4] K-means clustering is a simple algorithm that assigns observations to clusters with the nearest mean and adjusts the mean cluster values until a best fit is found.

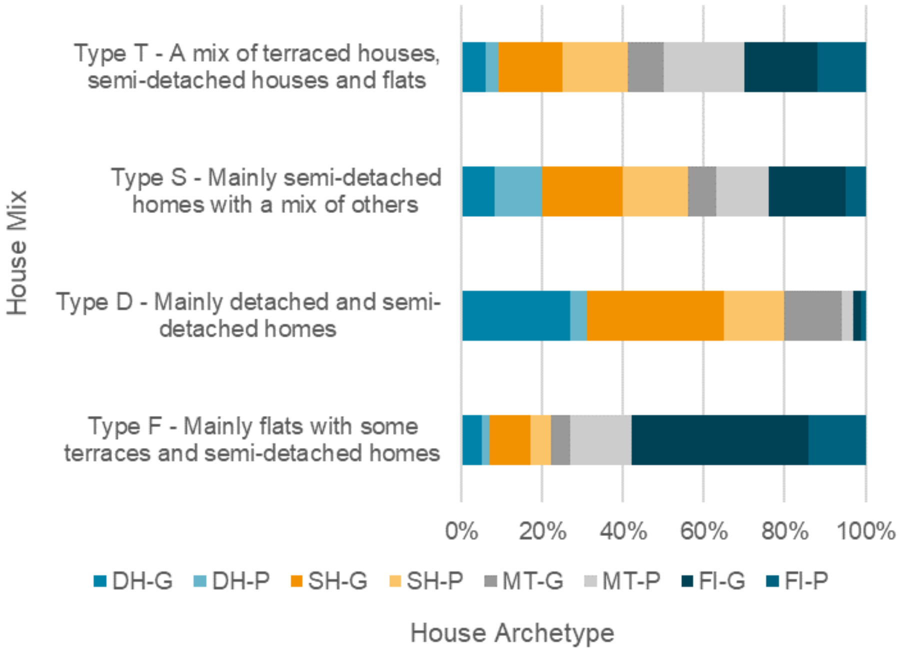

Figure 2: Four groupings of house archetypes determined from analysis of archetype mixes on each distribution substation (chart values are provided in Appendix B)

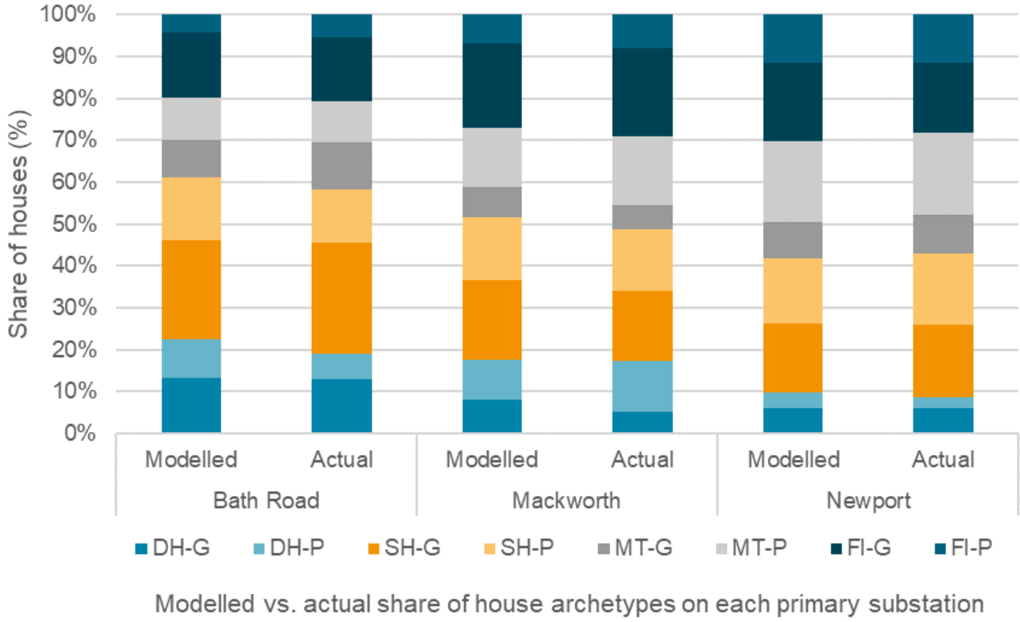

Figure 3: Modelled share of house archetypes on each primary substation using distribution substation archetypes versus actual share of house archetypes based on EPC analysis done in WP1 (chart values are provided in Appendix B)

Number of domestic customers connected to each substation

Figure 4 shows the number of domestic customers connected to all the substations under study, including those with less than 50 domestic customers. There is a relatively even spread of customer numbers up to about 350 customers, and a smaller number of substations with 350-600 customers.

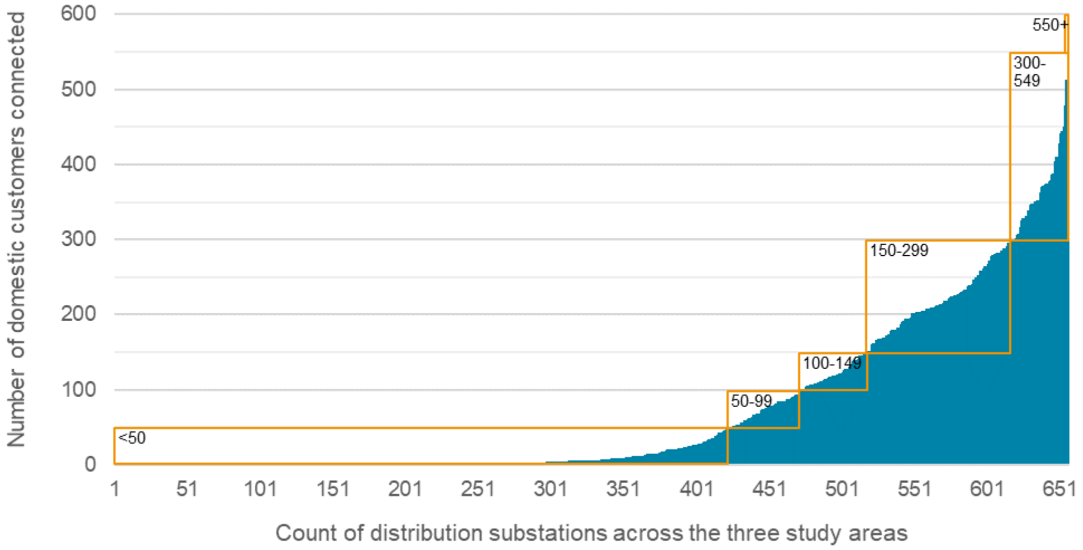

Figure 4: Number of domestic customers connected to all distribution substations under study; boxes indicate range of number of customers

Based on this spread, 5 groupings of customer numbers per substation were used to characterise the substation archetypes, as listed in Table 3. These were chosen to represent typical substations with relatively low customer numbers (50-99), relatively high customer numbers (>550), moderate customer numbers (150-299) as well as two intermediate categories (with customers numbers in the ranges 100-149 and 300-549, respectively). The numbers of substations falling into each of the categories guided the choice of boundaries, with most falling into the middle group, similar numbers falling in the intermediate groups, and only a few with higher customer numbers. The category covering 300-549 customers has the widest boundaries, and therefore has the most uncertainty in the results. The representative numbers of customers applied to each category to establish the substation archetypes, shown in Table 3, have been determined from the average of the actual customer numbers per substation in each category rather than the midpoint of the respective range. Any resulting discrepancies between the model results and actual substation demands could be mitigated by using a greater number of categories each covering a smaller range of customer numbers. However, the approach in this project has been to limit the number of categories to provide a manageable number of substation archetypes.

Table 3: Actual number of domestic customers on distribution substation versus number of customers on assigned substation archetype

Range of actual number of customers on substation	Number of modelled substations in this category	Modelled number of customers on assigned substation archetype
50-99	48	70
100-149	46	120
150-299	102	200
300-549	36	350
550+	2	600

The total number of customers modelled on each primary substation using the resulting substation archetypes is compared to the actual number of customers in Figure 5. The modelled number of customers is between 2-14% lower depending on the primary, meaning non-thermal loads will be slightly underestimated. This should be taken into account when interpreting the model results – substations with peak loads that come close to their rated limit in the modelled scenario results will likely be overloaded in reality.

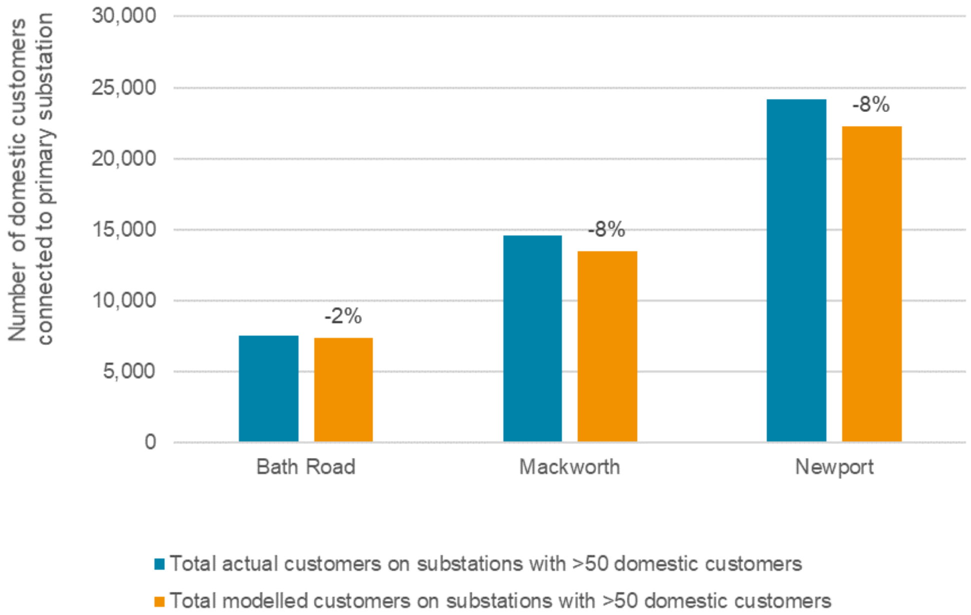

Figure 5: Modelled number of customers on each primary substation versus actual number of customers; percentage difference relative to total actual domestic customers on substations with >50 customers

Resulting substation archetypes

Combining the 4 typical house archetype groups and range of 5 modelled customer numbers per substation yielded 20 different distribution substation archetypes, though only 16 were used as there were instances where none of the analysed substations fell into 4 of the archetypes. The substation archetypes are listed in Table 4 on the following page, along with the number of each type connected to each of the three primaries.

Table 4: Number of distribution substation archetypes connected to each primary substation under study

Substation archetype code	House mix on substation	Number of domestic customers on substation	Number of secondary substations of each archetype on primary		
			Bath Road	Mackworth	Newport
D-70	Mainly detached and semi-detached homes	70	14	2	0
D-120		120	8	0	0
D-200		200	1	1	0
S-70	Mainly semi-detached homes with a mix of others	70	8	5	1
S-120		120	9		2
S-200		200	14	26	6
S-350		350	1	9	1
T-70	A mix of terraced houses, semi-detached houses and flats	70	0	3	12
T-120		120	0	2	12
T-200		200	0	3	47
T-350		350	0	1	22
T-600		600	0	1	1
F-70	Mainly flats with some terraces and semi-detached homes	70	0	1	2
F-120		120	0	1	1
F-200		200	2	1	1
F-350		350	0	2	0
Total number of substations			57	58	108
Total modelled number of customers			7,330	12,130	22,300

2.2. Assignment of heat pumps to houses under different scenarios

Two heat pump uptake scenarios were explored: one with a moderate level of heat pump uptake and one with a high level of uptake. Absolute levels of uptake were chosen based on the latest WPD DFES for the three primary substations, as described in section 2.2.1. Heat pumps were allocated to house archetypes based on which archetypes were judged to be most suitable for heat pumps, as described in section 2.2.2.

2.2.1. Heat pump uptake scenarios used based on DFES

In the moderate heat pump uptake scenario about 1,000 heat pumps were assumed to be installed on each primary substation – a level roughly in line with the level of uptake in 2025 in the DFES Consumer Transformation scenario. In the high uptake scenario this was increased to 2,500-3,500 per primary, in line with 2030 levels of uptake in this scenario for each area. This is illustrated in Figure 6, which presents both the absolute numbers and also the uptake percentage against the number of homes in each area. Figure 7 shows the four DFES for the Mackworth primary to 2050 with the modelled scenarios for comparison.

Relative to the total number of homes on each primary, heat pump uptake rate is highest on the Bath Road primary, which has the most detached/semi-detached houses and houses with non-gas fossil fuel boilers. It is lowest on the Newport East primary, which has a higher proportion of flats and mid-terrace houses.

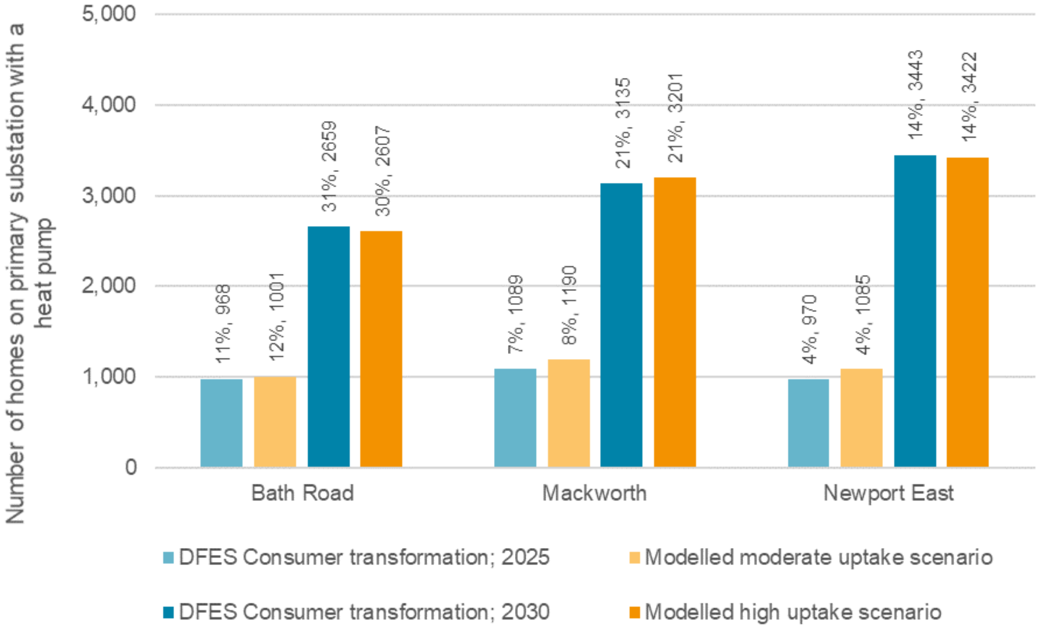

Figure 6: Number of homes on each primary substation with a heat pump installed under DFES and Peak Heat uptake scenarios; percentage share of total homes indicated above bars

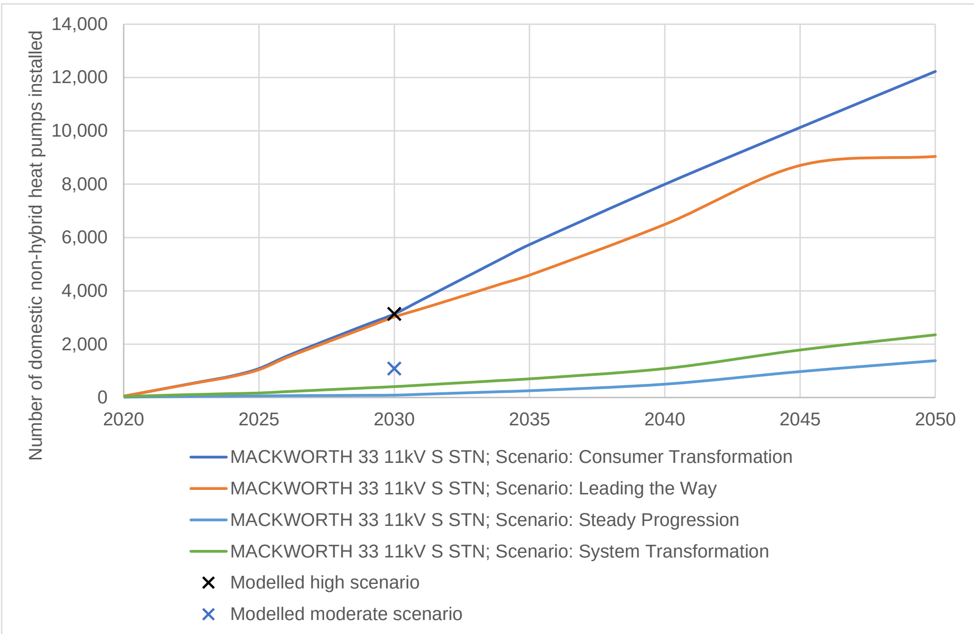

Figure 7: DFES for Mackworth substation versus modelled moderate and high uptake scenarios for 2030

2.2.2. Assignment of heat pumps to house archetypes for each distribution substation archetype

Heat pumps were assigned to house archetypes in order of suitability across the 16 distribution substation archetypes and then iteratively adjusted for each substation archetype until the uptake levels for the three primary substations were approximately aligned with the DFES. The initial heat pump uptake levels assigned across all substation archetypes before adjustments are given in Table 5 below.

Table 5: Initial heat pump uptake levels assigned to house archetypes across substation archetypes in moderate and high uptake scenarios before adjustment to align with DFES for primary substations

	Percentage of homes of each archetype with a heat pump installed								
	DH-G		DH-P	SH-G	SH-P	MT-G	MT-P	FL-G	FL-P
	ASHP	GSHP	GSHP	ASHP	ASHP	ASHP	ASHP	ASHP	ASHP
Moderate uptake scenario	25%	5%	5%	20%	10%	5%	2%	2%	1%
High uptake scenario	50%	10%	10%	50%	20%	15%	10%	10%	5%

The final absolute and relative numbers of heat pumps are presented in a matrix for each house archetype and substation archetype under the moderate and high uptake scenarios in Table 6 and Table 7 respectively.

Suitability for heat pumps was judged based on:

- **House type:** sufficient space is needed both outdoors and indoors for a heat pump, making detached and semi-detached houses the most likely to be suitable and flats the least likely to be suitable.
- **Thermal insulation:** properties with good levels of insulation are better suited to heat pumps as they are less likely to require significant energy efficiency improvements to be made before a heat pump can be installed.
- **Heat demand:** large, poorly insulated properties are less likely to be suitable for heat pumps given their high heat demand. However, larger properties are more likely to have the outdoor space for a ground source heat pump. For this reason, poorly insulated detached houses (DH-P) were only assigned ground source heat pumps. A small number of ground source heat pumps were also assigned to well insulated detached properties (DH-G), but not to any other house types.
- **Current heating type:** Gas boilers are the most common heating type in most house archetypes (see Table 16, Appendix A). Houses with non-fossil fuel boilers (most common in DH-G homes on Bath Road primary) are likely to be early heat pump adopters as they have more potential to save on fuel costs than gas-heated homes. Houses with electric storage heaters (common in flats on all three primaries) are harder to retrofit with hydronic heat pumps because a heat distribution system needs to be installed.

Table 6: Assignment of heat pumps to house archetypes for each substation archetype under moderate heat pump uptake scenario; percentage penetration within archetype group; absolute uptake vs. total houses on substation shown in brackets (ASHP: air source heat pump; GSHP: ground source heat pump)

Substation archetype	DH-G		DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P	Total
	ASHP	GSHP	GSHP	ASHP	ASHP	ASHP	ASHP	ASHP	ASHP	
D-70	37% (7/19)	5% (1/19)	0% (0/3)	29% (7/24)	9% (1/11)	10% (1/10)	0% (0/2)	0% (0/1)	0% (0/1)	24% (17/71)
D-120	38% (12/32)	3% (1/32)	0% (0/5)	29% (12/41)	11% (2/18)	12% (2/17)	0% (0/4)	0% (0/2)	0% (0/1)	24% (29/120)
D-200	35% (19/54)	4% (2/54)	0% (0/8)	28% (19/68)	13% (4/30)	4% (1/28)	0% (0/6)	0% (0/4)	0% (0/2)	23% (45/200)
S-70	33% (2/6)	0% (0/6)	0% (0/8)	21% (3/14)	9% (1/11)	0% (0/5)	0% (0/9)	0% (0/13)	0% (0/4)	9% (6/70)
S-120	30% (3/10)	0% (0/10)	7% (1/14)	21% (5/24)	5% (1/19)	0% (0/8)	0% (0/16)	0% (0/23)	0% (0/6)	8% (10/120)
S-200	31% (5/16)	6% (1/16)	4% (1/24)	23% (9/40)	6% (2/32)	7% (1/14)	4% (1/26)	3% (1/38)	0% (0/10)	11% (21/200)
S-350	25% (7/28)	4% (1/28)	5% (2/42)	20% (14/70)	5% (3/56)	4% (1/25)	2% (1/46)	1% (1/67)	0% (0/18)	9% (30/352)
T-70	25% (1/4)	0% (0/4)	0% (0/2)	18% (2/11)	9% (1/11)	0% (0/6)	0% (0/14)	0% (0/13)	0% (0/8)	6% (4/69)
T-120	29% (2/7)	0% (0/7)	0% (0/4)	21% (4/19)	5% (1/19)	9% (1/11)	0% (0/24)	0% (0/22)	0% (0/14)	7% (8/120)
T-200	8% (1/12)	0% (0/12)	0% (0/6)	9% (3/32)	3% (1/32)	6% (1/18)	3% (1/40)	3% (1/36)	0% (0/24)	4% (8/200)
T-350	14% (3/21)	0% (0/21)	9% (1/11)	11% (6/56)	4% (2/56)	3% (1/32)	1% (1/70)	2% (1/63)	0% (0/42)	4% (15/351)
T-600	17% (6/36)	3% (1/36)	6% (1/18)	15% (14/96)	3% (3/96)	4% (2/54)	2% (2/120)	1% (1/108)	0% (0/72)	5% (30/600)
F-70	25% (1/4)	0% (0/4)	0% (0/1)	14% (1/7)	0% (0/4)	0% (0/4)	0% (0/11)	3% (1/31)	0% (0/10)	4% (3/72)
F-120	33% (2/6)	0% (0/6)	0% (0/2)	17% (2/12)	0% (0/6)	0% (0/6)	0% (0/18)	2% (1/53)	0% (0/17)	4% (5/120)
F-200	30% (3/10)	0% (0/10)	0% (0/4)	20% (4/20)	10% (1/10)	10% (1/10)	3% (1/30)	2% (2/88)	4% (1/28)	6% (12/200)
F-350	28% (5/18)	6% (1/18)	0% (0/7)	20% (7/35)	6% (1/18)	6% (1/18)	2% (1/53)	2% (3/154)	2% (1/49)	5% (19/352)

Table 7: Assignment of heat pumps to house archetypes for each substation archetype under high heat pump uptake scenario; percentage penetration within archetype group; absolute uptake vs. total houses on substation shown in brackets (ASHP: air source heat pump; GSHP: ground source heat pump)

Substation archetype	DH-G		DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P	
	ASHP	GSHP	GSHP	ASHP	ASHP	ASHP	ASHP	ASHP	ASHP	Total
D-70	68% (13/19)	5% (1/19)	0% (0/3)	71% (17/24)	64% (7/11)	30% (3/10)	0% (0/2)	0% (0/1)	0% (0/1)	58% (41/71)
D-120	63% (20/32)	6% (2/32)	0% (0/5)	78% (32/41)	56% (10/18)	35% (6/17)	25% (1/4)	0% (0/2)	0% (0/1)	59% (71/120)
D-200	56% (30/54)	6% (3/54)	13% (1/8)	68% (46/68)	33% (10/30)	29% (8/28)	0% (0/6)	0% (0/4)	0% (0/2)	49% (98/200)
S-70	83% (5/6)	17% (1/6)	13% (1/8)	64% (9/14)	9% (1/11)	20% (1/5)	0% (0/9)	8% (1/13)	0% (0/4)	27% (19/70)
S-120	80% (8/10)	10% (1/10)	7% (1/14)	63% (15/24)	11% (2/19)	13% (1/8)	6% (1/16)	9% (2/23)	0% (0/6)	26% (31/120)
S-200	75% (12/16)	6% (1/16)	8% (2/24)	65% (26/40)	28% (9/32)	21% (3/14)	4% (1/26)	11% (4/38)	0% (0/10)	29% (58/200)
S-350	50% (14/28)	4% (1/28)	7% (3/42)	50% (35/70)	11% (6/56)	12% (3/25)	4% (2/46)	9% (6/67)	6% (1/18)	20% (70/352)
T-70	50% (2/4)	0% (0/4)	0% (0/2)	55% (6/11)	9% (1/11)	17% (1/6)	7% (1/14)	8% (1/13)	0% (0/8)	17% (12/69)
T-120	57% (4/7)	0% (0/7)	0% (0/4)	53% (10/19)	11% (2/19)	9% (1/11)	4% (1/24)	9% (2/22)	7% (1/14)	17% (20/120)
T-200	25% (3/12)	0% (0/12)	0% (0/6)	41% (13/32)	9% (3/32)	17% (3/18)	5% (2/40)	6% (2/36)	0% (0/24)	13% (26/200)
T-350	38% (8/21)	5% (1/21)	9% (1/11)	45% (25/56)	9% (5/56)	16% (5/32)	6% (4/70)	6% (4/63)	2% (1/42)	15% (53/351)
T-600	42% (15/36)	6% (2/36)	6% (1/18)	47% (45/96)	8% (8/96)	11% (6/54)	4% (5/120)	8% (9/108)	1% (1/72)	15% (91/600)
F-70	50% (2/4)	0% (0/4)	0% (0/1)	57% (4/7)	0% (0/4)	0% (0/4)	9% (1/11)	6% (2/31)	0% (0/10)	13% (9/72)
F-120	50% (3/6)	0% (0/6)	0% (0/2)	50% (6/12)	17% (1/6)	17% (1/6)	6% (1/18)	6% (3/53)	6% (1/17)	13% (15/120)
F-200	50% (5/10)	10% (1/10)	0% (0/4)	50% (10/20)	10% (1/10)	10% (1/10)	7% (2/30)	8% (7/88)	4% (1/28)	14% (27/200)
F-350	50% (9/18)	6% (1/18)	14% (1/7)	51% (18/35)	11% (2/18)	11% (2/18)	6% (3/53)	8% (13/154)	4% (2/49)	14% (49/352)

2.3. Modelling distribution substation archetypes in Plexos

The individual house archetype load profiles determined in WP3 were aggregated to model each of the substation archetypes. Rather than using the same load profiles for all houses of a particular archetype and simply applying a factor to account for diversity, Plexos was used to generate unique thermal and non-thermal demand profiles for each individual house in order to simulate diversity across the network.

2.3.1. Use of stochastic profiles in Plexos for heating and non-thermal demands

Plexos allows stochastic profiles to be generated based on a sample profile. This sample profile is treated as the mean value, and stochastic profiles are randomly generated based on a defined probability distribution.

To simulate diversity across the network, stochastic profiles were generated for:

- Heat loss from each house;
- Hot water demand of each house; and
- Non-thermal electrical demand of each house.

The profiles for the eight house archetypes created in WP3 were used as the sample profiles from which the stochastic profiles were generated.

The following properties were specified in Plexos to define the probability distributions:

- Min value: The minimum value a demand profile can take in a half hour.
- Max value: The maximum value a demand profile can take in a half hour.
- Std dev error: A percentage value between 0 and 100 indicating how widely distributed values are around the mean value for a given half hour. In a normal distribution, 68% of values fall within one standard deviation of the mean, and 95% of values fall within two standard deviations of the mean.
- Auto correlation: A percentage value between 0 and 100 indicating how strongly correlated the values in a half hour are with the values in the previous half hour. A high degree of correlation will result in relatively smooth profiles, whereas a low degree of correlation will result in profiles with large changes from half hour to half hour.
- Distribution type: Whether values follow a normal or lognormal statistical distribution.

2.3.2. Stochastic heat loss profiles

The rate at which houses lose heat depends on their insulation level and the relative difference between the indoor and outdoor temperatures. Figure 8 below from the WP3 report shows example heat loss profiles for the SH-G house archetype (semi-detached, good insulation) on a day in January.

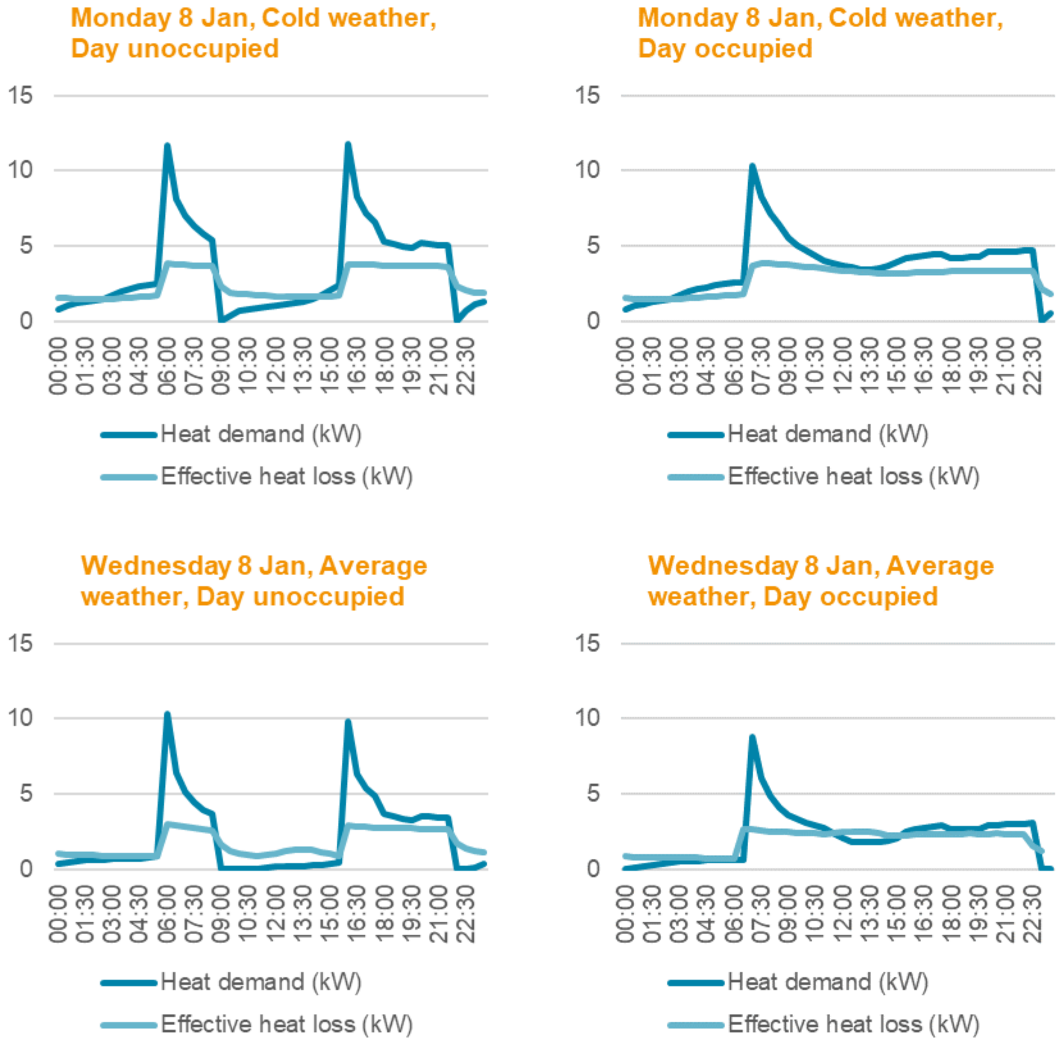

Figure 8:Heat demand and heat loss outputs from building physics model for Archetype C (semi-detached house, good insulation) on a day in January

Across houses of a particular archetype, differences in heat loss for a particular half hour will be due to:

- Different occupancy patterns from the average occupancy times assumed;
- Different indoor temperature preferences from the averages assumed; and
- Different heat loss rates due to differences in building thermal performance.

Differences due to building thermal performance are likely to be the most significant. Annual heating costs from the EPC analysis done in WP1 were used as a proxy to quantify differences in half hourly heat losses.

Figure 9 shows the distributions of annual heating cost estimates from the EPCs for the eight house archetypes. Based on these distributions, normal distributions with standard deviation errors of 50% were assumed for all house archetypes. Some archetypes could instead have been modelled with lognormal distributions, but a decision was taken to use normal distributions in order to have more stochastic profiles with above average values. This way the calculated substation electricity demands are more likely to be slightly overestimated rather than underestimated.

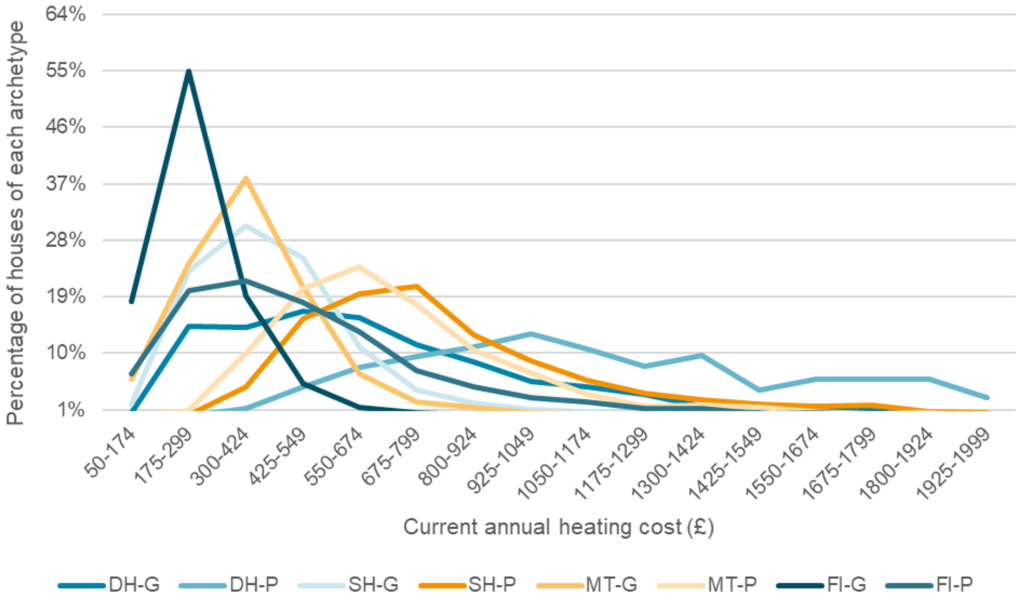

Figure 9: Distribution of current annual heating costs in EPCs analysed for the three primary substations; by house archetype

Heat pump capacities were different between the eight house archetypes, but fixed for all houses of the same archetype. Maximum values were therefore taken to be the maximum half hourly heat losses occurring for each archetype under cold weather conditions. Similarly, minimum values were based on the minimum half hourly heat losses occurring during the warmest modelled period.

Auto correlation was determined by plotting the half hourly heat loss values against the values for the previous half hour. This showed high levels of correlation of around 80% for all house archetypes.

The properties used in Plexos to create the stochastic heat loss profiles for all house archetypes are given in Table 8.

Table 8: Properties used in Plexos to create stochastic heat loss profiles for house archetypes

	DH-G	DH-P	SH-G	SH-P	MT-G	MT-P	FL-G	FL-P
Min value (heat loss kWth ÷ 7.5[5])	0.10	0.17	0.08	0.15	0.07	0.09	0.02	0.04
Max value (heat loss kWth ÷ 7.5[5])	0.90	1.61	0.64	0.95	0.38	0.57	0.12	0.21
Std dev error (%)	50							
Auto correlation (%)	80							
Distribution type	Normal							

Figure 10 shows an example of four stochastic heat loss profiles generated for well-insulated detached homes (DH-G) on a weekday in January.

Figure 10: Example stochastic heat loss profiles for four well-insulated detached house archetypes (DH-G), day unoccupied, on Tuesday 8 January in cold weather scenario

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[5] Certain input values needed to be divided by 7.5 in Plexos, the maximum potential COP of a heat pump, so that efficiency values ranged from 0-100%. This is explained in the WP3 report.

2.3.3. Stochastic hot water demand profiles

Hot water demand typically peaks in the morning and evening, as illustrated in Figure 11 below from the WP3 report.

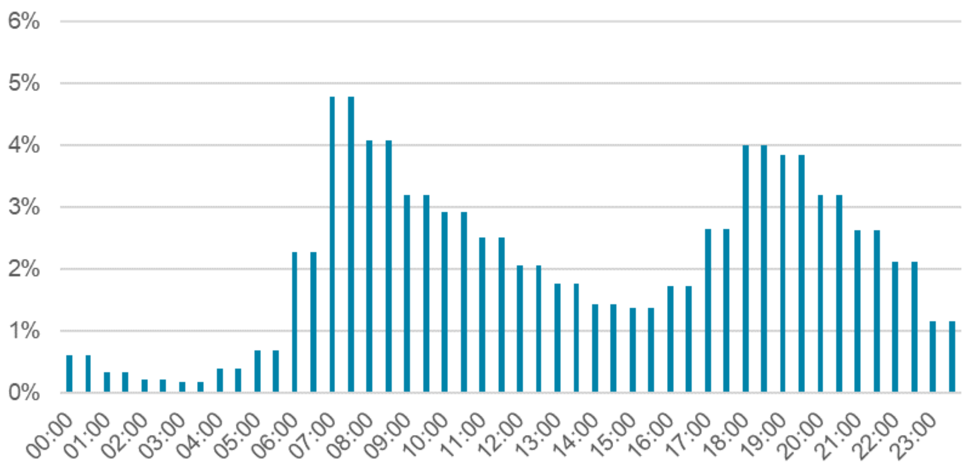

Figure 11: Average percentage of total daily hot water consumption in each half hour

For the generation of stochastic hot water demand profiles from the average profiles for each house archetype:

- A minimum value of 0 was assumed for all archetypes, as there can be periods when no hot water is used in a house.
- A maximum value equivalent to 15 litres/min was used for all archetypes, which is roughly the flow rate that could be provided by a high-pressure shower.
- A standard deviation error of 30% was used with a normal distribution, based on the range of daily demands observed across homes surveyed by the Energy Savings Trust[6].
- Auto correlation was determined by plotting the half hourly hot water demand values against the values for the previous half hour.

The properties used in Plexos to create the stochastic hot water demand profiles for all house archetypes are given in Table 9.

[6] Measurement of Domestic Hot Water Consumption in Dwellings, Energy Savings Trust, 2008: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48188/3147-measure-domestic-hot-water-consump.pdf

Table 9: Properties used in Plexos to create stochastic hot water demand profiles for house archetypes

	All house archetypes
Min value (hot water demand kWth ÷ 7.5[7])	0
Max value (hot water demand kWth ÷ 7.5[6])	0.15
Std dev error (%)	30
Auto correlation (%)	50
Distribution type	Normal

2.3.4. Stochastic non-thermal electricity demand profiles

Non-thermal electricity demand depends on factors such as property size, occupancy and weather conditions. The non-thermal electricity demand profiles used for each property type are shown on the following page in Figure 12 from the WP3 report.

For the generation of stochastic non-thermal electricity demand profiles from the average profiles for each house archetype:

- A minimum value of 0.1 kWe was assumed for all archetypes.
- A maximum value of 4 kWe, equivalent to having multiple appliances such as an electric oven, washing machine, and lighting on during a half hour.
- A standard deviation error of 40% was used with a normal distribution, based on the range of annual demands observed across homes in the Household Electricity Survey[8].
- Auto correlation was determined by plotting the half hourly electricity demand values against the values for the previous half hour.

The properties used in Plexos to create the stochastic non-thermal electricity demand profiles for all house archetypes are given in Table 10 on the next page.

[7] Certain input values needed to be divided by 7.5 in Plexos, the maximum potential COP of a heat pump, so that efficiency values ranged from 0-100%. This is explained in the WP3 report.
[8] Household Electricity Survey: A study of domestic electrical product usage, 2012: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/208097/10043_R66141HouseholdElectricitySurveyFinalReportissue4.pdf

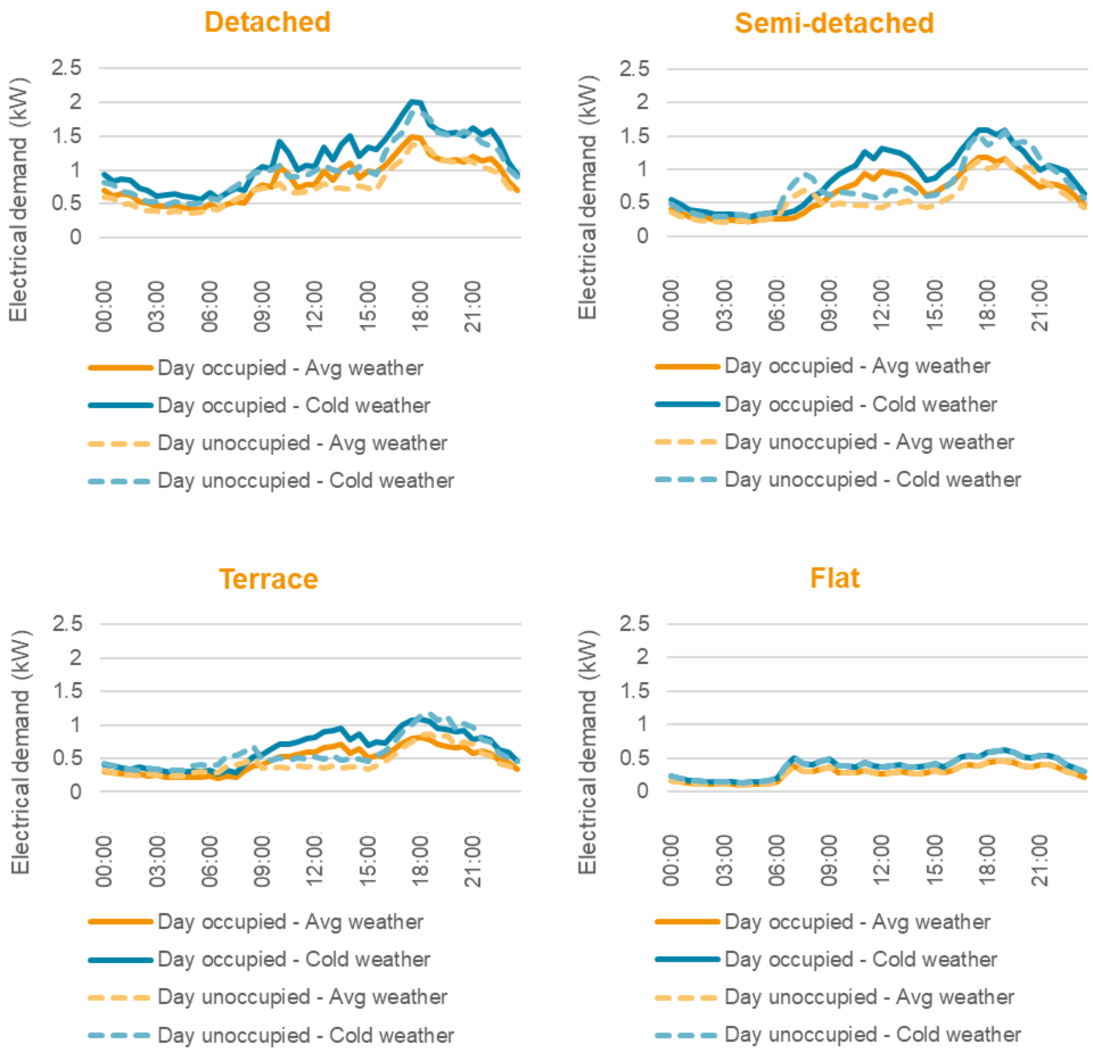

Figure 12: Average Non-thermal electrical demand profiles for each house type under different occupancy and weather conditions (average winter or coldest days)

Table 10: Properties used in Plexos to create stochastic non-thermal electricity profiles for house archetypes

	All house archetypes
Min value (kWe)	0.1
Max value (kWe)	4
Std dev error (%)	40
Auto correlation (%)	60
Distribution type	Normal

2.4. Addition of non-modelled loads

The load forecasts generated for the 16 substation archetypes did not include:

- Non-domestic loads, such as commercial buildings or industry; or
- Electric heating loads currently in houses, such as immersion heaters, electric boilers or electric storage heaters.

WPD provided historical load profiles for the three primary substations, as well as maximum demand indicators for all the distribution substations. Together these were used to estimate baseline average load profiles on each of the 234 modelled distribution substations before the installation of heat pumps. The modelled additional demand from heat pumps under different scenarios was then added to these baseline load profiles to determine whether each distribution / primary substation was likely to be overloaded.

Figure 13 shows the relative load profile on the peak day for each of the three primary substations based on the historical demand data. These profiles were scaled for each distribution substation using their historical maximum demand indicators.

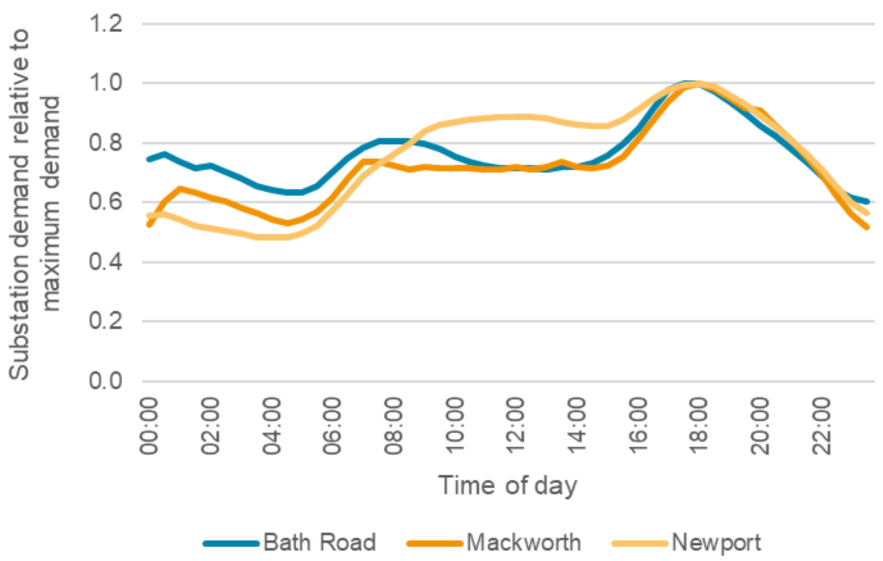

Figure 13: Relative substation load profile on peak day based on historical demand data

3. Results

Several scenarios were run in Plexos to determine the impact of different weather conditions, heat pump uptake levels and flexibility measures on substation loads. Results for the 16 distribution substation archetypes were then applied to the three primary substations under study. Of the 234 substations analysed, 22 are likely to be overloaded with moderate levels of heat pump uptake, and an additional 50 would be overloaded with high levels of heat pump uptake.

Allowing flexible hot water generation allows roughly 1% of demand to be shifted out of peak periods. Having flexible indoor temperatures has a negligible impact (<1%) on peak demands. Use of buffer tanks also only reduces peaks by 1-2%, and is therefore unlikely to be a cost effective flexibility measure. Installing electrical batteries in 50% of homes with heat pumps (which is a highly ambitious figure well in excess of DFES uptake projections, but considered for illustrative purposes in this study) can reduce peak demands by up to 9%, depending on the substation. Across the three primaries analysed, this could reduce the number of overloaded substations in a high heat pump uptake scenario from 94 to 51. Because heat pumps produce 2-3 units of heat for every unit of electricity, electrical batteries are a much more space efficient form of storage than thermal stores. WP5 will look at how the costs of electrical batteries compares to the cost of substation upgrades.

The results of the WP4 modelling are presented in this section. This section begins with an explanation of the different scenarios modelled and why these scenarios were chosen. Results are then presented for the distribution substation archetypes under each of the scenarios. The final section looks at what these results mean for the WPD areas under study.

3.1. Modelled scenarios

Many different scenarios were possible based on the variables used in this analysis. The variable inputs for the substation level modelling were as follows:

- **Weather:** average or cold weather profile
- **Heat pump uptake:** moderate or high uptake
- **Indoor temperature requirement:** set or flexible, with more allowance for pre-heating and slightly lower set temperatures
- **Hot water generation:** maintain 80% charge level or flexible, with no minimum charge level requirement
- **Buffer tank uptake:** how many homes with heat pumps also have buffer tanks
- **Electrical battery uptake:** how many homes with heat pumps also have batteries
- **Electricity price:** fixed or variable

Given the research objectives of this study to estimate the impact of heat pump uptake on peak demand and how much peaks can be reduced with heat flexibility measures, model runs were done for the 12 scenarios listed in Table 11. The choice of scenario variables is explained below. Note that the scenarios effectively assume 100% uptake of flexibility measures, except in the case of electrical batteries which are assumed to be installed in 50% of homes with heat pumps, and should therefore be treated as illustrative rather than predictive.

Table 11: Inputs for modelled scenarios for each distribution substation archetype

No.	Scenario	Weather	Heat pump uptake	Indoor temperature profile	Hot water generation	Buffer tank uptake	Electrical battery uptake	Electricity price
1	Baseline	Average	Moderate	Set	Maintain 80% charge	None	None	Fixed
2	Baseline	Average	High	Set	Maintain 80% charge	None	None	Fixed
3	Baseline	Cold	Moderate	Set	Maintain 80% charge	None	None	Fixed
4	Baseline	Cold	High	Set	Maintain 80% charge	None	None	Fixed
5	Scenario	Cold	Moderate	Set	Flexible	None	None	Variable
6	Scenario	Cold	Moderate	Flexible	Flexible	None	None	Variable

No.	Scenario	Weather	Heat pump uptake	Indoor temperature profile	Hot water generation	Buffer tank uptake	Electrical battery uptake	Electricity price
7	Scenario	Cold	Moderate	Set	Flexible	In all homes with heat pumps	None	Variable
8	Scenario	Cold	Moderate	Set	Flexible	None	In 50% of homes with heat pumps	Variable
9	Scenario	Cold	High	Set	Flexible	None	None	Variable
10	Scenario	Cold	High	Flexible	Flexible	None	None	Variable
11	Scenario	Cold	High	Set	Flexible	In all homes with heat pumps	None	Variable
12	Scenario	Cold	High	Set	Flexible	None	In 50% of homes with heat pumps	Variable

Weather

Baseline model runs were done for both the average and cold weather profiles. Scenario model runs were only done for the cold weather profile, as peak/maximum demands will occur under these conditions.

Heat pump uptake

All baseline and scenario model runs were done for both moderate and high levels of heat pump uptake (see Section 2.2 for how uptake levels were defined).

Indoor temperature requirement

Baseline model runs were done with a set indoor temperature profile. In test model runs where the flexible temperature profile was used, it was found that the reduction in peak demand was negligibly small. For this reason, and because this measure would be complex to implement in practice, the flexible temperature profile was only adopted with 100% uptake in two scenarios and zero uptake in the others for illustrative purposes.

Hot water generation

In the baseline scenarios, hot water cylinders are set to maintain a level of charge of at least 80%, which results in most hot water generation occurring after the morning and evening usage periods. In all other scenarios flexible hot water generation is allowed, meaning no minimum charge level is required provided that hot water demand can always be met. For illustrative purposes, this flexible generation was applied with 100% uptake in all non-baseline scenarios as it would be relatively easy to implement in practice by programming when hot water cylinders can and cannot charge during the day.

Buffer tank uptake

Before considering likely levels of buffer tank uptake among households, a test model scenario was run where all homes with heat pumps installed buffer tanks. In this scenario the buffer tanks enabled only a small reduction in peak demand. For this reason, lower levels of buffer tank uptake were not tested in other scenarios. As such, a similar approach has been adopted as for the previous flexibility measures such that an illustrative uptake of 100% was assumed for buffer tanks in the two scenarios where they were considered, and zero uptake in all other scenarios.

An additional test scenario was run with both flexible indoor temperatures and buffer tanks, but again the impact on peak reduction is minimal, so this combination was not included in the final modelled scenarios.

Electrical battery uptake

Various levels of battery uptake among homes with heat pumps were tested when choosing scenarios. It was found that higher levels of uptake resulted in greater peak demand reductions, but only up to a point. Reasons for this are discussed in Section 3.2.3. The point at which additional batteries made little difference in peak demand reduction was at around 50% of homes with heat pumps also installing batteries. Up until this point the reduction in peak demand increased approximately linearly with level of battery uptake. Batteries being installed in 50% of homes with heat pumps would be a high level of battery uptake in practice, but it has been used in the modelled scenarios to illustrate the theoretical levels of demand reduction achievable with batteries.

By way of explanation, whilst installation of electrical batteries in 50% of homes with heat pumps provides demand reductions, this level of uptake differs significantly from the assumptions adopted in the DFES. Figure 14 presents a comparison of the capacity of electrical battery uptake in 2030 and 2050 from DFES for the primary substation areas considered in Peak Heat alongside the equivalent capacity based on the assumption that 50% of the homes with heat pumps in 2030 would also have electrical batteries installed.

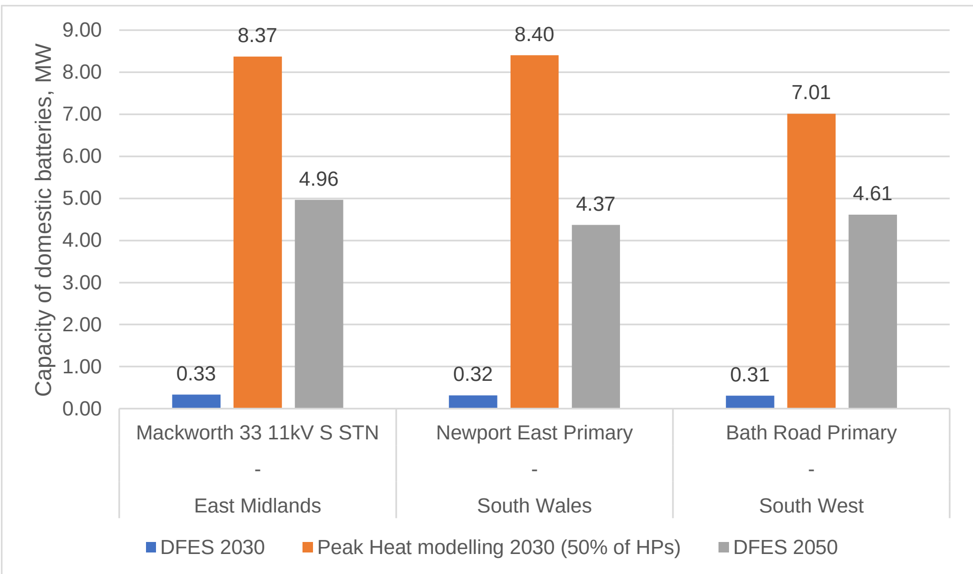

Figure 14: Comparison of electrical battery uptake assumptions from DFES and Peak Heat modelling

Figure 14 shows that, based on the battery capacities defined for each house archetype in the WP3 report, the assumption of 50% uptake of electrical batteries in homes with heat pumps in the Peak Heat modelling corresponds to 7.0-8.4 MW of battery capacity in the primary areas considered. These values exceed the DFES projected uptakes of battery capacity in 2030 (factors of between 22-27) and 2050 (factors of between 1.5-1.9). In line with the approach adopted for other flexibility measures, the value of 50% uptake has been selected as an illustrative figure corresponding to the upper limit for the demand reductions that can be derived from batteries. This level of uptake is ambitious, but could be achieved in practice if strong enough financial incentives were offered to encourage households to install batteries and allow their loads to be managed.

Batteries were assigned to house archetypes in line with the assignment of heat pumps (see Section 2.2), with houses having higher uptake of batteries and flats having lower uptake.

Electricity price

In WP3 a variable tariff was used based on the Octopus Agile tariff for the study area. At the individual house level with the Agile tariff profile it was found that all flexible loads moved from the high price evening period to the lowest price period around 03:00, causing peak demands to be shifted rather than reduced. Electricity supply limits were introduced in WP3 to prevent this peak shifting effect and instead force peak reduction.

At the substation level in WP4 it was found that under moderate level of heat pump uptake, adding flexibility measures and using an Agile tariff profile resulted in an overall reduction in peak demand. However, at high levels of heat pump uptake with an Agile tariff profile, a high number of hot water cylinders and batteries charging in the lowest price period between 02:00 and 05:00 could cause a small overall increase in peak demand. An example of this is shown in Figure 15, where an additional example model run was done with flexible hot water generation and batteries on an Agile tariff profile. In this case it can be seen that all hot water cylinders and batteries are charged mostly between 02:00 and 05:00, causing spikes in demand.

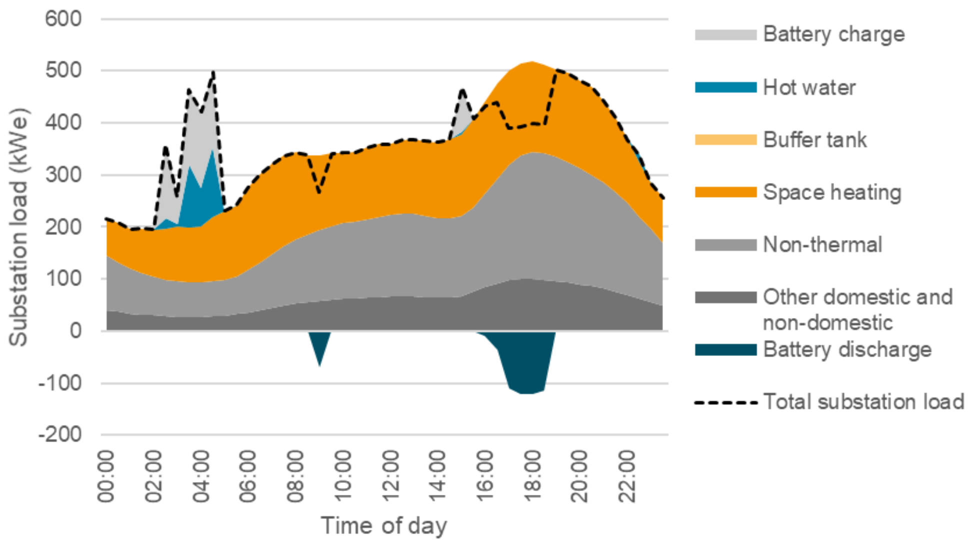

Figure 15: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) with high levels of heat pump uptake in additional example scenario on an Agile tariff profile with flexible hot water generation and electrical batteries in 50% of houses with heat pumps

Rather than introducing any kind of electricity supply limits in WP4, the time-of-use tariff profile was iteratively adjusted to encourage the desired peak reduction. The resulting variable tariff profile is shown in Figure 16 in orange. As can be seen from the chart, this profile has flat prices in the off-peak periods between 22:00 and 06:30, giving a wide window in which hot water cylinders and electrical batteries can charge at optimal cost. This combined with the use of stochastic demand profiles (see Section 2.3) yielded reasonable levels of diversity in the flexible load profiles. A peak price was introduced between 16:00 and 19:30 to align with peak non-thermal electricity demand. A gradual increase in price leading up to the peak price period was introduced to prevent flexible loads from concentrating in the hour or so before the price goes up at 16:00. A gradual decrease in price between 19:30 and 22:00 was used rather than a step down to off-peak, as spikes in heating demand occurred at this step down when more flexible indoor temperatures were allowed.

It should be noted that the cost optimisation algorithm used in this analysis responds to relative differences in price rather than absolute price values. Higher variable prices could have been used in line with current market rates, but the results would be the same provided the relative changes in price were unchanged.

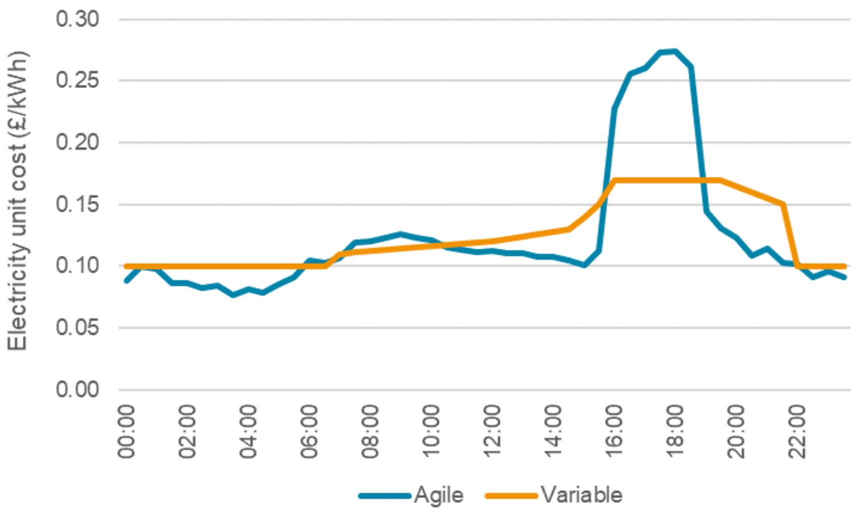

Figure 16: Agile time-of-use tariff profile used in WP3 and variable time-of-use profile used in WP4

3.2. Distribution substation archetype results

3.2.1. Distribution Transformer Ratings

The capacity analysis carried out as part of this study has been based on nameplate (continuous) ratings of distribution transformers from WPD's Enterprise Asset Management (EAM) system, CROWN. It is recognised that the reinforcement/replacement of individual transformers would consider the application of a cyclic rating, which can range from 10% to 40% larger than continuous rating depending on the type of transformer, the location (indoor, outdoor, underground, pole-mounted etc.) and load factor specific to each site. This more detailed analysis is normally undertaken using power system analysis software to determine the bespoke cyclic rating that can be applied to the transformer. In addition, the assessment will also require the user to investigate possible factors that could limit the capacity such as the associated switchgear/fusegear, protection devices and connections. Hence, for this desktop study the use of continuous nameplate ratings have been applied in the analysis. This approach aligns with other WPD policy documentation for similar studies. The results of the capacity assessment using this approach indicate earlier reinforcement intervention compared with an approach where bespoke cyclic ratings are used. A detailed analysis of each site would be required to obtain accurate cyclic ratings, however, our initial analysis shows that intervention could be delayed by around four years if a cyclic rating of 130% were applied across all sites. A recommendation from this study would be to carry out further investigation into individual sites and the possible load factor changes (considering the uptake of EVs in addition to HPs) in order to accurately calculate appropriate cyclic ratings for each site.

3.2.2. Peak loads on distribution substation archetypes in modelled scenarios

Table 12 and Table 13 show the peak/maximum half hourly demands occurring on each of the 16 distribution substation archetypes under the 12 modelled scenarios for moderate and high HP uptake, respectively. They also give the typical continuous nameplate ratings of each substation archetype for comparison, based on the data provided for the substations in the three study areas. The colours indicate whether these substation archetypes are likely to be overloaded under different scenarios (green: unlikely, yellow: possibly depending on rating, red: likely). The relative changes in peak demands and relative reductions achieved with heat flexibility measures are provided in Appendix C for reference.

From these results it can be seen that relative peak demand increases range widely depending on the substation archetype and level of heat pump uptake, from as little as 4% up to over 80%. The relative increase in peak demand is highest on substations with more detached (D) and semi-detached (S) properties, where heat pump uptake is likely to be concentrated.

It is also evident that half the substation archetypes (representing about half the modelled substations) are likely to have sufficient capacity to handle even high levels of heat pump uptake under cold weather conditions. These tend to be the substations with fewer customers currently (70 or 120 homes) and moderate-high capacities (500 kW or higher). Conversely, it was also noted that some substations might already have maximum demands above their continuous nameplate ratings (see S-350 and T-600). However, it is suggested that data quality issues may exist such that previous upgrades to substation capacities have not been recorded in the data used for this analysis. In addition, as stated in section 3.2.1, during winter, maximum demands can be allowed to exceed the continuous nameplate rating during daily peak periods without causing transformer damage, given a certain load profile. Winter cyclic ratings used for design purposes are 10-40% higher than continuous nameplate ratings.

Some substations archetypes are likely to have sufficient capacity for moderate levels of heat pump uptake but not high levels (see D-70, D-120, S-200 and F-350). For some of the substation archetypes that would be overloaded with high levels of heat pump uptake, the use of flexibility measures can keep peak demands within substation limits (e.g. see D-120). However, there are also substation archetypes for which these measures are unlikely to be sufficient to avoid substation upgrades (see D-70 and F-350).

Introducing flexible hot water generation (scenarios 5 and 9) moves all hot water loads out of peak periods, but because this only accounts for a small share of demand, the impact on peak reduction is minimal (~1-2%).

Allowing more flexibility in indoor temperatures (scenarios 6 and 10) gives almost no further reduction in peak demand (<1%). Reasons for this are discussed in the next section.

The addition of buffer tanks in all homes with heat pumps (scenarios 7 and 11) also gives only a minor reduction in total peak demand (~1-2% in addition to the reduction from flexible hot water generation). The impact of buffer tanks is limited because the heat storage capacity of buffer tanks is small relative to total daily heat demand. This is discussed further in the following section.

Electrical batteries are the most effective measure for reducing peak demands (scenarios 8 and 12), with 50% battery uptake among homes with heat pumps giving a further ~2-9% reduction in peak demand depending on the substation archetype. This is still a relatively small difference overall, but it can be enough to prevent substations being overloaded by the addition of space heating demand.

Table 12: Modelled scenario results for all distribution substation archetypes with moderate levels of heat pump uptake; maximum half hourly electricity demand (kW), time of maximum demand, date of maximum demand; colours indicate likely substation overload relative to typical continuous load nameplate rating, ignoring cyclic enhancements – green: unlikely, yellow: possibly depending on rating, red: likely

	Maximum demand on substation and time and date of maximum demand							
Scenario	**Present day**	**1**	**3**	**5**	**6**	**7**	**8**	**Typical distribution substation continuous load nameplate rating (kW)**
Weather		Average	Cold	Cold	Cold	Cold	Cold	
HP uptake		Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
D-70	206 kW 18:00 03/01	249 kW 18:00 03/01	261 kW 18:00 12/01	256 kW 18:00 13/01	256 kW 18:00 13/01	257 kW 18:00 12/01	238 kW 19:30 12/01	300 or 500
D-120	277 kW 18:00 03/01	349 kW 18:00 03/01	369 kW 18:00 12/01	363 kW 18:00 12/01	363 kW 18:00 12/01	359 kW 18:00 12/01	339 kW 19:30 12/01	500
D-200	397 kW 18:00 03/01	514 kW 18:00 03/01	549 kW 18:00 12/01	544 kW 18:00 12/01	543 kW 18:00 12/01	535 kW 18:00 12/01	514 kW 19:00 12/01	500
S-70	188 kW 18:00 03/01	204 kW 18:00 03/01	209 kW 18:00 12/01	207 kW 18:00 13/01	207 kW 18:00 13/01	207 kW 18:00 13/01	197 kW 18:00 12/01	315
S-120	249 kW 18:00 03/01	278 kW 18:00 01/01	285 kW 18:00 12/01	284 kW 18:00 12/01	283 kW 18:00 13/01	282 kW 18:00 12/01	272 kW 18:30 12/01	500
S-200	349 kW 18:00 03/01	399 kW 18:00 03/01	417 kW 18:00 12/01	415 kW 18:00 12/01	414 kW 18:00 12/01	410 kW 18:00 12/01	401 kW 19:00 12/01	500
S-350	539 kW 18:00 01/01	611 kW 18:00 03/01	630 kW 18:00 12/01	623 kW 18:00 11/01	622 kW 18:00 13/01	620 kW 18:00 11/01	589 kW 18:30 12/01	500 or 800
T-70	177 kW 18:00 03/01	188 kW 18:00 03/01	190 kW 18:00 12/01	190 kW 18:00 11/01	190 kW 18:00 11/01	189 kW 18:00 11/01	184 kW 18:30 12/01	315 or 500
T-120	234 kW 18:00 03/01	255 kW 18:00 03/01	262 kW 18:00 12/01	261 kW 18:00 12/01	261 kW 18:00 12/01	260 kW 18:00 12/01	253 kW 18:30 12/01	500 or 800
T-200	327 kW 18:00 03/01	342 kW 18:00 03/01	349 kW 18:00 12/01	347 kW 18:00 13/01	347 kW 18:00 13/01	346 kW 18:00 12/01	337 kW 18:30 12/01	500
T-350	493 kW 18:30 03/01	529 kW 18:30 03/01	541 kW 18:00 12/01	539 kW 18:00 12/01	539 kW 18:00 12/01	537 kW 18:00 12/01	520 kW 18:30 12/01	500 or 800
T-600	769 kW 18:30 03/01	836 kW 18:00 03/01	868 kW 18:30 12/01	863 kW 18:30 12/01	862 kW 18:30 12/01	857 kW 18:00 12/01	836 kW 18:30 12/01	500
F-70	167 kW 18:00 01/01	173 kW 18:00 03/01	175 kW 18:00 11/01	174 kW 18:00 13/01	174 kW 18:00 13/01	173 kW 18:00 12/01	168 kW 18:30 11/01	500
F-120	209 kW 18:00 03/01	221 kW 18:00 01/01	224 kW 18:00 12/01	223 kW 18:00 12/01	223 kW 18:00 12/01	222 kW 18:00 12/01	217 kW 18:00 12/01	500
F-200	282 kW 18:30 01/01	308 kW 18:30 01/01	316 kW 18:30 12/01	314 kW 18:00 11/01	314 kW 18:00 11/01	311 kW 18:00 12/01	302 kW 19:00 12/01	500
F-350	422 kW 18:30 03/01	462 kW 18:30 01/01	470 kW 18:00 12/01	465 kW 18:00 12/01	465 kW 18:00 13/01	464 kW 18:00 12/01	447 kW 19:00 12/01	500 or 750

Table 13: Modelled scenario results for all distribution substation archetypes with high levels of heat pump uptake; maximum half hourly electricity demand (kW), time of maximum demand, date of maximum demand; colours indicate likely substation overload relative to typical continuous load nameplate rating, ignoring cyclic enhancements – green: unlikely, yellow: possibly depending on rating, red: likely

	Maximum demand on substation and time and date of maximum demand							
Scenario	**Present day**	**2**	**4**	**9**	**10**	**11**	**12**	**Typical distribution substation continuous load nameplate rating (kW)**
Weather		Average	Cold	Cold	Cold	Cold	Cold	
HP uptake		High	High	High	High	High	High	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
D-70	206 kW 18:00 03/01	311 kW 17:30 13/01	340 kW 18:00 11/01	337 kW 18:00 12/01	336 kW 18:00 12/01	329 kW 18:00 12/01	312 kW 19:30 00/01	300 or 500
D-120	277 kW 18:00 03/01	450 kW 18:00 13/01	504 kW 18:00 12/01	497 kW 18:00 12/01	497 kW 18:00 12/01	486 kW 18:00 12/01	454 kW 19:30 00/01	500
D-200	397 kW 18:00 03/01	635 kW 18:00 12/01	702 kW 18:30 12/01	692 kW 18:00 12/01	689 kW 18:00 12/01	675 kW 18:00 12/01	648 kW 19:30 00/01	500
S-70	188 kW 18:00 03/01	234 kW 17:30 13/01	247 kW 18:00 13/01	244 kW 18:00 12/01	243 kW 18:00 12/01	241 kW 18:00 12/01	227 kW 19:30 00/01	315
S-120	249 kW 18:00 03/01	320 kW 18:00 13/01	346 kW 18:00 12/01	343 kW 18:00 12/01	343 kW 18:00 12/01	338 kW 18:00 12/01	309 kW 19:30 00/01	500
S-200	349 kW 18:00 03/01	491 kW 18:00 12/01	524 kW 18:00 12/01	518 kW 18:00 12/01	517 kW 18:00 12/01	506 kW 18:00 12/01	480 kW 19:30 00/01	500
S-350	539 kW 18:00 01/01	695 kW 18:00 13/01	751 kW 18:00 11/01	742 kW 18:00 12/01	741 kW 18:00 12/01	731 kW 18:00 12/01	700 kW 19:00 00/01	500 or 800
T-70	177 kW 18:00 03/01	206 kW 18:00 11/01	211 kW 18:00 11/01	210 kW 18:00 12/01	210 kW 18:00 13/01	208 kW 18:00 12/01	197 kW 19:00 00/01	315 or 500
T-120	234 kW 18:00 03/01	279 kW 18:00 12/01	294 kW 18:30 12/01	292 kW 18:00 12/01	293 kW 18:00 12/01	288 kW 18:00 12/01	280 kW 19:00 00/01	500 or 800
T-200	327 kW 18:00 03/01	376 kW 18:00 13/01	398 kW 18:00 13/01	395 kW 18:00 12/01	395 kW 18:00 12/01	391 kW 18:00 12/01	377 kW 19:00 00/01	500
T-350	493 kW 18:30 03/01	616 kW 18:00 12/01	644 kW 18:30 12/01	638 kW 18:00 12/01	636 kW 18:00 12/01	629 kW 18:00 12/01	601 kW 19:00 00/01	500 or 800
T-600	769 kW 18:30 03/01	970 kW 18:30 12/01	1,035kW 18:30 12/01	1,020kW 18:00 12/01	1,019kW 18:00 12/01	1,003kW 18:00 12/01	978 kW 19:00 00/01	500
F-70	167 kW 18:00 01/01	186 kW 18:00 13/01	189 kW 18:00 13/01	188 kW 18:00 11/01	188 kW 18:00 11/01	186 kW 18:00 12/01	178 kW 19:00 00/01	500
F-120	209 kW 18:00 03/01	239 kW 18:30 12/01	249 kW 18:00 12/01	247 kW 18:00 12/01	246 kW 18:00 12/01	244 kW 18:00 12/01	234 kW 19:00 00/01	500
F-200	282 kW 18:30 01/01	333 kW 18:30 12/01	348 kW 18:00 11/01	345 kW 18:00 12/01	345 kW 18:00 12/01	340 kW 18:00 12/01	326 kW 19:00 00/01	500
F-350	422 kW 18:30 03/01	508 kW 18:30 13/01	546 kW 18:30 12/01	539 kW 18:00 12/01	537 kW 18:00 12/01	530 kW 18:00 12/01	512 kW 19:00 00/01	500 or 750

3.2.3. Example half-hourly results for S-200 substation archetype

To give an example of what the half-hourly load profiles look like for the substation archetypes on the peak day, breakdowns are shown in Figure 17 to Figure 23 below for the S-200 archetype. S-200 was chosen because there are several substations of this archetype on each of the three primary substations, and about 20% of domestic customers are connected to substations of this archetype.

Figure 17 shows the baseline load profile under the high heat pump uptake scenario. Here it can be seen that heat demand is relatively constant throughout the day, and that the evening peak is mainly attributable to non-thermal electrical demands.

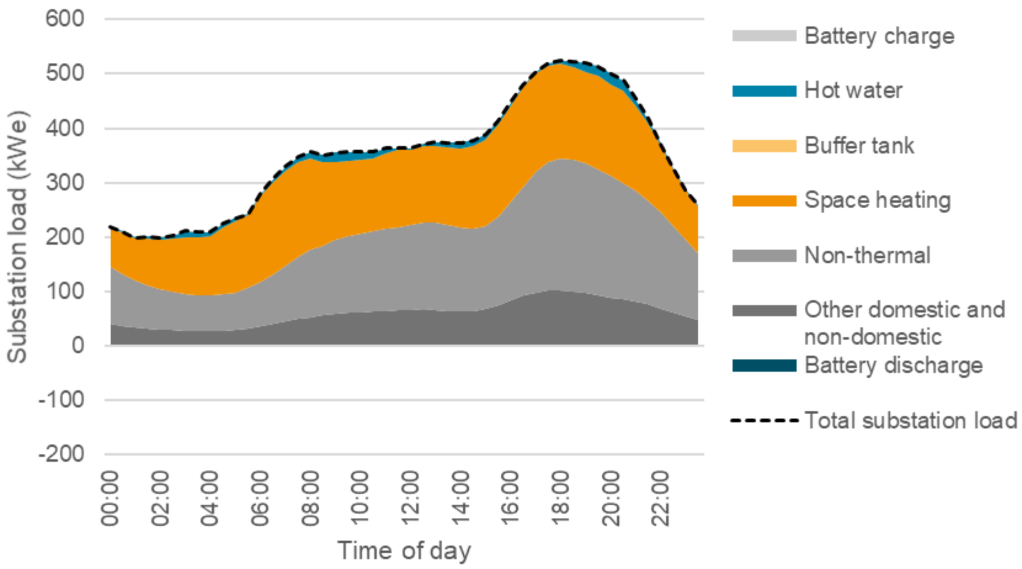

Figure 17: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in baseline scenario (4) with a fixed electricity price and no flexibility measures

Figure 18 shows how the introduction of the variable tariff and flexible hot water generation cause all hot water generation to be shifted to the lowest cost periods between 22:00 and 06:00. Because hot water generation only accounts for a small share of total demand, the impact on peak demand is minimal (~1-2% reduction).

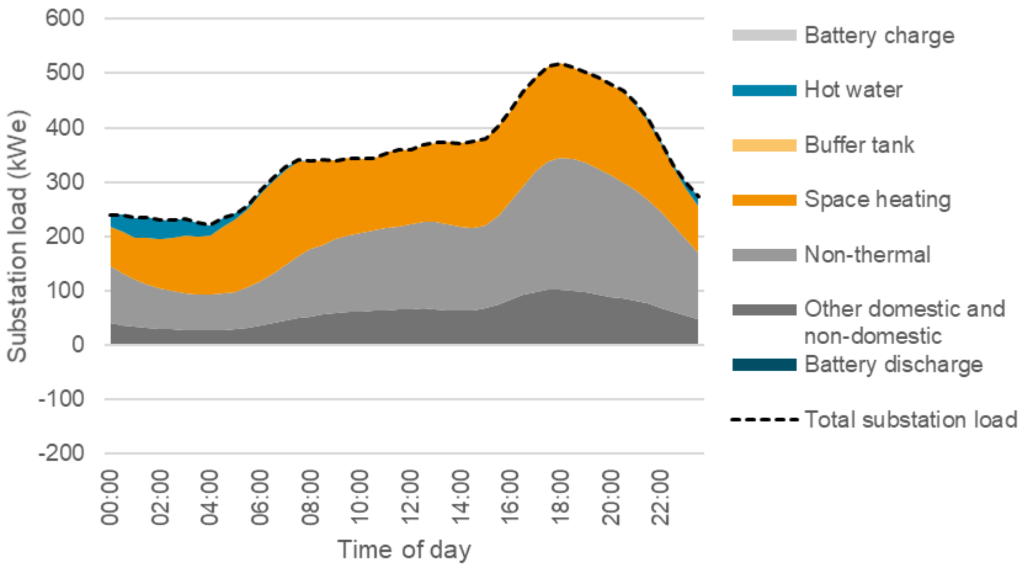

Figure 18: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in scenario (9) with a variable electricity price and flexible hot water generation

Figure 19 shows how allowing flexible indoor temperatures results in small changes to the space heating load profile, with minimal impact on total peak demand in the evening (~1% reduction). The impact is minimal because only a small change in temperature was allowed in this scenario, with optional pre-heating up to 21°C in the afternoon and 21±1°C during occupied periods (versus a baseline with preheating up to 19°C in the afternoon and 21±0.5°C during occupied periods). Whether homes are then pre-heated in the model will depend on whether it is cost-effective to do so, which in turn will depend on relative changes in electricity price and heat pump efficiency over the day. Pre-heating will be less effective during very cold conditions, when heat loss rates from houses to the surrounding environment are highest.

Figure 20 shows the average indoor temperature in the baseline and flexible temperature scenarios, along with the corresponding space heating demand profiles. In the flexible temperature scenario it can be seen that homes are heated to an average of 21°C shortly ahead of the evening peak, after which temperatures fall gradually to an average of about 20.5°C by the end of the heating period.

Also included in Figure 20 is an illustrative scenario with greater temperature flexibility where homes are allowed to be pre-heated to up to 25°C in the afternoon and temperatures can fall as low as 17°C during the evening heating period. In this more extreme example, there is a greater reduction in heating demand during the evening peak, which would give an overall reduction in substation peak demand of closer to 4% when added to the other substation loads. This added example demonstrates that even large changes in indoor temperature – which might not be acceptable to households – provide only small reductions in peak demands during very cold winter conditions.

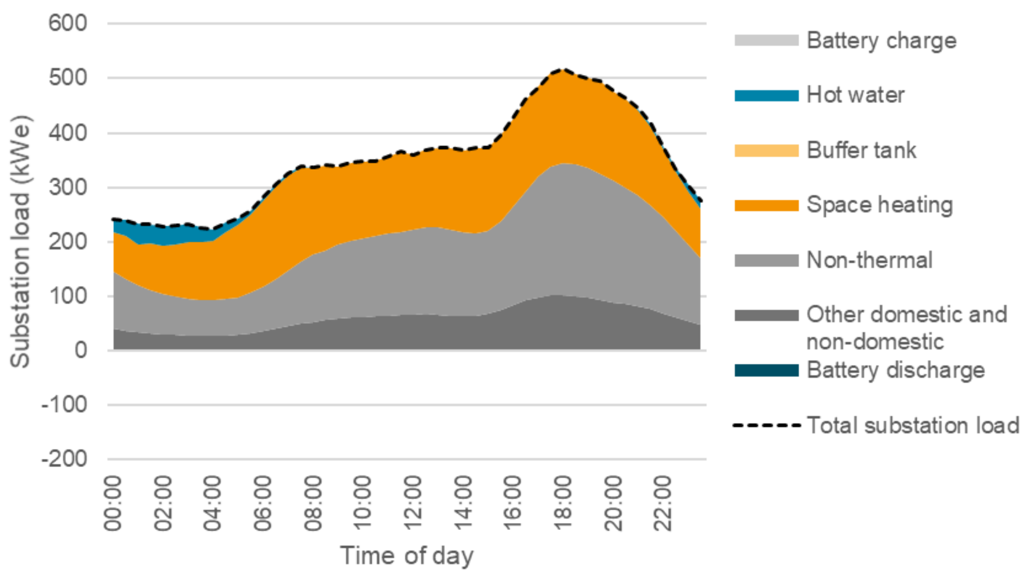

Figure 19: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in scenario (10) with a variable electricity price, flexible hot water generation and flexible indoor temperature requirements

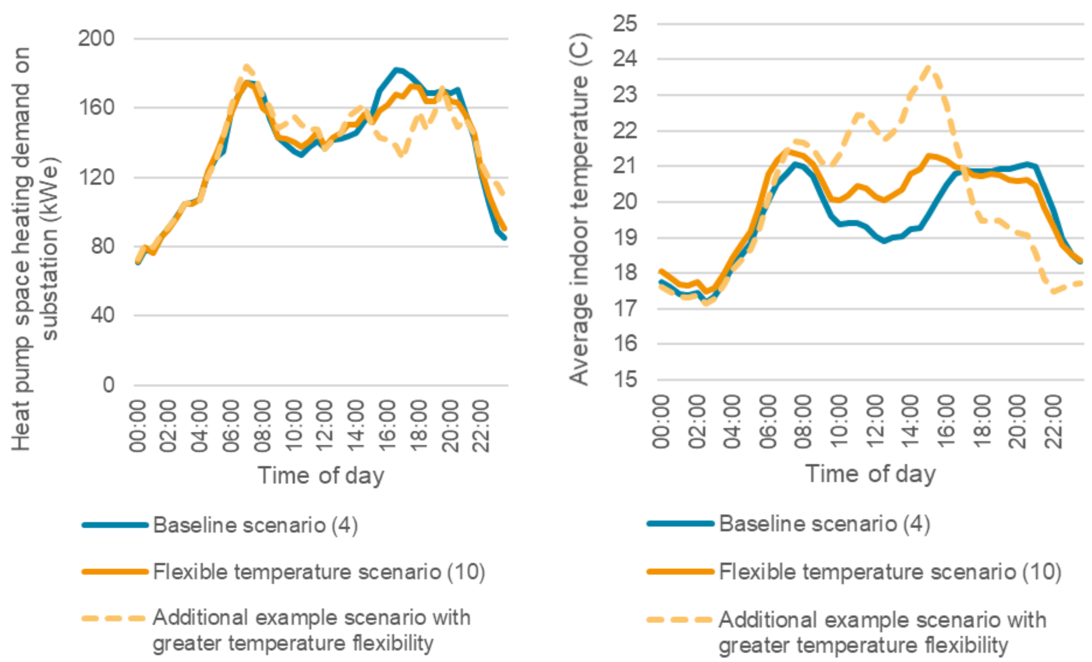

Figure 20: Demand on substation archetype S-200 due to heat pump demand for space heating and corresponding average indoor temperatures on coldest day (12 Jan) in baseline scenario (4), flexible temperature scenario (10) with high levels of heat pump uptake, and additional example scenario with greater temperature flexibility

The addition of buffer tanks in all homes with heat pumps also gives only a minor reduction in total peak demand (~1-2% in addition to the reduction from flexible hot water generation). Figure 21 shows how with the introduction of buffer tanks, total demand from heat pumps is split between direct space heating and charging the buffer tanks, as the tanks are continually charged and discharged throughout the day in response to small changes in heat pump efficiency.

The impact of buffer tanks is limited because the heat storage capacity of buffer tanks is small relative to total daily heat demand. For example, a 100 litre buffer tank storing water at about 40°C holds about 3kWh of heat, whereas a well-insulated detached house will use anywhere between 50-160 kWh of heat per day during winter. A buffer tank can therefore only provide up to about 15 minutes worth of space heating during evening peak periods. As an alternative to buffer tanks, heat batteries[9] with storage capacities of up to 14 kWh are available that could feasibly be installed in homes – a 14 kWh unit measures roughly 1m tall, 60cm across and 350cm deep. Figure 22 shows an additional illustrative scenario where 14 kWh thermal stores have been installed in all homes with heat pumps. Note that this example is illustrative, and that uptake levels would be lower in reality. In this example the thermal stores behave more like electrical batteries, and provide an overall reduction in peak substation demand of almost 15% relative to the baseline scenario. These differences highlight the importance of having the "right" thermal stores for managing loads on networks: buffer tanks do not store sufficient heat to shift significant load out of peak, and hot water would need to be stored in very large volumes to achieve this. Only high capacity thermal stores like heat batteries should be considered practical and effective for shifting space heating demands outside of peak periods.

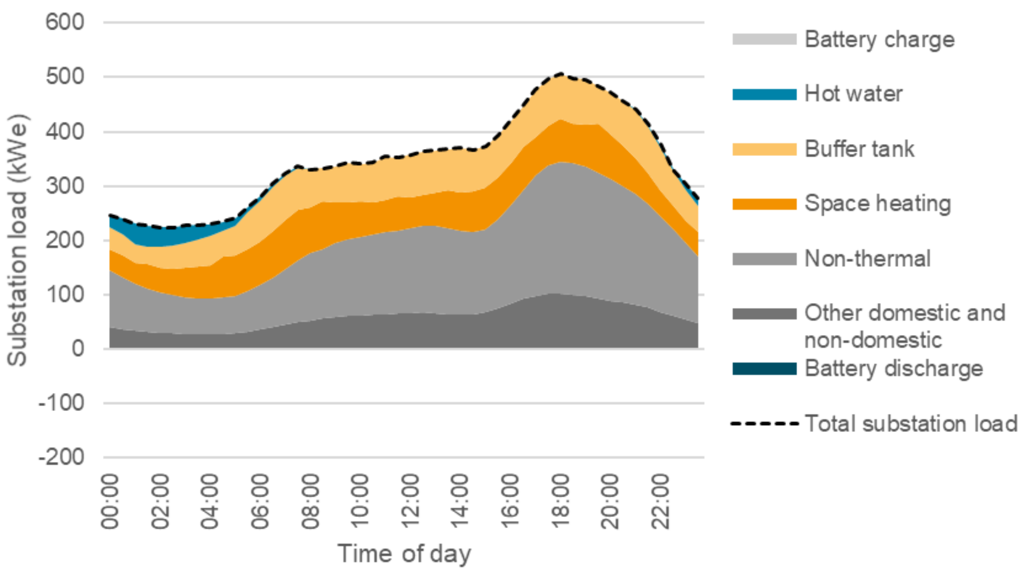

Figure 21: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in scenario (11) with a variable electricity price, flexible hot water generation and buffer tanks installed in all homes with heat pumps

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[9] More information on phase change material (PCM) heat batteries is provided in the WP2 report, including technical characteristics and current market status.

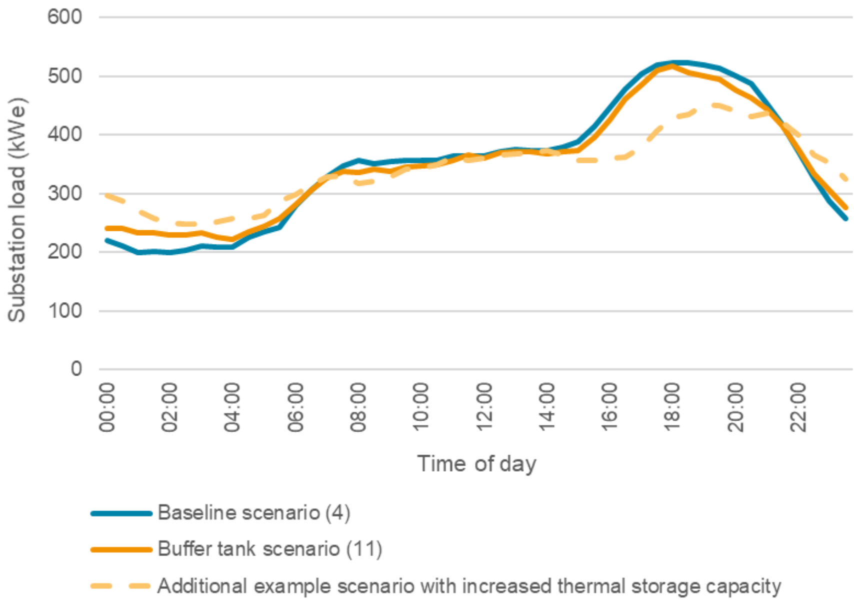

Figure 22: Total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in baseline scenario (4), scenario (11) with flexible hot water generation and buffer tanks, and additional scenario with 14 kWh thermal stores in all homes with heat pumps

Finally, Figure 23 shows the addition of electrical batteries (with capacities between 5 – 13.5 kWh and charge/discharge rates of 3 – 7 kW depending on property size) in 50% of homes with heat pumps. Electrical batteries are the most effective measure for reducing peak, with 50% battery uptake among homes with heat pumps giving a further ~2-9% reduction in peak demand depending on the substation archetype. This is still a relatively small difference overall, but as the previous results in Table 9 and Table 10 illustrate, it can be enough to prevent substations being overloaded by the addition of space heating demand. These batteries charge in the off-peak periods between 22:00 and 12:00. Some begin discharging at 15:00 as the price increases to the peak level at 16:00, and the majority discharge between 16:00 and 18:00, which reduces the substation peak demand to below the typical limit of 500 kW.

Adding more batteries yielded a greater reduction in demand between 16:00 and 18:00, but left the overall peak at 19:30 roughly the same. With further modification to the variable tariff profile, it might be possible to incentivise batteries to discharge more consistently though the peak period in order to achieve a greater overall peak reduction. Modifications could include increasing the electricity price further between 18:00 and 20:00 to increase battery discharge between these times.

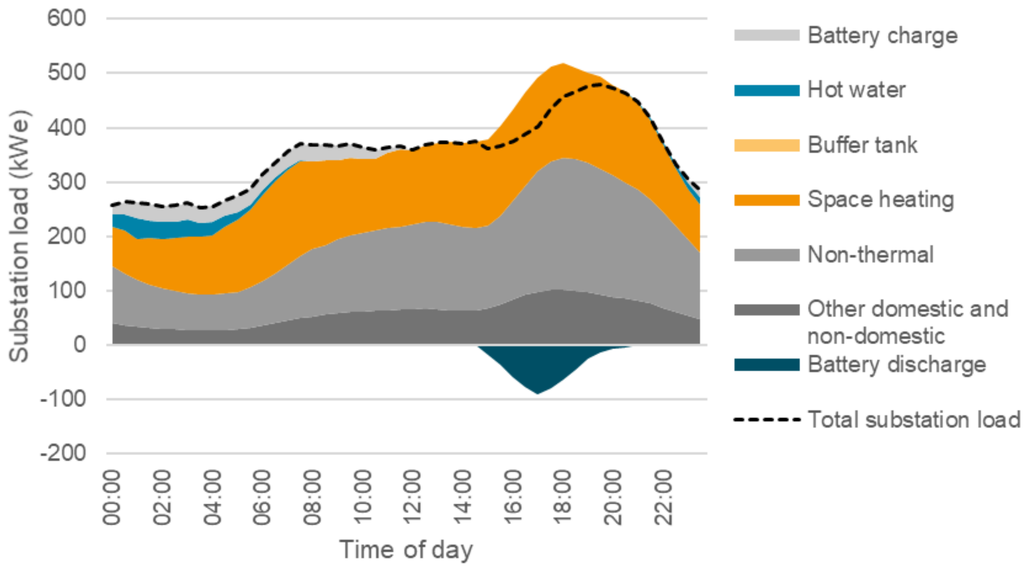

Figure 23: Breakdown of total half-hourly demand on substation archetype S-200 on coldest day (Friday 12 Jan) in scenario (12) with a variable electricity price, flexible hot water generation and electrical batteries installed in half of homes with heat pumps

The above examples showed the substation load profiles on the coldest day. Figure 24 shows the substation load duration curves for the full two-month modelled period under the different scenarios.

Comparing the baseline scenario (4, grey line) to the present day (black line) in Figure 24, it can be seen that heat pumps increase maximum substation demands by about 50% (from ~350 kW to ~520 kW), whereas minimum demands are only increased by about 30% (from ~70 kW to ~95 kW). This is because demand from heat pumps varies widely based on temperature: on milder winter days, heat losses are lower and heat pumps are also more efficient, whereas on colder days heat losses are higher and heat pump efficiencies are reduced, causing a disproportionate increase in heat pump electrical demand. Utilising storage solutions such as electrical batteries (scenario 12, light orange dotted line) helps reduce this disparity by increasing loads during off-peak periods and limiting peak demands.

Figure 24 also illustrates that a S-200 substation with a 500kW continuous nameplate rating with high levels of heat pump uptake would only be slightly overloaded for a small percentage of the time over the two-month cold modelled period. In the baseline scenario (4, grey line) it is overloaded for just 8 hours. With flexible hot water generation (9, dark blue line) it is overloaded for 4 hours. With greater temperature flexibility (10, light blue dotted line) it is overloaded for 3 hours. With buffer tanks (11, dark orange line) it is overloaded for 1 hour, and with electrical batteries it is not overloaded. Note that these levels of demand would still be within the substation's design rating.

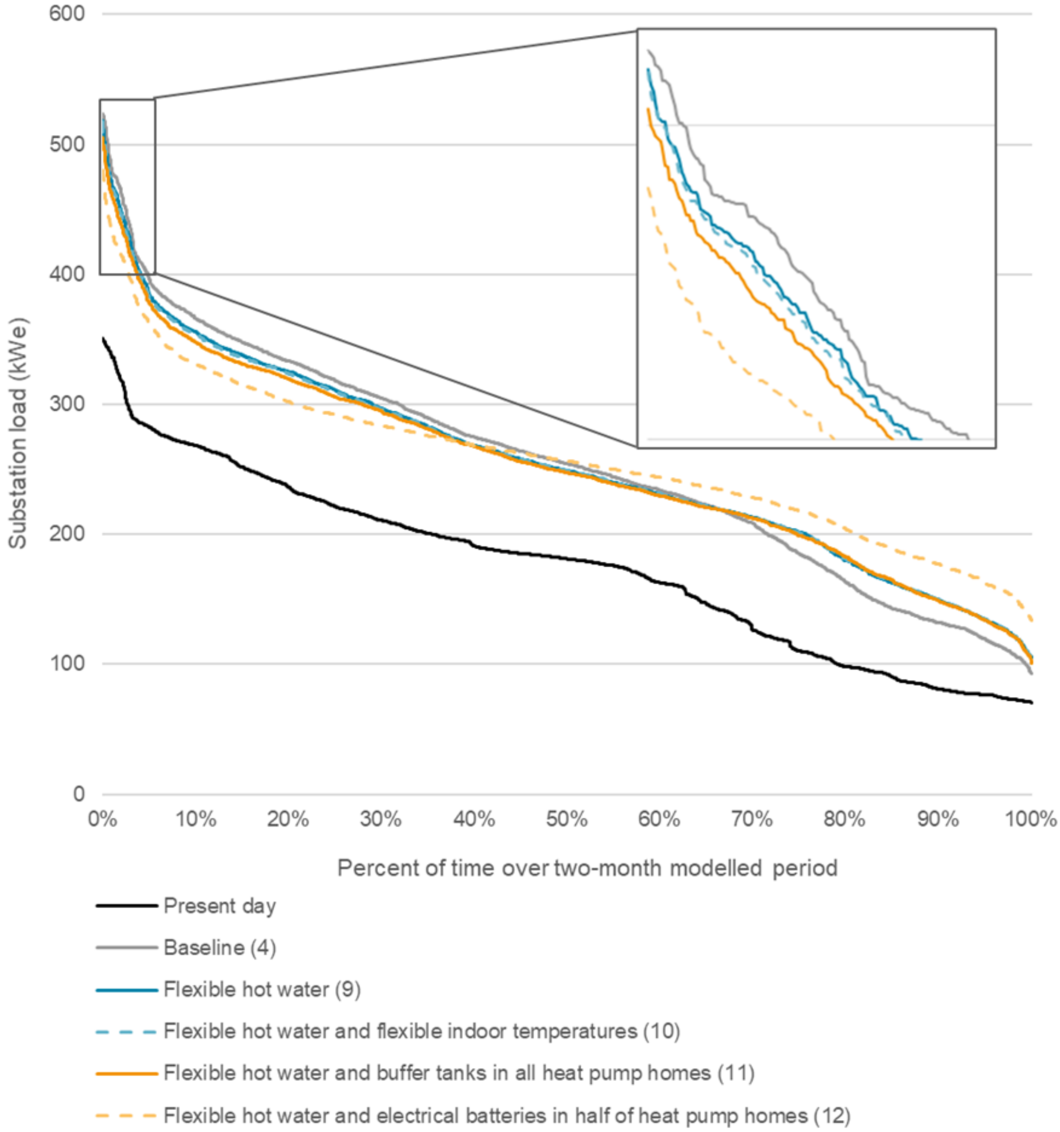

Figure 24: Load duration curves for S-200 substation archetype over two-month modelled period with cold winter conditions and high levels of heat pump uptake, with different flexibility measures applied

3.3. Application of substation archetype results to WPD study areas

Table 14 and Table 15 on the following pages show the number of distribution substations of each archetype on each of the three primary substations, as well as how many of these substations are likely to have maximum demands over their continuous load nameplate ratings under the different modelled scenarios. As stated in section 3.2.1, in practice the reinforcement/replacement of individual transformers would consider the application of a cyclic rating, which can range from 10% to 40% larger than continuous rating, based on detailed assessment of a range of factors that could limit the capacity. However, for this desktop study the use of continuous load nameplate ratings have been applied in the analysis.

In the moderate heat pump uptake scenarios, 44 of the 234 substations analysed across the three primaries are likely to be overloaded on peak days relative to their continuous load nameplate ratings.

With high levels of heat pump uptake, the number of substations with maximum demands above their continuous nameplate ratings increases to 94 out of 234. Of these substations, 6 are likely to be only slightly overloaded, and so peak demands can be kept within rated capacities by shifting hot water generation out of peak periods. Installing batteries in 50% of homes with heat pumps would bring the number of overloaded substations down from 94 to 51, meaning significant cost savings on substation upgrades. WP5 will look at how the costs of installing or incentivising the installation of electrical batteries compares to the cost of substation upgrades.

Note that for this desktop study continuous load nameplate ratings have been applied in the analysis reinforcement/replacement of substations. In practice the reinforcement/replacement of individual transformers would consider the application of a cyclic rating, which can range from 10% to 40% larger than continuous rating, based on detailed assessment of a range of factors that could limit the capacity. This approach in this study is therefore more conservative and aligns with other WPD policy documentation for similar studies. Use of cyclic ratings would significantly reduce the number of distribution substations that are "overloaded" in this analysis.

Figure 25 shows the current maximum demands on each of the three primary substations and the additional demand from heat pumps in the high uptake scenario during peak periods. These were determined by adding the additional peak demands from heat pumps across all the modelled distribution substations and to the current substation maximum demands. Half hourly historical demand data for the three primaries confirmed that current maximum demands occur in the evening peak period. Primary substation maximum demands cannot be determined by adding the total demands on all modelled distribution substations, as this would miss out non-domestic demands on any of the substations excluded from the analysis.

From Figure 24 it is evident that all three primaries currently have maximum demands near or above their rated capacities. A high level of heat pump uptake would increase maximum demands by about 10-20%, depending on the primary. Heat flexibility measures enable a relatively small reduction in overall maximum demands on the three primaries. The Bath Road and Mackworth primary substations remain overloaded in all heat flexibility scenarios. However, the Newport primary is an example of a substation that is only slightly overloaded at this level of heat pump uptake, and so flexibility measures can be used to keep demand within the firm capacity of the substation.

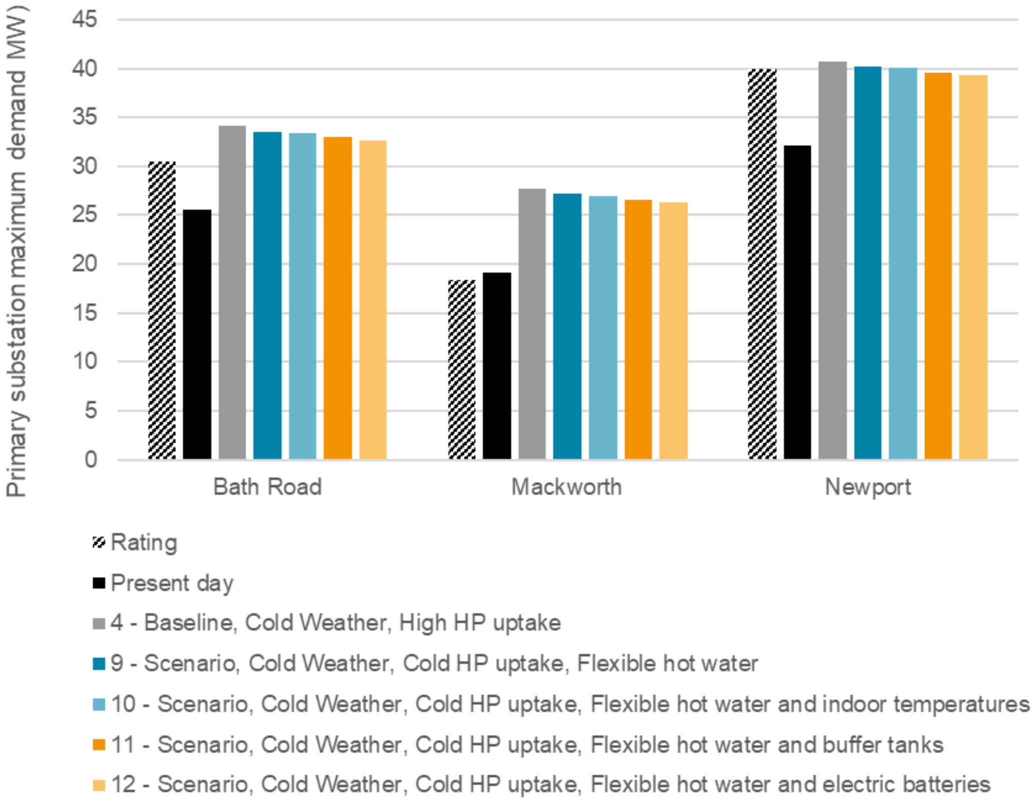

Figure 25: Primary substation ratings and maximum demands currently and in high heat pump uptake scenario with different flexibility measures applied under cold weather conditions

Table 14: Number of distribution substations on each primary likely to have maximum demands above continuous load nameplate ratings under moderate HP uptake scenario

Scenario	Present day	Total number of substations of each archetype with maximum demands above continuous load nameplate rating						Total number of substations of each archetype connected at present
		1	3	5	6	7	8	
Weather		Average	Cold	Cold	Cold	Cold	Cold	
HP uptake		Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
Bath Road - Total	**8**	**14**	**14**	**14**	**14**	**14**	**12**	**57**
D-70	3	3	3	3	3	3	3	14
D-120	0	3	3	3	3	3	3	8
D-200	0	1	1	1	1	1	1	1
S-70	1	3	3	3	3	3	1	8
S-120	0	0	0	0	0	0	0	9
S-200	3	3	3	3	3	3	3	14
S-350	1	1	1	1	1	1	1	1
F-200	0	0	0	0	0	0	0	2
Mackworth - Total	**9**	**10**	**10**	**10**	**10**	**10**	**10**	**68**
D-70	1	1	1	1	1	1	1	2
D-200	0	1	1	1	1	1	1	1
S-70	0	0	0	0	0	0	0	5
S-120	0	0	0	0	0	0	0	11
S-200	3	3	3	3	3	3	3	26
S-350	4	4	4	4	4	4	4	9
T-70	0	0	0	0	0	0	0	3
T-120	0	0	0	0	0	0	0	2
T-200	0	0	0	0	0	0	0	3
T-350	0	0	0	0	0	0	0	1
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	1
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
F-350	0	0	0	0	0	0	0	2
Newport - Total	**5**	**20**	**20**	**20**	**20**	**20**	**20**	**108**
S-70	0	0	0	0	0	0	0	1
S-120	0	0	0	0	0	0	0	2
S-200	0	0	0	0	0	0	0	6
S-350	0	0	0	0	0	0	0	1
T-70	0	0	0	0	0	0	0	12
T-120	0	0	0	0	0	0	0	12
T-200	4	4	4	4	4	4	4	47
T-350	0	15	15	15	15	15	15	22
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	2
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
Grand Total	**22**	**44**	**44**	**44**	**44**	**44**	**42**	**234**

Table 15: Number of distribution substations on each primary likely to have maximum demands above continuous load nameplate ratings under high HP uptake scenario

Scenario	Present day	2	4	9	10	11	12	Total number of substations of each archetype connected at present
		Total number of substations of each archetype with maximum demands above continuous load nameplate rating						
Weather		Average	Cold	Cold	Cold	Cold	Cold	
HP uptake		High	High	High	High	High	High	
Price		Fixed	Fixed	Variable	Variable	Variable	Variable	
Measures		None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	
Bath Road - Total	**8**	**18**	**34**	**30**	**30**	**30**	**18**	**57**
D-70	3	6	9	9	9	9	6	14
D-120	0	3	7	3	3	3	3	8
D-200	0	1	1	1	1	1	1	1
S-70	1	3	3	3	3	3	3	8
S-120	0	1	1	1	1	1	1	9
S-200	3	3	12	12	12	12	3	14
S-350	1	1	1	1	1	1	1	1
F-200	0	0	0	0	0	0	0	2
Mackworth - Total	**9**	**15**	**32**	**31**	**31**	**31**	**13**	**68**
D-70	1	2	2	2	2	2	2	2
D-200	0	1	1	1	1	1	1	1
S-70	0	0	0	0	0	0	0	5
S-120	0	3	3	3	3	3	1	11
S-200	3	3	19	19	19	19	3	26
S-350	4	4	5	4	4	4	4	9
T-70	0	0	0	0	0	0	0	3
T-120	0	0	0	0	0	0	0	2
T-200	0	0	0	0	0	0	0	3
T-350	0	0	0	0	0	0	0	1
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	1
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
F-350	0	1	1	1	1	1	1	2
Newport - Total	**5**	**21**	**28**	**27**	**27**	**27**	**20**	**108**
S-70	0	0	0	0	0	0	0	1
S-120	0	1	1	1	1	1	0	2
S-200	0	0	6	6	6	6	0	6
S-350	0	0	1	0	0	0	0	1
T-70	0	0	0	0	0	0	0	12
T-120	0	0	0	0	0	0	0	12
T-200	4	4	4	4	4	4	4	47
T-350	0	15	15	15	15	15	15	22
T-600	1	1	1	1	1	1	1	1
F-70	0	0	0	0	0	0	0	2
F-120	0	0	0	0	0	0	0	1
F-200	0	0	0	0	0	0	0	1
Grand Total	**22**	**54**	**94**	**88**	**88**	**88**	**51**	**234**

4. Conclusions and recommendations

The key model assumptions and their limitations are briefly summarised in this section. Preliminary conclusions are drawn about the effectiveness of different flexibility measures for reducing peak demands on substations, and some recommendations for further study are discussed.

4.1. Limitations of model assumptions

Many assumptions and simplifications have been made in generating the results for both the house archetypes and the substation archetypes. The key assumptions and limitations at the individual house level were discussed in the WP3 report. Because the community level network modelling builds on the individual house modelling, these limitations apply here too.

In addition, the following assumptions made in the WP4 modelling are considered to have the greatest impact on the conclusions of the results:

- **Distribution transformer ratings:** For this desktop study continuous load nameplate ratings have been applied in the reinforcement/replacement analysis of substations. In practice the reinforcement/replacement of individual transformers would consider the application of a cyclic rating, which can range from 10% to 40% larger than continuous rating, based on detailed assessment of a range of factors that could limit the capacity. The approach used in this study is therefore more conservative and aligns with other WPD policy documentation for similar studies. Use of cyclic ratings would significantly reduce the number of distribution substations that are “overloaded” in this analysis.
- **Classification of distribution substations into archetypes:** The simplification likely to have the most impact on the results is the classification of 234 unique distribution substations into 16 substation archetypes. Substations classed as having 200 homes might only have 150 homes in reality, or they might have almost 300 homes. They might have more or less detached homes than in the archetype, and hence have a different number of heat pumps installed. As a result, some substations that are overloaded in the results might not be overloaded in reality, whereas others that aren’t overloaded in the results will be in reality. It is expected that many of these will cancel out, making the results here broadly representative overall. Given the assumptions made, it is more likely that the number of substations overloaded due to the installation of heat pumps will be slightly higher in reality than estimated here.
- **Stochastic profile assumptions:** Stochastic profiles were used to re-introduce diversity at the household level after classifying thousands of unique properties into 8

house archetypes. The assumptions made to generate these profiles were based on the best information available at the time, but could be improved if better information becomes available in future. For example, diversity in heat losses was estimated based on heating costs reported in EPC data, but the ideal would be to have a range of heat pump demand profiles based on actual observed differences in operation.

- **Assignment of heat pumps to house archetypes:** Heat pumps were assigned to house archetypes based on the judgement of Delta-EE experts. While these assignments were made considering all relevant information today, some of these assumptions might change in future. For example, new solutions could be found that make mid-terrace properties better suited to heat pumps, making uptake among mid-terrace homes higher in reality than estimated here.
- **Magnitude and timing of heat pump uptake scenarios:** Heat pump uptake scenarios have been chosen that align with the more ambitious DFES scenarios for 2025 and 2030. In reality these levels of heat pump uptake might only actually be reached in 2028 and 2032, for example. Actual weather conditions in these years will also differ from the conditions assumed. The moderate and high uptake scenarios here should therefore be treated as illustrative for the purposes of evaluating the potential benefits of flexibility measures, rather than exact forecasts for particular years.
- **Electrical battery uptake scenarios:** A value of 50% uptake of electrical batteries in homes with heat pumps has been selected as an illustrative figure. This value is substantially higher than the uptake assumptions in the DFES, but corresponds to the upper limit for the demand reductions that can be derived from batteries. The approach adopted provides consistency in the illustrative uptake assumptions for all of the flexibility measures considered.
- **Low voltage feeder capacity and network outages:** It is assumed that distribution substation capacity is the limiting factor on how much additional demand can be accommodated, rather than capacity on the low voltage cables. Cables are sized based on the capacity of the substation, so are generally unlikely to be overloaded before a substation is overloaded. In addition heat pump assignment to homes was based on the postcode location of distribution of substations, and would have required knowledge of the postcodes served by each feeder in order to accurately distinguish between feeders on a substation. The modelling also does not account for any network outages, after which demand could be higher than estimated if many heat pumps then came on at once in order to bring homes back up to temperature.

4.2. Conclusions and recommendations for further study

Preliminary conclusions from the research findings so far are discussed below, along with some recommendations for further study. The next and final work package (WP5) of the Peak Heat project will compare the costs and benefits of the various flexibility measures tested, from which final conclusions can be drawn.

Heat pumps should be programmed to only generate hot water outside of peak periods, but diversity in off-peak periods must be incentivised

Although hot water generation accounts for only a small proportion of total demand on substations, it can easily be shifted outside of peak periods by simply programming times when heat pumps should generate hot water. There is a risk that a large number of heat pumps are programmed in such a way that they all generate hot water in the same narrow period, causing a peak in demand. This can be avoided with appropriate variable tariff structures, and/or programming in a randomised delay in response to price/weather signals. Other potential solutions could be explored in future research.

Indoor temperature flexibility is unlikely to be effective for reducing peak loads

Based on the results of this modelling it appears highly unlikely that small changes in indoor temperature will provide sufficient levels of demand reduction to prevent substations from being overloaded on peak days. Future research could explore whether greater reductions in indoor temperatures during peak periods and more allowance for pre-heating could provide significantly more flexibility. However, the high costs of incentivising these levels of demand reduction are likely to outweigh any potential benefits.

Buffer tanks should not be considered as thermal stores, but other thermal storage alternatives could be explored

While buffer tanks do help to prevent heat pumps from short cycling, they do not provide sufficient heat storage capacity to move significant heating loads out of peak periods. Alternative thermal stores such as heat batteries could be evaluated in future research, though the costs and space requirements would need to be competitive with electrical batteries, which store more capacity in a smaller volume and reduce substation loads more significantly during peak periods.

Electrical batteries are the most effective flexibility measure tested for reducing peak demands, but the volumes are likely to be limited and the costs will need to be compared with costs of substation upgrades

As discussed in Section 3, installing electrical batteries in homes with heat pumps to shift additional heating demands away from peak periods could potentially prevent a significant number of distribution substations from needing to be upgraded. However, the DFES assumptions indicate low volumes of electrical batteries to provide such benefits. WP5 will compare the costs of procuring flexibility from these electrical batteries to the costs of substation upgrades to determine which is more economical. Further research could explore the impact of different electricity tariff profiles on battery discharge profiles to maximise the reduction in peak demand. Ways of incentivising battery uptake among households (particularly in view of the demand reduction benefits for network operators) should also be considered and compared to alternatives such as commercial scale batteries connected at the distribution substation level.

Because heat pumps produce 2-3 units of heat for every unit of electricity, electrical batteries are a much more space efficient form of storage than thermal stores. Batteries are typically installed with solar PV panels. This makes them useful both in summer for storing excess solar generation, and in winter for shifting heat pump loads out of peak periods. This is especially beneficial for a house that has an EV charger, which might also need power at peak times. Batteries therefore have the added benefit over thermal stores in being able to shift various electrical loads rather than just thermal electrical loads.

Use of distribution substation archetypes can simplify analysis of the low voltage network and be expanded to the full WPD network area relatively easily

Classifying distribution substations into a small number of substation archetypes has its limitations, but is an effective way of producing high level estimates for large areas of the network. In order to extend the analysis done in this project to the rest of the WPD network, the following inputs would be necessary:

- EPC data for all houses on the WPD network to classify properties into house archetypes and determine the mix of house archetypes in each postcode area.

- Locations of all distribution substations to determine house mix on each substation based on their postcode area.
- Domestic customer numbers on each distribution substation to determine which customer group to assign substations to.
- Historical half hourly and maximum demand data for all substations to estimate any non-modelled demands. Alternatively, a method of estimating the additional demands per non-domestic customer could be used to simplify the analysis, potentially based on the Elexon profile class profiles.

The substation archetypes in this analysis were determined based on data for three primaries. Some modification to the archetype characteristics might be necessary to make them more representative of the entire network. The accuracy of the method could be improved by increasing the number of substation archetypes used – the four house mix categories are likely sufficient, but more customer number groups would be beneficial.

Appendix A: House archetype descriptions

Table 16: Archetype building and occupancy characteristics determined in WP1 (see WP1 report for methodology)

Archetype code	Description	Number of occupants; Daytime occupancy (Yes/No); Most common heating type		
		Newport	Mackworth	Bath Road
DH-G	Detached house, good wall insulation performance	3 No Gas boiler	4 Yes Gas boiler	4 Yes Non-gas fossil fuel boiler
DH-P	Detached house, poor wall insulation performance	4 Yes Gas boiler	2 Yes Gas boiler	4 Yes Gas boiler
SH-G	Semi-detached house, good wall insulation performance	4 Yes Gas boiler	2 No Gas boiler	2 No Gas boiler
SH-P	Semi-detached house, poor wall insulation performance	1 Yes Gas boiler	3 No Gas boiler	2 Yes Gas boiler
MT-G	Mid-terrace house, good wall insulation performance	3 No Gas boiler	4 Yes Gas boiler	1 No Gas boiler
MT-P	Mid-terrace house, poor wall insulation performance	2 No Gas boiler	1 Yes Gas boiler	3 No Gas boiler
FI-G	Flat, good wall insulation performance	1 No Gas boiler	1 No Storage heating	1 Yes Storage heating
FI-P	Flat, poor wall insulation performance	2 Yes Storage heating	3 No Gas boiler	3 No Gas boiler

Appendix B: House archetype groupings for substation archetypes

Table 17: Values corresponding to chart shown in Figure 2 - Four groupings of house archetypes determined from analysis of archetype mixes on each distribution substation

	DH-G	DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P
Type F - Mainly flats with some terraces and semi-detached homes	5%	2%	10%	5%	5%	15%	44%	14%
Type D - Mainly detached and semi-detached homes	27%	4%	34%	15%	14%	3%	2%	1%
Type S - Mainly semi-detached homes with a mix of others	8%	12%	20%	16%	7%	13%	19%	5%
Type T - A mix of terraced houses, semi-detached houses and flats	6%	3%	16%	16%	9%	20%	18%	12%

Table 18: Values corresponding to chart shown in Figure 3 - Modelled share of house archetypes on each primary substation using distribution substation archetypes versus actual share of house archetypes based on EPC analysis done in WP1

		DH-G	DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P
Bath Road	Modelled	13%	9%	24%	15%	9%	10%	15%	4%
	Actual	13%	6%	26%	13%	11%	10%	15%	6%
	Difference	0%	3%	-3%	2%	-3%	0%	0%	-1%
Mackworth	Modelled	8%	10%	19%	15%	7%	14%	20%	7%
	Actual	5%	12%	17%	15%	6%	16%	21%	8%
	Difference	3%	-2%	2%	0%	1%	-2%	-1%	-1%
Newport	Modelled	6%	4%	16%	16%	9%	19%	19%	11%
	Actual	6%	2%	17%	17%	9%	19%	17%	11%
	Difference	0%	1%	-1%	-1%	-1%	0%	2%	0%

Appendix C: Impact of heat pump uptake and flexibility measures on substation archetypes

Table 19: Increase in half hourly maximum demand relative to present electrical demands without heat pumps on all substation archetypes under moderate heat pump uptake scenarios

Scenario	1	3	5	6	7	8
Weather	Average	Cold	Cold	Cold	Cold	Cold
HP uptake	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Price	Fixed	Fixed	Variable	Variable	Variable	Variable
Measures	None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries
D-70	21%	27%	24%	24%	25%	16%
D-120	26%	33%	31%	31%	30%	22%
D-200	30%	38%	37%	37%	35%	29%
S-70	9%	11%	10%	10%	10%	5%
S-120	12%	14%	14%	14%	13%	9%
S-200	14%	20%	19%	19%	17%	15%
S-350	13%	17%	16%	15%	15%	9%
T-70	6%	7%	7%	7%	7%	4%
T-120	9%	12%	11%	11%	11%	8%
T-200	5%	7%	6%	6%	6%	3%
T-350	7%	10%	9%	9%	9%	5%
T-600	9%	13%	12%	12%	11%	9%
F-70	4%	4%	4%	4%	4%	0%
F-120	6%	7%	7%	7%	6%	4%
F-200	9%	12%	11%	11%	10%	7%
F-350	10%	11%	10%	10%	10%	6%

Table 20: Increase in half hourly maximum demand relative to present electrical demands without heat pumps on all substation archetypes under high heat pump uptake scenarios

Scenario	**2**	**4**	**9**	**10**	**11**	**12**
Weather	Average	Cold	Cold	Cold	Cold	Cold
HP uptake	High	High	High	High	High	High
Price	Fixed	Fixed	Variable	Variable	Variable	Variable
Measures	None	None	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries
D-70	51%	66%	64%	63%	60%	52%
D-120	62%	82%	79%	79%	76%	64%
D-200	60%	77%	74%	74%	70%	63%
S-70	25%	31%	30%	29%	28%	21%
S-120	28%	39%	38%	37%	36%	24%
S-200	41%	50%	48%	48%	45%	38%
S-350	29%	39%	38%	38%	36%	30%
T-70	16%	19%	19%	19%	18%	11%
T-120	19%	26%	25%	25%	23%	19%
T-200	15%	22%	21%	21%	19%	15%
T-350	25%	30%	29%	29%	27%	22%
T-600	26%	34%	33%	32%	30%	27%
F-70	11%	13%	12%	12%	11%	7%
F-120	14%	19%	18%	18%	17%	12%
F-200	18%	23%	22%	22%	21%	16%
F-350	20%	29%	28%	27%	26%	21%

Table 21: Reduction in half hourly maximum demand relative to baseline scenarios on all substation archetypes under moderate and high heat pump uptake scenarios

Scenario	5	6	7	8	9	10	11	12
Weather	Cold	Cold	Cold	Cold	Cold	Cold	Cold	Cold
HP uptake	Moderate	Moderate	Moderate	Moderate	High	High	High	High
Price	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable
Measures	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries	Hot water	Hot water, Temp	Hot water, Buffer tanks	Hot water, Batteries
D-70	-1.8%	-1.8%	-1.3%	-8.8%	-1.1%	-1.4%	-3.3%	-8.2%
D-120	-1.6%	-1.5%	-2.6%	-8.2%	-1.4%	-1.4%	-3.5%	-9.8%
D-200	-0.8%	-1.0%	-2.5%	-6.3%	-1.5%	-1.8%	-3.8%	-7.8%
S-70	-1.0%	-1.0%	-0.8%	-5.7%	-0.9%	-1.5%	-2.3%	-8.0%
S-120	-0.6%	-0.6%	-1.0%	-4.6%	-0.9%	-1.1%	-2.3%	-10.8%
S-200	-0.6%	-0.8%	-1.8%	-3.9%	-1.1%	-1.3%	-3.5%	-8.4%
S-350	-1.1%	-1.3%	-1.6%	-6.5%	-1.2%	-1.3%	-2.6%	-6.8%
T-70	-0.2%	-0.1%	-0.5%	-3.3%	-0.4%	-0.4%	-1.5%	-6.7%
T-120	-0.4%	-0.4%	-0.5%	-3.4%	-0.7%	-0.6%	-2.0%	-5.0%
T-200	-0.7%	-0.6%	-0.8%	-3.6%	-0.6%	-0.6%	-1.8%	-5.2%
T-350	-0.4%	-0.4%	-0.9%	-4.0%	-0.9%	-1.3%	-2.4%	-6.7%
T-600	-0.6%	-0.6%	-1.3%	-3.7%	-1.4%	-1.5%	-3.0%	-5.5%
F-70	-0.4%	-0.3%	-0.7%	-3.9%	-0.5%	-0.7%	-1.8%	-5.6%
F-120	-0.2%	-0.2%	-0.7%	-3.1%	-0.7%	-1.0%	-1.9%	-6.1%
F-200	-0.8%	-0.8%	-1.6%	-4.6%	-0.8%	-0.9%	-2.2%	-6.3%
F-350	-1.0%	-1.0%	-1.2%	-4.8%	-1.3%	-1.7%	-3.0%	-6.3%

