Peak Heat WP3: Individual property modelling

Peak Heat Project

Western Power Distribution

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Contents

Executive summary

WP3 covered the modelling of heat flexibility solutions at the individual house level. The objective was to determine:

- The baseline electrical load profiles for each of the eight house archetypes heated by heat pumps; and
- The impact of adding flexibility measures such as thermal and electrical storage on these load profiles.

The modelling of individual houses in WP3 was done primarily in Plexos, a power market simulation and optimisation software. Plexos has a wide range of built-in objects representing different components of networks. To model each house, four battery objects were used as illustrated in Figure 2 to represent:

1. The house requiring space heating – which loses (discharges) heat to the surrounding environment and must be heated (charged) by the heat pump to maintain a set indoor temperature (state of charge);
2. The hot water cylinder – where domestic hot water produced by the heat pump is stored before use;
3. The optional buffer tank – where water heated by the heat pump is stored before being fed through the space heating distribution system; and
4. The optional electrical battery where electricity from the grid can be stored to supply either the heat pump or the non-thermal electrical loads.

A building physics model was used to determine the half hourly heat loss profiles from each house archetype under average and 1 in 20 weather conditions. These results were used as inputs into the Plexos model, which was calibrated to match the building physics model heat generation results. Literature findings were used to estimate: the size and efficiency of the heat pumps; hot water usage profiles; capacities of the hot water cylinders, buffer tanks and electrical batteries; non-thermal demand profiles and; electricity price profiles.

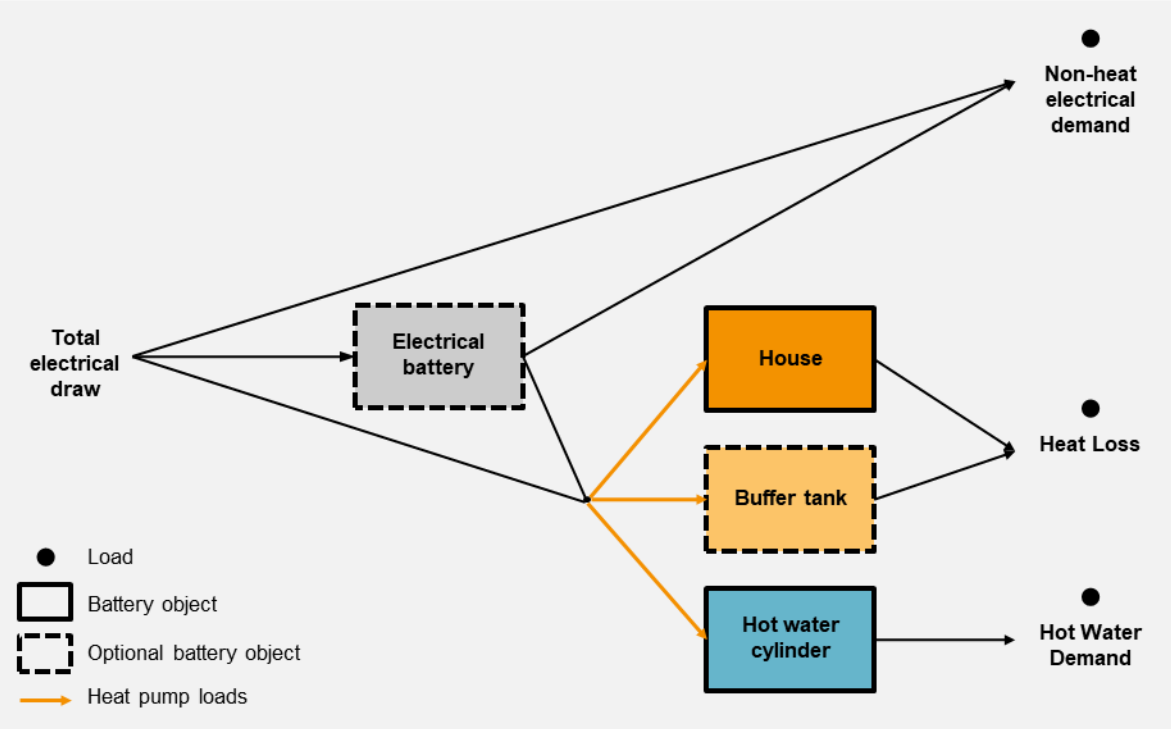


Figure 2: Individual house model set up in Plexos with four battery objects and three loads

Several scenarios were run in Plexos to determine the electrical demand profiles of each archetype under different conditions and with different flexibility measures applied.

Figure 22 shows the total (non-thermal plus thermal) peak electrical demand for each archetype under different weather and occupancy (occupied or unoccupied during the day on weekdays) conditions with no flexibility measures applied. Non-thermal electrical demand peaks are included for comparison and it can be seen that total demand peaks are around 4 to 6 times higher, depending on the archetype. This confirms that peak loads on electricity networks would be significantly higher if a large proportion of homes were to switch from gas/oil/LPG heating to electrically-driven air-source heat pumps.

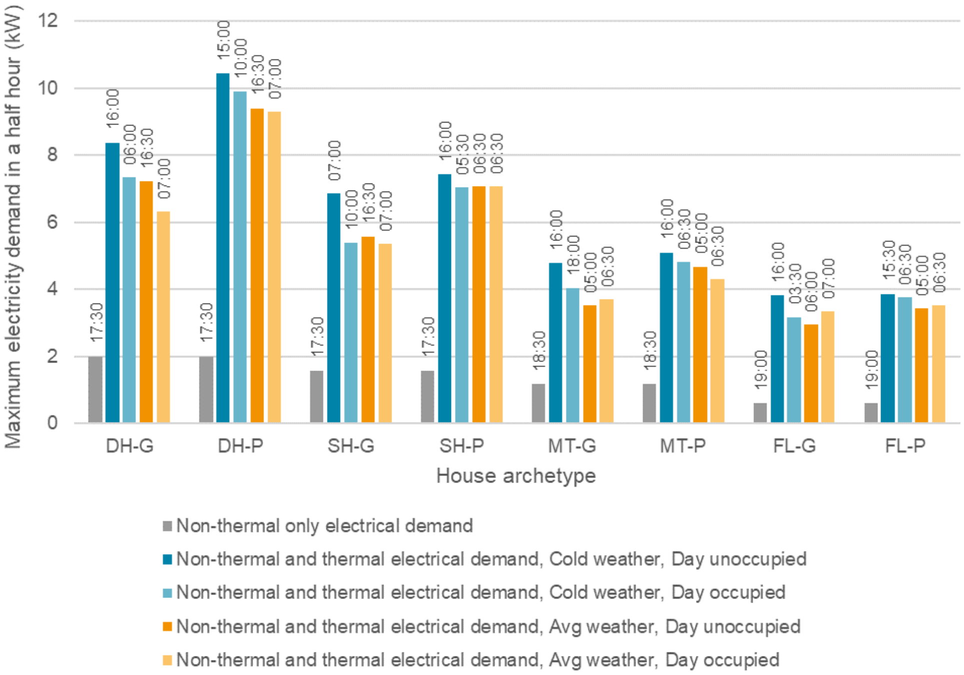


Figure 22: Peak non-thermal and thermal electricity demands in baseline scenarios with no flexibility measures; half hour in which peak demand occurs shown above bars

Figure 25 shows the average half hourly demand profiles for each archetype over the two-month modelled period under cold weather conditions, with heating peaks occurring in the morning and evening.

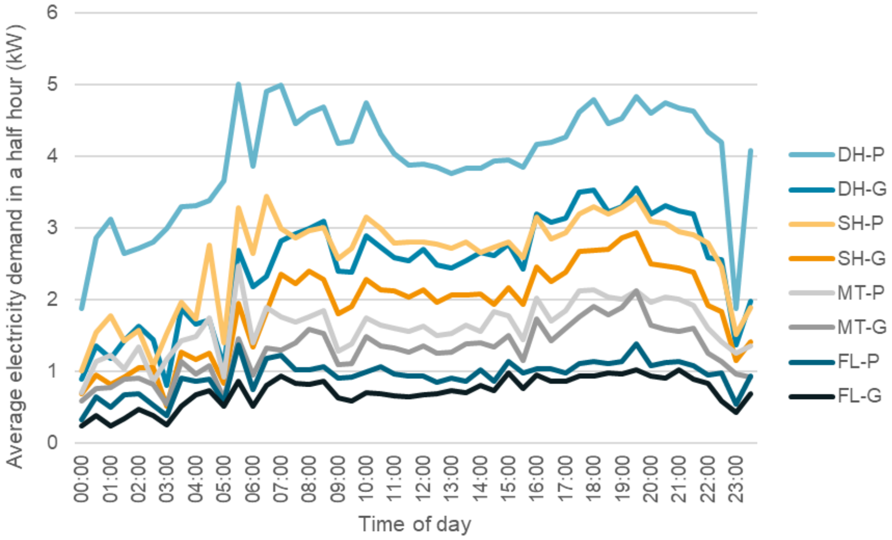


Figure 25: Average daily electricity demand profiles over the two-month modelled period for different house archetypes heated by an air-source heat pump under cold weather conditions with no flexibility measures; based on weighted average occupancy characteristics per archetype

Adding flexibility measures can enable a significant portion of demand to be shifted outside of peak hours. Figure 30 shows that allowing more flexibility around set indoor temperatures and shifting hot water generation can reduce loads during the evening peak by 10-20%, depending on the archetype. The addition of a buffer tank can shift a further ~5-15% of demand, and an electrical battery can shift up to 80 or almost 100% of demand, depending on weather conditions, insulation levels and the size of storage devices assumed.

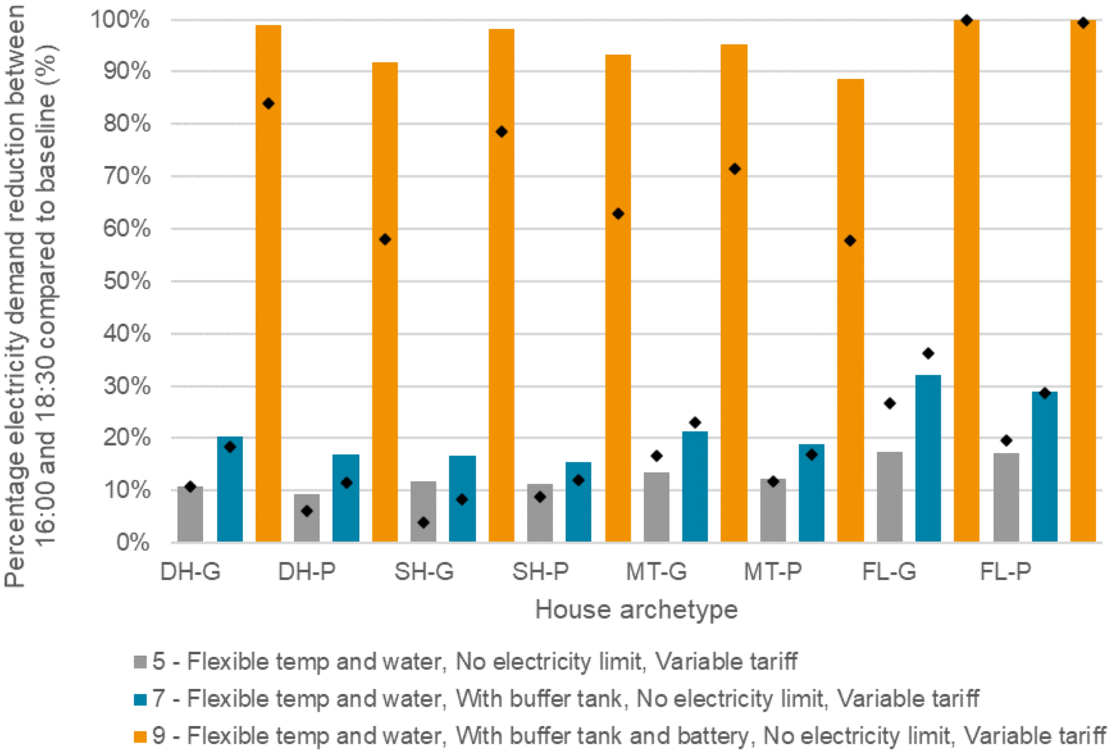


Figure 30: Percentage demand reduction during peak period between 16:00 and 18:30 compared to baseline under different flexibility scenarios, on average under cold weather conditions (shown by bars), and on the coldest day (shown by black markers)

At the individual house level it was found that adding flexibility measures simply shifted peaks from high price evening periods to low price morning periods, without reducing peaks overall. This is likely to still be useful for reducing peaks and smoothing demand profiles at the network level when only a minority of homes have heat pumps. However, this peak shifting impact could start to be seen at the network level when more homes are equipped with heat pumps and flexibility measures. WP4 will explore how these flexibility measures impact load profiles at the secondary substation level under different levels of heat pump uptake.

To test how much peak demands could be reduced rather than shifted for individual homes, electrical supply limits were applied in the test scenarios. Figure 26 presents the total household peak demands for the Baseline scenario (under cold weather conditions, unoccupied during weekdays) and with combinations temperature flexibility allowed, buffer tanks and batteries being installed, and of supply limits being applied in scenarios 5-10. This showed that flexible heat and hot water generation can enable electricity supply requirements to be reduced by around 20-30% (difference between scenarios 1 and 6), buffer tanks by a further ~10-20% (difference between scenarios 6 and 8), and electrical batteries by an additional ~10-20% (difference between scenarios 8 and 10), as illustrated in Figure 26.

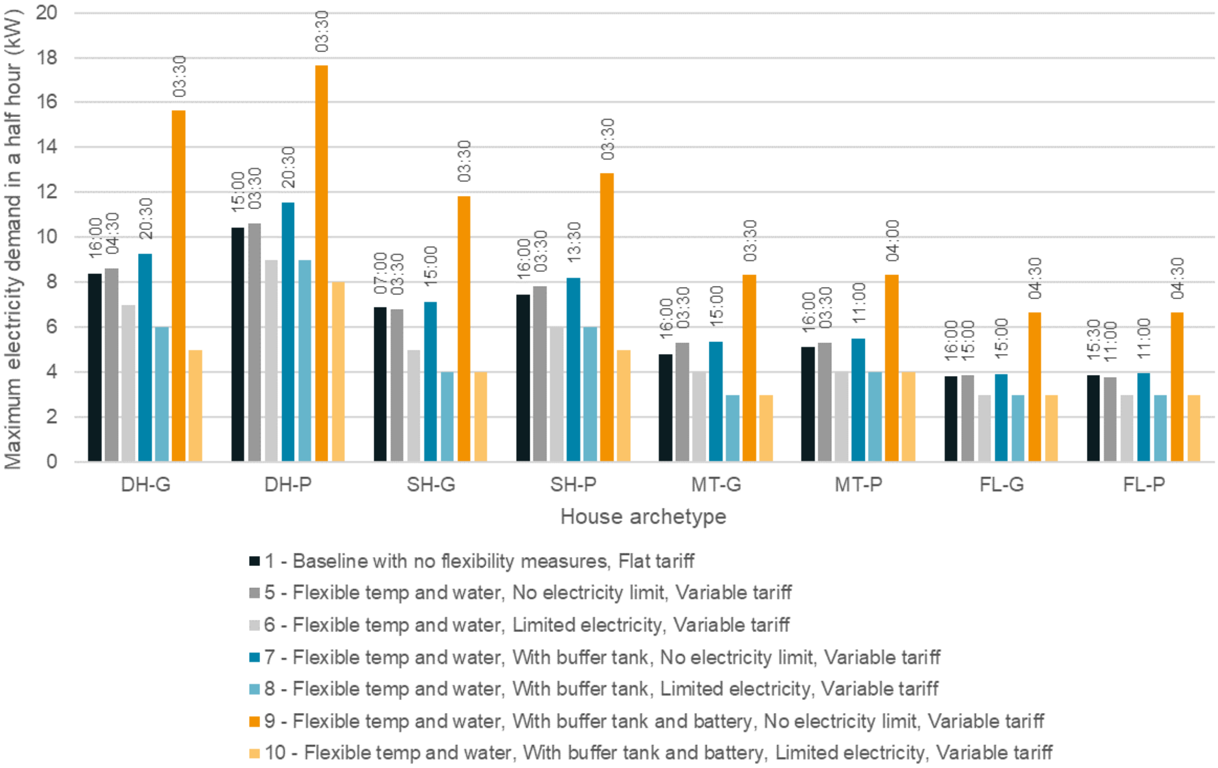


Figure 26: Peak electricity demands for each house archetype under scenarios (numbered) with added flexibility measures, a variable tariff and electricity supply limits; half hour in which peak demand occurs shown above bars (not shown for electricity supply limit scenarios as limit is reached multiple times in a day)

For electricity network operators, the results so far suggest that flexible control of heating could enable significant reductions in network loads, particularly with the addition of storage devices. However, the right incentives will be needed to ensure the use of these flexibility measures is sufficiently diverse, so that peak demands are reduced overall rather than just shifted to other times.

In WP4, the impacts of flexibility measures will be tested at the secondary substation level with different levels of heat pump uptake and taking into account diversity of demand within archetype groups.

1. Work package scope, methodology and outputs

This work package covered the modelling of heat flexibility solutions at the individual house level. The modelling of individual houses in WP3 was done primarily in Plexos, a power market simulation software package. Inputs to the Plexos models were derived from building physics modelling as well as estimates from the relevant literature. The outputs of the work package are this methodology report and the half hourly electrical power demand profiles for each archetype under scenarios with different flexibility measures applied.

1.1. Work package scope

WP3 covered the modelling of heat flexibility solutions at the individual house level. This involved:

1. Using building physics models to generate baseline heat demand profiles for the house archetypes under average winter conditions and 1 in 20 weather conditions;
2. Converting the baseline heat demand profiles into baseline electricity demand profiles for heat pumps, taking into account heat pump efficiency and control strategies; and
3. Assessing the impact of energy storage solutions, control strategies and pricing strategies on heat pump load profiles at the individual house level for each archetype.

The eight house archetypes modelled in WP3 were determined as part of WP1. The characteristics of these archetypes are given in Table 1 for reference. In WP4 the load profiles for individual houses from WP3 will be aggregated to estimate the total loads at the primary and secondary substation level.

1.2. Work package methodology

The modelling of individual houses in WP3 was done primarily in Plexos, a power market simulation software package. The steps taken and inputs required for WP3 are illustrated in Figure 1.

The first step was estimating the building heat losses and space heating demand profiles for each of the eight house archetypes defined in WP1 under different weather conditions. This was conducted by AECOM using building physics modelling software. Details of the methodology are provided in Section 3.1.

Space heating demand profiles were then converted into heat pump electrical demand profiles. The first step here was replicating the building physics model results in Plexos by modelling each house as a battery, with battery discharge representing heat losses, battery charge representing heat generation, and level of charge representing the indoor temperature. The second step was estimating electrical demand required for heat generation given the efficiency profile of the heat pump. Details of the methodology are provided in Section 2 and Section 3.2.

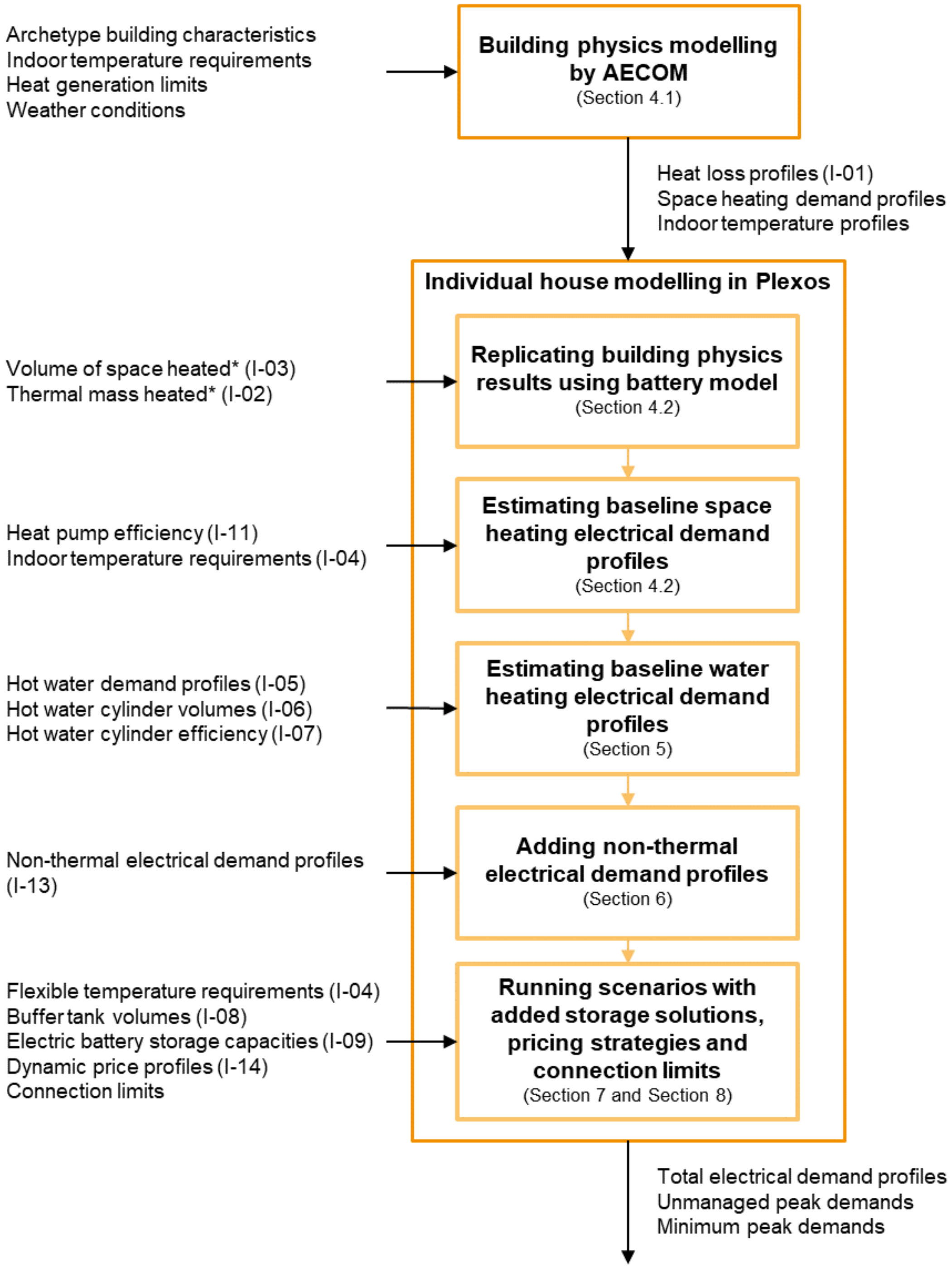
The next step was to determine electrical demand profiles for hot water generation by the heat pump. This was also done in Plexos by modelling the hot water cylinder as a battery. Details of the methodology are provided in Section 2 and Section 4.

Non-thermal electrical demand profiles were added as an additional load in Plexos for each house archetype. Details are provided in Section 5.

Once baseline electrical demand profiles for space heating, hot water and non-thermal loads were modelled in Plexos, the final step was to add two further batteries representing a buffer tank for thermal storage and an electrical battery for electrical storage. Scenarios were then run with different combinations of flexibility sources, electricity prices and connection limits to determine a) the potential maximum peak demand for each archetype and b) how much the peak demand could possibly be reduced by. Details of the methodology are provided in Section 2, 6 and 7 and a summary of the results is presented in Section 8.

Table 1: Archetype building and occupancy characteristics determined in WP1 (see WP1 report for methodology)

Archetype code	Description	Number of occupants and Daytime occupancy (Yes/No)		
		Newport	Mackworth	Bath Road
DH-G	Detached house, good wall insulation performance	3 No	4 Yes	4 Yes
DH-P	Detached house, poor wall insulation performance	4 Yes	2 Yes	4 Yes
SH-G	Semi-detached house, good wall insulation performance	4 Yes	2 No	2 No
SH-P	Semi-detached house, poor wall insulation performance	1 Yes	3 No	2 Yes
MT-G	Mid-terrace house, good wall insulation performance	3 No	4 Yes	1 No
MT-P	Mid-terrace house, poor wall insulation performance	2 No	1 Yes	3 No
Fl-G	Flat, good wall insulation performance	1 No	1 No	1 Yes
Fl-P	Flat, poor wall insulation performance	2 Yes	3 No	3 No



*Calibration variables adjusted in Plexos to match building physics model results

Figure 1: WP3 methodology steps and inputs required to determine electrical demand profiles for individual house archetypes; input references correspond to input numbers in Table 2; section numbers refer to sections in this report where further information is provided on that step

1.3. Work package outputs

The outputs of WP3 are:

- Half hourly input power demand profiles at the individual house level for each archetype under average and 1 in 20 weather conditions and with different flexibility measures applied (attached Excel spreadsheet); and
- This report detailing how these profiles were derived.

2. Modelling household electrical loads in Plexos

Plexos was used to model the electrical demand profiles at the individual house level for space heating and hot water generation, plus the impact of adding thermal and electrical storage. This section describes the inputs required and how battery objects in Plexos were used to represent: the house requiring space heating; the hot water cylinder where domestic hot water is stored; the optional buffer tank where heated water is stored before being fed through the heat distribution system; and the optional electrical battery.

The modelling of individual houses in WP3 was done primarily in Plexos. Plexos is a power market simulation and optimisation software used by utilities, network operators, regulators and consultants for operations and risk planning as well as market and network analysis. This section describes how Plexos was set up to model electrical loads at the individual house level. Further details of how the model inputs were derived, how the Plexos optimisation solver works, and the model results are provided in subsequent sections.

2.1. The benefits of modelling individual houses in Plexos

It was initially proposed that modelling at the individual house level would be done in MS Excel, but it was determined that this could be done more effectively in Plexos. There are two main benefits of using Plexos for WP3 rather than MS Excel:

1. Scaling up from the individual house level to the network level in WP4 can be done more efficiently, with no need to translate Excel model outputs from WP3 into Plexos inputs for WP4; and
2. Plexos has a more powerful optimisation solver than MS Excel, which enables cost optimal operation strategies to be determined at the individual house level.

The outputs of the Plexos model can be generated in MS Excel format and made available for further review and analysis.

2.2. Plexos model inputs and outputs

All the inputs to and outputs from the Plexos model for each house are listed in Table 2 and Table 3 below. Details of how these were derived are provided in subsequent sections. Numbers are assigned to each of the inputs and outputs for reference elsewhere in the report and the accompanying results spreadsheet.

Table 2: Summary of Plexos inputs for individual house models

No.	Input	Units	Time series	Source	Report section
I-01	House heat loss to environment	kWth	Half-hourly	Building physics modelling by AECOM	Section 3.1
I-02	Heat transferred to thermal mass	kWth	Half-hourly	Determined through calibration to match building physics modelling results	Section 3.2
I-03	Volume of space heated	kWhth	Fixed	Determined through calibration to match building physics modelling results	Section 3.2
I-04	Minimum and maximum indoor temperature requirements	°C	Half-hourly	Assumed temperature preferences	Section 3.2
I-05	Hot water consumption	kWth	Half-hourly	Literature values	Section 4
I-06	Hot water cylinder capacity	kWhth	Fixed	Assumption based on cylinder sizing heuristics in literature	Section 4
I-07	Hot water cylinder discharge efficiency	%	Fixed	Literature values	Section 4
I-08	Buffer tank capacity	kWhth	Fixed	Assumption based on standard buffer tank capacities and house size	Section 7
I-09	Electrical battery capacity	kWhe	Fixed	Assumption based on standard electrical battery capacities and house size	Section 7
I-10	Electrical battery charge and discharge efficiency	%	Fixed	Literature values	Section 7
I-11	Heat pump COP for space heating and hot water generation	kWth/kWe	Half-hourly	Calculated based on literature values and outdoor temperature profiles used in building physics modelling	Section 3.2
I-12	Maximum heat pump electrical draw	kWe	Fixed	Assumption based on heat pump product specifications	Section 3.2
I-13	Non-thermal electrical demand profiles	kWe	Half-hourly	Literature values	Section 5
I-14	Electricity price	£/kWe	Half-hourly	Calculated based on historical electricity prices	Section 6

Table 3: Plexos outputs for individual house model

No.	Output	Units	Time series
O-01	Heat pump electrical draw for space heating generation	kWe	Half-hourly
O-02	Actual indoor temperature of the house	°C	Half-hourly
O-03	Heat pump electrical draw to charge buffer tank	kWe	Half-hourly
O-04	Buffer tank level of charge	%	Half-hourly
O-05	Heat pump electrical draw for hot water generation	kWe	Half-hourly
O-06	Hot water level in the hot water cylinder	%	Half-hourly
O-07	Electricity draw to charge electrical battery	kWe	Half-hourly
O-08	Electricity generation by electrical battery	kWe	Half-hourly
O-09	Electrical battery charge level	%	Half-hourly

2.3. Plexos set up for an individual house

Plexos has a wide range of built-in objects representing different components of networks. To model each house, four battery objects were used to represent:

1. The house requiring space heating;
2. The hot water cylinder where domestic hot water is stored;
3. The buffer tank where heated water is stored before being fed through the heat distribution system (optional); and
4. The electrical battery where electricity from the grid can be stored to supply either the heat pump or the non-thermal electrical loads (optional).

This set up is illustrated in Figure 2.

2.3.1. Object representations

Objects in Plexos are assigned standard properties such as battery capacity, charge efficiency and maximum power draw. For each of the battery objects used in the Plexos model, the battery properties represent the properties of the house and/or heating system. These are explained below using the corresponding Plexos terminology.

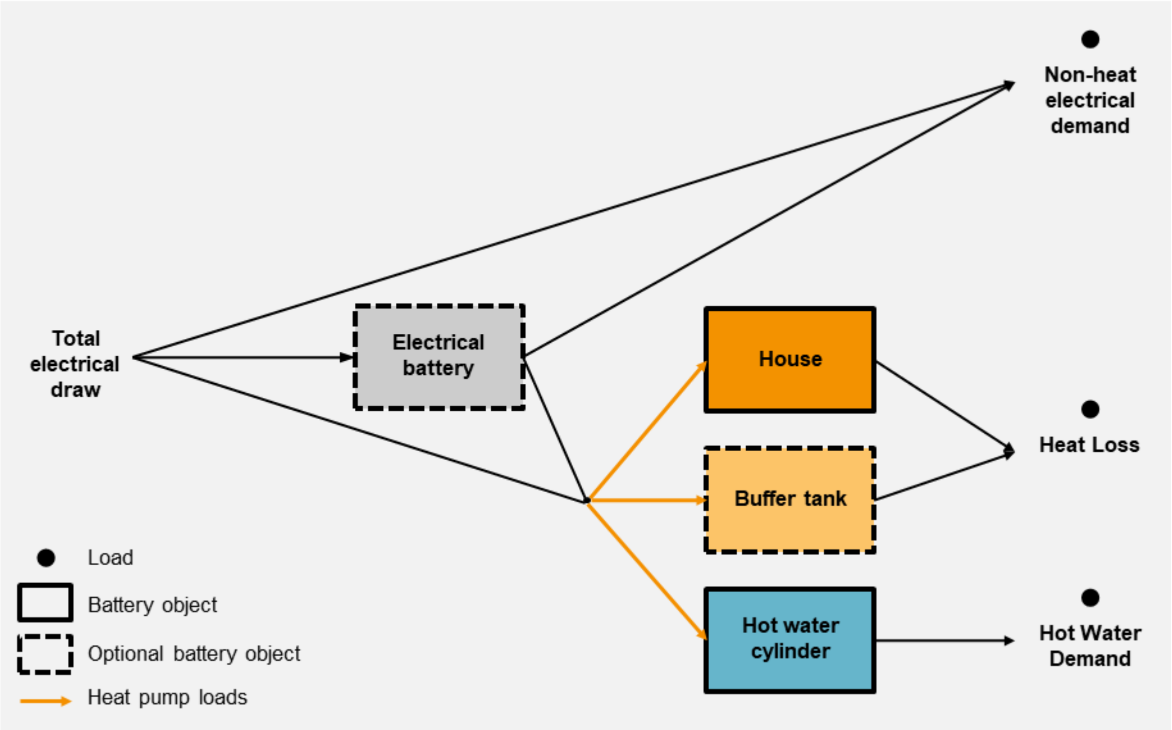


Figure 2: Individual house model set up in Plexos with four battery objects and three loads

House model

The house requiring space heating was modelled as a battery in Plexos. Houses lose heat constantly to the surrounding environment in winter. These heat losses were input into the Plexos model as “battery generation”, as illustrated in Figure 3. Note that battery generation in this case is constrained to equal the heat loss profile, meaning it cannot be dispatched as an electrical battery would be. The “battery capacity”, which represents the volume of space heated, was scaled such that battery state of charge was equivalent to the indoor air temperature of the house.

Temperature requirements were set based on the time of day and occupancy patterns. The “battery load”, which is equal to heat pump electrical draw, required to achieve those temperatures given the heat losses was then calculated based on the COP[1] of the heat pump. A maximum power limit was applied to ensure the heat pump did not exceed its maximum current draw.

Some of the heat generated by the heat pump goes towards heating the fabric of the building rather than the indoor air. This heat transfer to the building thermal mass was accounted for using the “discharge efficiency” property of the battery. Details of how the inputs for the house battery were derived are provided in Section 3.2.

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[1] Coefficient of performance (COP) is the ratio of heat generated (kWth) to electricity used (kWe) by the heat pump

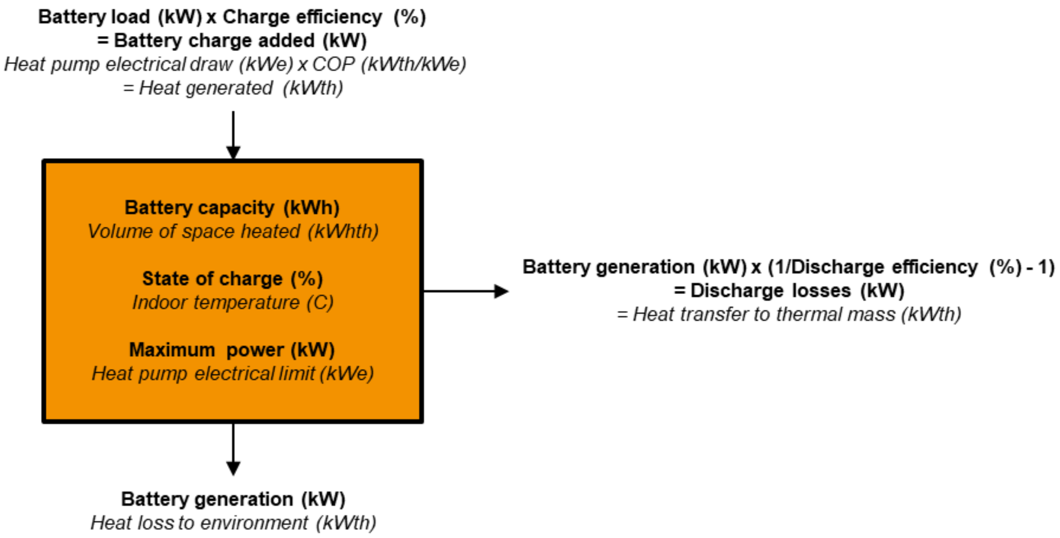

Figure 3: How the house requiring space heating was modelled as a battery in Plexos; Plexos properties shown in bold, physical equivalents shown in italics

Hot water cylinder model

The hot water cylinder was also modelled as a battery in Plexos, as illustrated in Figure 4. The hot water consumption half hourly profile from the cylinder was input into the Plexos model as battery generation. Battery capacity represents the volume of the hot water cylinder. Battery load, which represents heat pump electrical draw, required to generate hot water was calculated based on the COP and maximum electrical draw of the heat pump. Heat losses from the hot water cylinder to the surroundings were accounted for using the discharge efficiency property of the battery. Details of how the inputs for the hot water cylinder battery were derived are provided in Section 4.

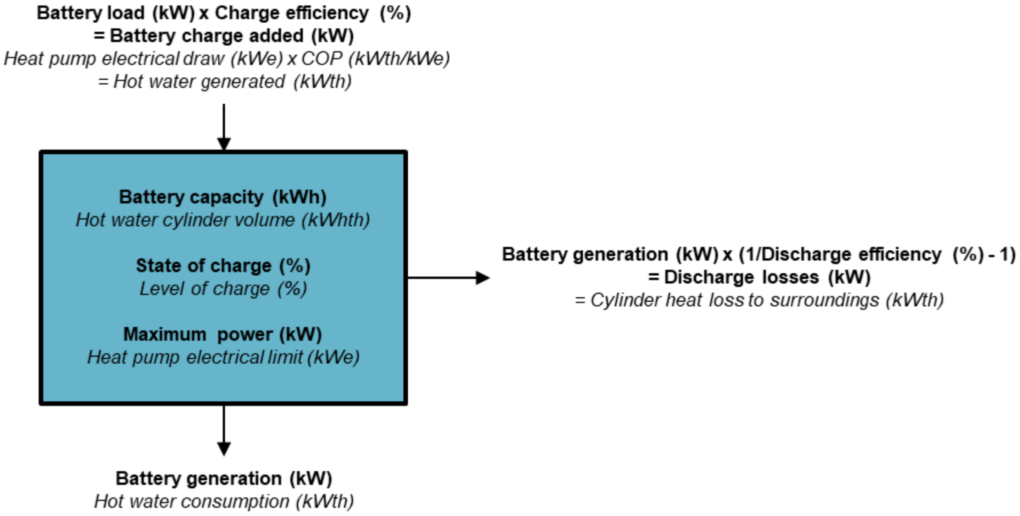

Figure 4: How the hot water cylinder was modelled as a battery in Plexos; Plexos properties shown in bold, physical equivalents shown in italics

Buffer tank model

To provide space heating to the home, water heated by the heat pump is pumped through radiators or underfloor heating pipes. This heated water can be stored temporarily in a buffer tank before being supplied to the distribution system to provide some flexibility to when the heat pump operates. The optional buffer tank in a house was modelled as a battery, as illustrated in Figure 5. Like the battery used to model space heating, battery generation and discharge losses represented heat lost from the house to the environment or transferred to the thermal mass of the building. A constraint was applied within Plexos to ensure that the sum of the "battery generation" by the house battery and by the buffer tank battery were equal to the half hourly heat loss values input into the model. This means that when the buffer tank battery is dispatched/discharged, less heat is lost/transferred from the house battery object, and the temperature (modelled as the state of charge of the house battery) is higher as a result.

Battery capacity was determined based on the volume of the buffer tank. Battery load representing heat pump electrical draw to charge the buffer tank was calculated based on the COP of the heat pump and maximum electrical draw. Details of how the inputs for the buffer tank were derived are provided in Section 7.

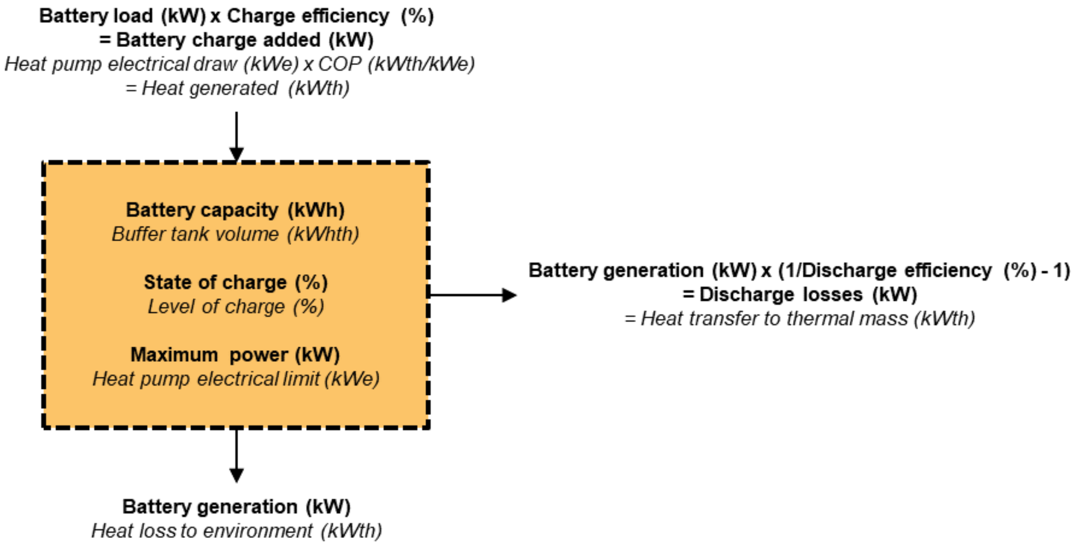

Figure 5: How the optional buffer tank was modelled as a battery in Plexos; Plexos properties shown in bold, physical equivalents shown in italics

Electrical battery model

Electricity from the grid used to power the heat pump or other non-thermal loads can be stored in an electrical battery before use to provide flexibility. The optional electrical battery in a house was also modelled as a battery in Plexos using the Plexos properties for an electrical battery. These are shown in Figure 6. Details of how the inputs for the battery were derived are provided in Section 8.

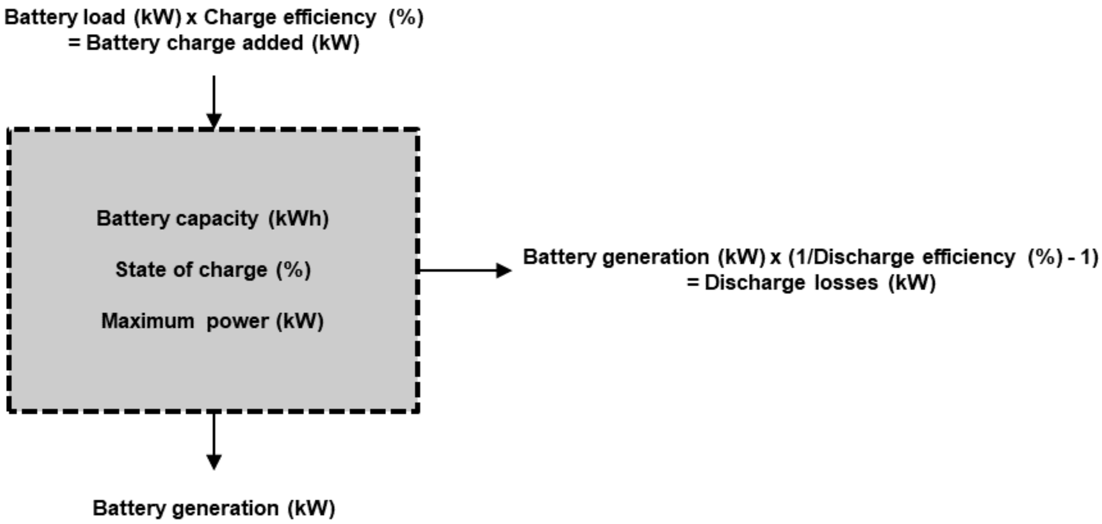

Figure 6: How the optional electrical battery was modelled in Plexos using battery object properties

2.3.2. Battery object constraints

The space heat distribution system, hot water cylinder and buffer tank (if present) are all supplied by the heat pump. A constraint was applied within Plexos to ensure the total electrical draw across these three loads could not exceed the maximum electrical draw of the heat pump.

3. Generating house archetype space heating demand profiles

A building physics model was used to estimate the heat loss and heat demand profiles for each house archetype under different conditions. This section explains the assumptions made in the building physics modelling, such as weather conditions, indoor temperature requirements and heat generation characteristics. It also describes how these results were then replicated in Plexos, where each house was modelled as a battery that effectively discharges (loses) heat to the environment and must be charged (heated) in order to maintain a set level of charge (indoor temperature).

3.1. Building physics modelling

A building physics model was used to estimate the half-hourly heat losses and heat demand for each of the house archetypes. This was conducted by AECOM, using the IES <VE> dynamic simulation modelling suite of software. Calculations within the model are based on first-principles models of the heat transfer process occurring within and around a building and are driven by real weather data. The program provides an environment for the detailed evaluation of building and system designs, allowing them to be optimised with regard to comfort criteria and energy use.

3.1.1. Modelling inputs

Several inputs and assumptions were required to model heat demand of the houses. These were agreed through discussions between AECOM and Delta-EE.

Time period

Model runs were done for the months of January and February in order to capture maximum heating demands in the middle of winter.

Weather scenarios

Two weather scenarios were used: one representing average winter conditions and one representing 1 in 20 winter conditions. AECOM has existing sets of weather data that it uses in its building physics models. It selected sets of weather data that aligned with average winter conditions and with 1 in 20 conditions similar to those seen in late February 2018.

For the average winter conditions, a CIBSE TRY[2] weather tape for Nottingham was used as this was the nearest location with available data to the location of the Mackworth primary (one of the 3 primary substations selected as study areas). A weather tape is the recorded half hourly dry bulb temperature for this average period.

For the '1 in 20' weather event, AECOM identified the salient features of this period, e.g. minimum and average temperatures over the period of interest and the frequency of minimum temperatures being reached. Dry bulb temperature was assumed to be the key determinant parameter. The weather conditions experienced during the 2018 winter period. Salient characteristics were identified from the weather in February 2018 in Derby, England from timeanddate.com[3] to be:

- Several days of continuous cycling into sub-zero temperatures
- Dry bulb temperature of high of 10°C, low of -6°C, average of 2°C

From these conditions, a weather tape was chosen exhibiting the most similar salient characteristics. The model was set up to run with these two weather tapes.

Indoor temperature requirements

Two occupancy profiles were used: one where occupants are in the house for the entire day and one where occupants are out the house from morning to evening. For these profiles the following temperature requirements were applied in the building physics model:

- Daytime occupied profile applied to all days for the occupied household profile and weekend days for the unoccupied household profile:
  - 21°C set temperature from 07h00- 23h00 (16 hours)
  - 16°C setback temperature overnight (8 hours)
- Daytime un-occupied applied to weekdays for the unoccupied household profile:
  - 21°C set temperature from 06h00-09h00 (3 hours) and 16h30-22h00 (5.5 hours)
  - 16°C setback temperature from 09h00-16h30 (7.5 hours) and overnight (8 hours)

A setback temperature of 16°C was used in order to limit the heat generation rate required during the morning heating period to a level achievable by a domestic heat pump. This means a

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[2] CIBSE licenses historic weather data from the UK Meteorological Office (MO) for 13 locations across the UK (in England and Wales these are Cardiff, Birmingham, Leeds, London, Manchester, Newcastle, Norwich, Nottingham, Plymouth, Southampton and Swindon). Test Reference Year (TRY) weather files represent a typical year and are composed of 12 separate months of data each chosen to be the most average month from 20 years of collected data. This data is comprised of hourly weather variables (including temperature) The TRY is used for energy analysis and for compliance with UK Building Regulations (Part L) - https://www.cibse.org/weatherdata

[3] https://www.timeanddate.com/weather/uk/derby/historic?month=2&year=2018

small amount of heat generation is sometimes required overnight, particularly on colder nights and for larger homes with less insulation.

A pre-heating period was allowed to ensure the homes reach 21°C at the time the set temperature period starts. The duration of the pre-heating period varied dynamically based on the outdoor temperature, and could be anywhere from half an hour for a well-insulated flat on a warmer day to almost four hours for a poorly-insulated house on a very cold day.

Heat generation rate limits

Heat generation rate limits were applied to ensure the heat generation profiles roughly matched what could be achieved by a domestic heat pump in reality. These were determined using the building physics modelling software to estimate the minimum heat generation rate possible to achieve set temperatures within a pre-heating period of up to 3.5 hours on the coldest day scenario. It was noted that the heat pump sizes for the detached house archetypes, particularly the poorly insulated detached house, were larger than the typical maximum size for a domestic heat pump (16 kW nominal capacity). This indicates that these homes would either need insulation upgrades or would likely require buffer tanks if they were to be fitted with heat pumps. A buffer tank would enable some heat to be generated ahead of when it is required and thus allow a smaller heat pump to be installed.

Table 4: Heat generation rate limits used in building physics model

Archetype code	Heat generation limit (kW)
DH-G	17
DH-P	20
SH-G	12
SH-P	14
MT-G	8
MT-P	9
FI-G	6
FI-P	6

Building physics assumptions

For each of the archetypes, specifications were made around the building fabric and internal gains and profiles. These included specifying the building U-values (the rate of transfer of heat through a structure - which can be a single material or a composite - per 1 Kelvin, units $W/m^2.K$), g-value (a measure of the fraction of solar radiation transmitted by a window, expressed as a number between 0 and 1). Indicative values were specified for each archetype based on the average archetype characteristics provided from WP1, as well as using appropriate U-values for different building elements as identified in the literature (see Appendix A for more detail). These U-values were attributed to ‘Good’ and ‘Poor’ variations of each archetype, and based on the age of the building, the type of construction (solid wall, cavity, etc.), and indicative air tightness. The details of each of these for each building archetype, along with all other key assumptions, are included in Appendix A.

In order to limit the budget for the project, heat loss and heat demand profiles were generated using existing AECOM housing models for the typologies identified in this project. These models were chosen to be typical or generic for each typology, with thermal mass, building fabric and window elements a reflection of what one would typically find in that type and age of building (and not characteristics that one might find in e.g. a low cost or high-end build of that archetype). For example, the well-insulated flat (FL-G) archetype will include modern flats built within the last 20 years, but the most common age band for this archetype is 1950-1996. Input assumptions were made based on these average characteristics for each archetype. Diversity within archetypes will be accounted for using stochastic heat loss profiles in WP4.

Building geometry of the various types of homes modelled generally assumed low surface area to volume ratio so as not to exaggerate heat loss. All properties were assumed to have punch windows and the number assumed for each archetype is typical for each property type. For each archetype, these windows were assumed to cover around 25-30% of total wall area. There was no accounting for a ‘maintenance factor’ impacting the thermal performance of the fabric, rather the condition of the building fabric is assumed to be a direct and indirect result of the state of building maintenance and so will already be reflected in the averaged sets of heat transfer coefficients of each of the fabric elements (see Appendix A).

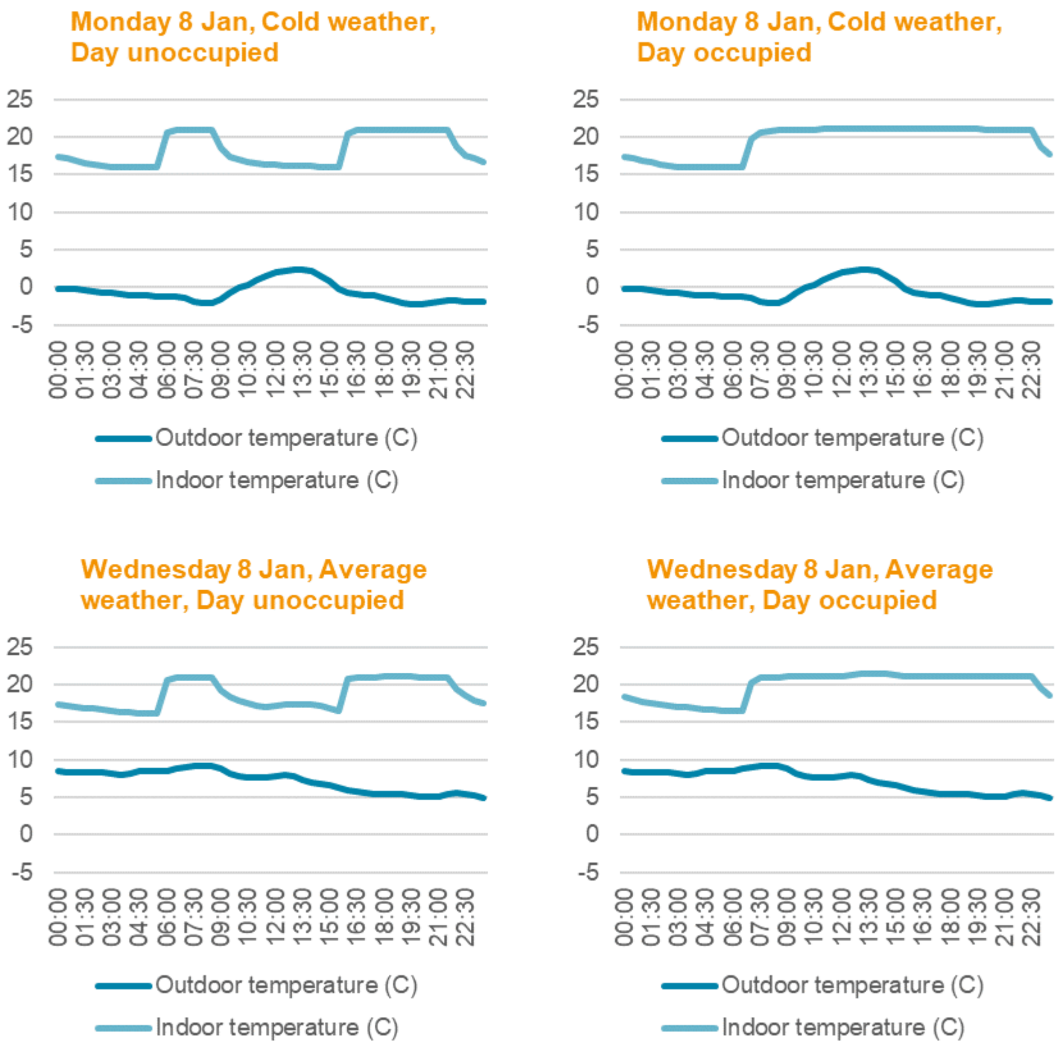
Area weighted U-values (for the wall/floor area of each respective fabric element) were applied across the model (as is typical for this type of modelling). More granular modelling, such as the use of specific U-values for individual windows for example, whilst possible, would unlikely provide much additional value to the overall aims of this part of the research, which was to identify representations of the heating profiles of existing typical good and typical poor performing building typologies with the study areas.

The resulting heat loss modelled by AECOM is built up for each archetype through the interaction of different fabric element assumptions, and so varying the rating of each of these elements (for example changing between ‘good’ and ‘poor’ assumed U-values) has a notable impact on the heat loss profile of the building over the study period as well as on magnitudes of peaks under different ambient conditions. However, due to the outputs being a result of the interaction of a large number of variables, it is difficult to quantify the degree of sensitivity of the modelling to each of these elements without carrying out further parametric analysis.

A general point on the selection of values – the aim of the exercise was to create typologies that are representative. To achieve this within the study limitations, some broad assumptions have had to be made to represent a wide range of physical characteristics. This means it is not possible to reference directly single values from the literature, but instead indicative values have been used. The impacts of doing this are likely to be negligible on peak loads (the key focus of Peak Heat), and more likely to impact on overall demands, especially in shoulder months where for example solar gains will be higher.

3.1.2. Modelling outputs

Four building physics model runs were done in total for each house archetype covering both weather scenarios and both occupancy scenarios. Full results are provided in the attached Excel spreadsheet. Example outputs are shown in Figure 7 and Figure 8 below for the well-insulated semi-detached archetype.



Monday 8 Jan, Cold weather, Day unoccupied

Monday 8 Jan, Cold weather, Day occupied

Wednesday 8 Jan, Average weather, Day unoccupied

Wednesday 8 Jan, Average weather, Day occupied

Figure 7: Indoor and outdoor temperature outputs from building physics model for Archetype B (semi-detached house, good insulation) on a day in January

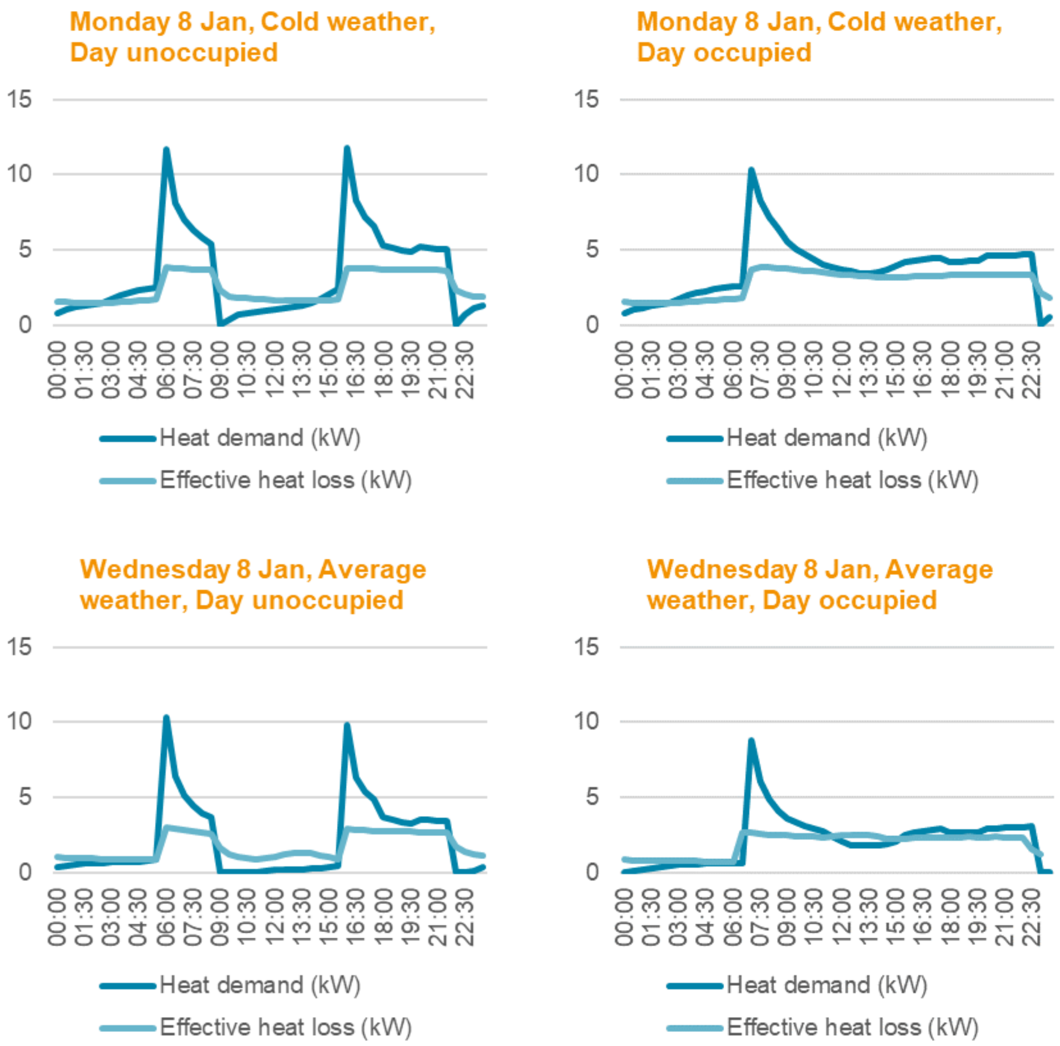


Figure 8: Heat demand and heat loss outputs from building physics model for Archetype B (semi-detached house, good insulation) on a day in January

Heat loss rate depends on the fabric of the building as well as the difference between the indoor and outdoor temperatures. The effective heat loss values from the building physics model also account for any additional gains within the thermal envelope of the building, such as solar gains or heat given off by appliances, which reduce the amount of space heating required to achieve set temperatures.

3.2. Replicating building physics modelling results in Plexos

To confirm that the building physics modelling results could be replicated in Plexos using the simplified representation of a house as a battery, the heat loss values and indoor temperatures from the building physics model were used as inputs in Plexos and the output heat demand from Plexos was compared to the heat demand estimated from the building physics model.

This section details the Plexos inputs used to model the space heating and the calibration variables used to match the building physics model outputs.

3.2.1. Model inputs

Heat pump sizing

The maximum power draw of the house battery in Plexos is equivalent to the maximum power draw of the heat pump. Maximum running currents for heat pumps are proportional to their nominal heat output[4], with some variation by product and by manufacturer. Based on a comparison of maximum current ratings of air-source heat pumps from leading UK suppliers (see Table 5), generic maximum power draws for the heat pumps in each archetype were applied. These electrical limits were derived from the thermal (heat generation) limits applied in the building physics modelling (see Table 4), based on conversions informed by heat pump product specifications.

Table 5: Maximum current ratings of selected air-source heat pump models[5]

Producer	Air-source heat pump nominal heating capacity (kW)	Phase	Maximum running current (A)	Maximum electrical draw at 230V (kW)
Mitsubishi Electric	4.8	Single	13.0	3.0
Vaillant	5.0	Single	16.0	3.7
Samsung	5.0	Single	16.0	3.7
Mitsubishi Electric	5.25	Single	13.0	3.0
Mitsubishi Electric	7.0	Single	19.0	4.4
Vaillant	8.0	Single	16.0	3.7
Samsung	8.0	Single	22.0	5.1
Mitsubishi Electric	8.3	Single	23.0	5.3
Mitsubishi Electric	11.0	Single	29.5	6.8

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[4] Heat pump sizes are generally quoted as nominal heat output rates at an outdoor temperature of 7°C and a flow temperature of 35°C.

[5] Product specification sheets are available online from Mitsubishi Electric (https://library.mitsubishielectric.co.uk/pdf/book/Heating_for_Domestic_Applications_Brochure_2016#page-31), Vaillant (https://www.vaillant.co.uk/downloads/product-brochures/arotherm-brochure-2006193.pdf) and Samsung (https://images.samsung.com/is/content/samsung/p5/uk/business/climate/for-installer/SEACE_EHS_Catalogue_2020_2021-single_LR_dr01bwt.pdf)

Producer	Air-source heat pump nominal heating capacity (kW)	Phase	Maximum running current (A)	Maximum electrical draw at 230V (kW)
Vaillant	11.0	Single	20.0	4.6
Mitsubishi Electric	11.2	Single	29.5	6.8
Samsung	12.0	Single	28.0	6.4
Mitsubishi Electric	14.0	Single	35.0	8.1
Vaillant	15.0	Single	25.0	5.8
Samsung	16.0	Single	32.0	7.4

Table 6: Maximum electrical draws specified for house battery objects in Plexos model (input I-12)

Archetype code	Maximum electrical draw (kW)
DH-G	8.0
DH-P	8.0
SH-G	6.5
SH-P	7.5
MT-G	5.0
MT-P	5.0
FI-G	3.5
FI-P	3.5

Heat pump performance and heat distribution system flow temperature

Heat pump COPs vary by product and manufacturer, and are a function of difference between outdoor temperature and flow temperature required in the heat distribution system.

Flow temperature should vary throughout the day depending on outdoor temperature, if the heat pump system is properly set up, with higher flow temperatures when it is colder outside and lower flow temperatures when it is warmer[6]. The MCS Best Practice Guide for domestic heat pumps[7] shows the following typical heat pump weather compensation line. This was used to calculate flow temperature as a linear function of half-hourly outdoor temperature for all house archetypes.

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[6] This is referred to as weather compensation or ambient air temperature load correction

[7] MCS Best Practice Guide for domestic heat pumps: https://mcscertified.com/wp-content/uploads/2020/07/Heat-Pump-Guide.pdf

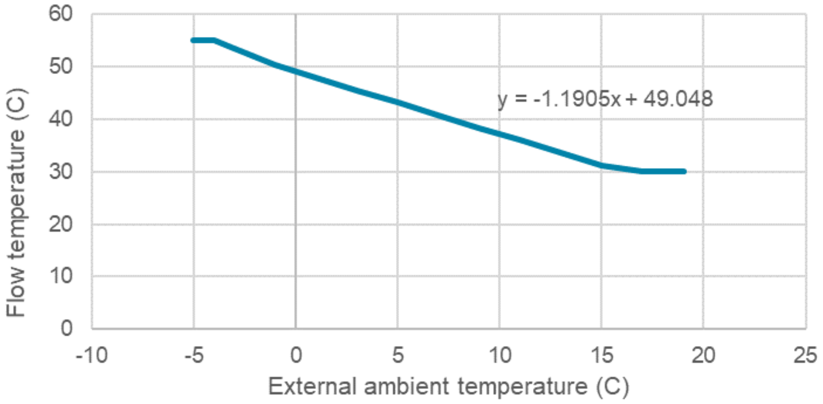

Figure 9: Typical heat pump weather compensation line for recommended operation

Heat pump COPs reported in Figure 21 of the WP2 report as a function of outdoor temperature and flow temperature are shown below as a function of the temperature difference[8]. This quadratic relationship was used to calculate half-hourly COPs based on outdoor temperature and flow temperature for the house archetypes with air-source heat pumps.

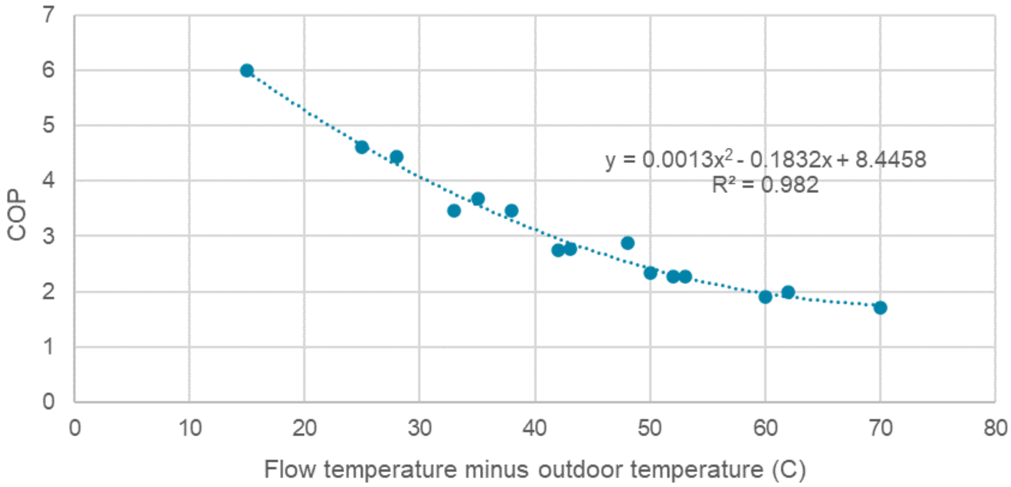

Figure 10: Average COPs for heat pumps as a function of the difference between flow temperature and outdoor temperature (input I-11)

Ground source heat pumps operate with a more constant COP between about 3 and 4, as the temperature of the ground is warmer and varies less than the temperature of the air. For model runs with a ground source heat pump, a fixed COP of 3.5 was assumed for space heating and 2.3 for hot water generation.

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[8] These are COPs achieved under lab conditions. Actual COPs tend to be lower in practice due to problems with installations, but insufficient performance data is available currently to say definitively what COPs should be assumed for real installations. We elected to use lab COPs on the assumption that heat pump installation quality by 2030 will have improved significantly, which should be the case the target of installing hundreds of thousands of heat pumps a year is achieved.

In Plexos, battery charge efficiency needs to be a value between 0-100%, while COP values range from around 2-4 in practice. To convert absolute COP values to percentage equivalents, COP was divided by a maximum COP of 7.5 – a value that would be achievable theoretically at an outdoor temperature of 20°C and flow temperature of 25°C. Battery capacity and battery output values were divided by the same value to balance the equation. An example calculation is included in Appendix B to illustrate this.

Indoor temperature requirements

Indoor temperature requirements are set in Plexos by limiting the minimum and maximum state of charge of the house battery. Two temperature profiles ('set' and 'flexible') were created for each occupancy scenario:

- A set temperature profile where:
  - The temperature can be 21 ± 0.5°C when 21°C is required;
  - 3.5 hour heat up or cool down periods are allowed either side of the 21°C set temperature periods, with the maximum temperature changing by 1°C per hour and the minimum temperature set to 16°C; and
  - A setback temperature of 16°C outside of the heating periods, with an 18°C maximum in the middle of the night and a 19°C maximum in the middle of the day.
- A flexible temperature profile with an additional 0.5°C of flexibility allowed around the set temperature and a maximum of 21°C when the home is unoccupied in the middle of the day. This temperature profile was used for testing the amount of flexibility available from allowing slight over- or under-heating the houses.

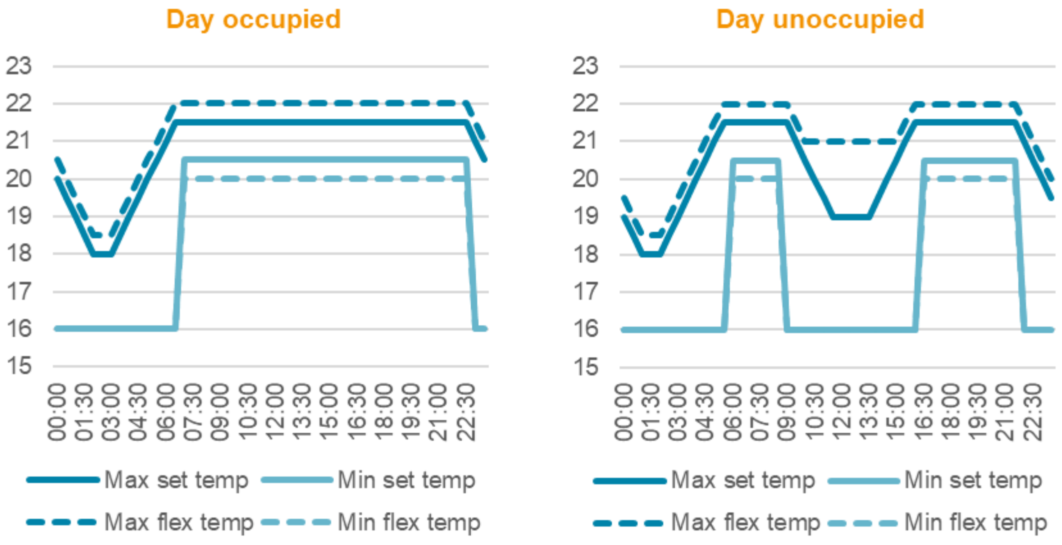

Figure 11: Minimum and maximum temperatures allowed in the houses under different occupancy and flexibility scenarios (input I-04)

3.2.2. Model calibration

It was found that the most effective way to determine the capacity property of the house battery for each archetype was by adjusting the value until the half-hourly heat demand results from Plexos approximately matched the results from the building physics model. Figure 12 shows the heat demand predicted by the Plexos model versus the building physics results for Archetype A (detached house, good insulation) over 5 days after calibration of the house battery capacity. A straight line correlation is shown in Figure 13 for each half hour in the full two month period of the model. The correlation coefficient (R^2) value was above 0.85 for all eight archetypes under both weather scenarios.

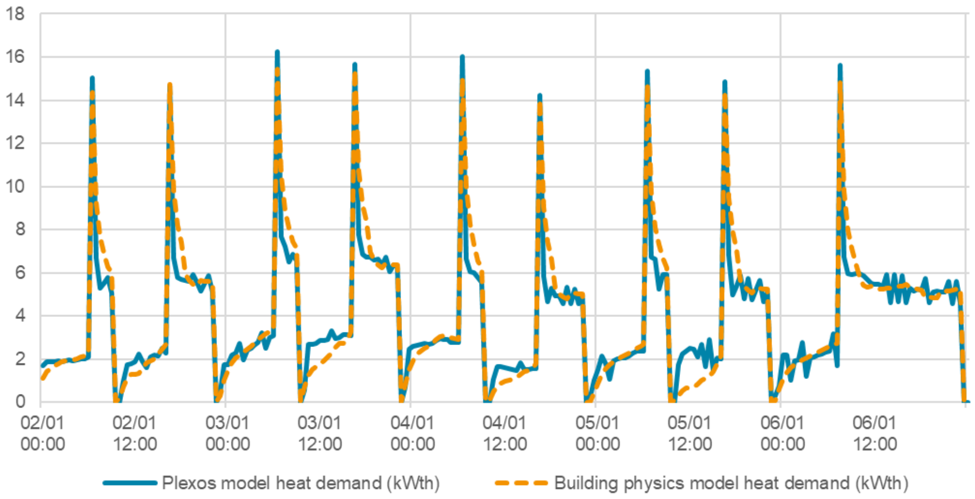

Figure 12: Half-hourly heat demand predicted by Plexos model versus building physics model for Archetype A (detached house with good insulation), unoccupied during weekdays, including thermal mass effects, from Tuesday 2 Jan to Saturday 6 Jan

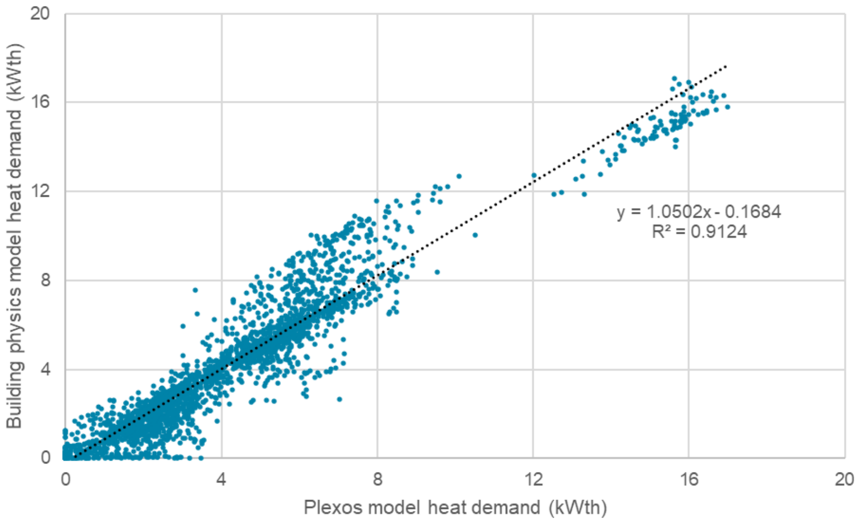

Figure 13: Correlation between half-hourly heat demand predicted by Plexos model versus building physics model results over two month modelled period for Archetype A under cold weather conditions (detached house with good insulation)

The house battery capacities determined for each of the archetypes are given in Table 7.

Table 7: House battery capacities determined for each archetype, representing the volume of space heated (input I-03)

Archetype code	House battery capacity (kWhth)
DH-G	13.0
DH-P	12.5
SH-G	10.0
SH-P	10.0
MT-G	6.6
MT-P	7.0
FI-G	7.5
FI-P	8.0

It was also noted that total heat demand predicted by the building physics model over a 24 hour period was around 20% higher than heat losses over the same period on average, with greater deviations on colder days and lesser deviations on warmer days, as illustrated in Figure 14 below.

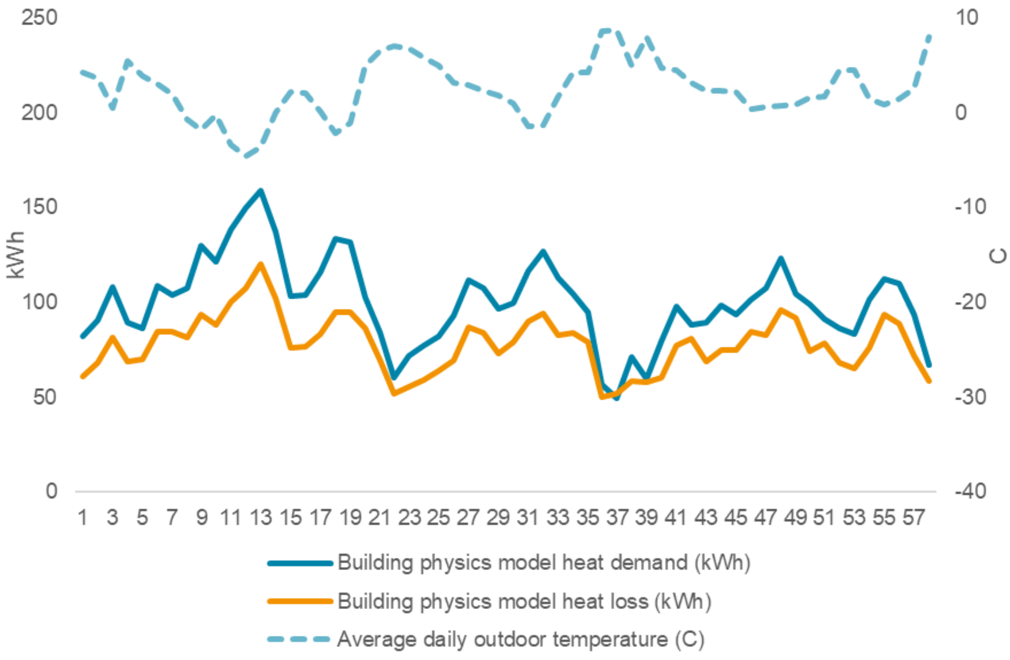

Figure 14: Building physics model predicted daily heat demand versus heat loss for Archetype A (detached house with good insulation) and average outdoor temperature for the 1 in 20 winter scenario

This was thought to be largely a result of the thermal mass of the building, which retains heat without increasing the indoor temperature. Efficiency losses from the heat distribution system may also have been a contributing factor. Because the battery object used to model the houses in Plexos cannot capture the effects of thermal mass, an adjustment was made to the heat loss values to reflect the additional heat transferred to the material of building itself. This was done using the discharge efficiency property of the battery[9], where discharge efficiency was calculated on a half-hourly basis as a linear function of outdoor temperature, where both a and b are positive values:

Discharge efficiency = a x (Outdoor temperature) + b

e.g. 78% = 1 x (-2°C) + 80

The coefficients a and b were determined through iterative adjustments until daily heat demand was more closely matched to the building physics model results. Figure 15 shows the heat demand predicted by the Plexos model before and after the adjustments to account for thermal mass.

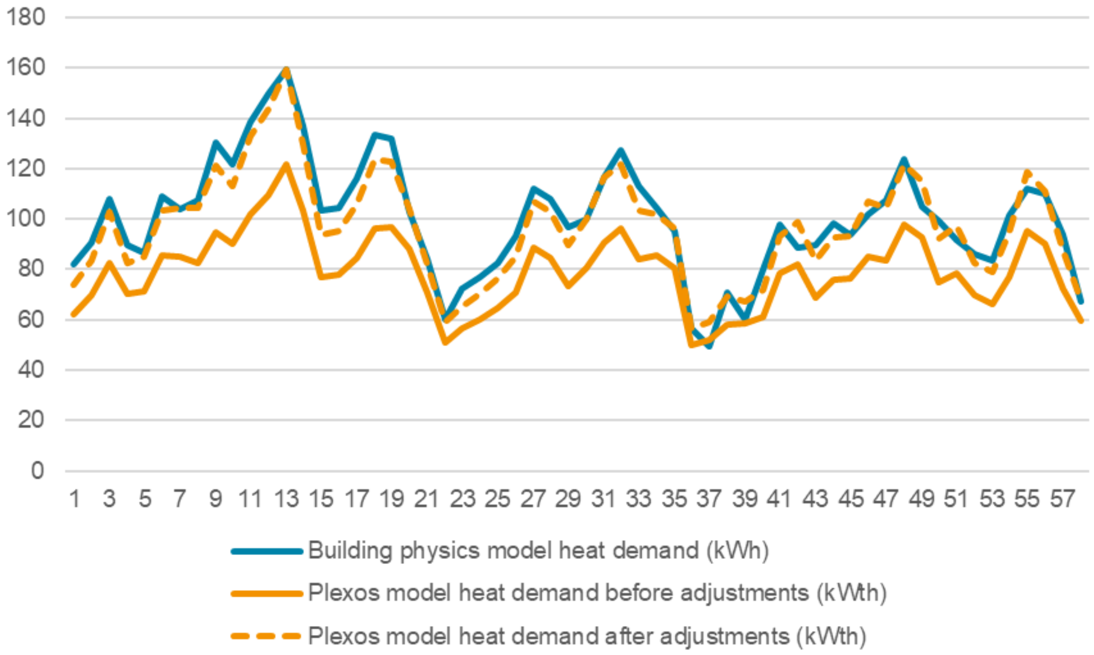

Figure 15: Daily heat demand predicted by building physics model versus Plexos model before and after adjustments for thermal mass for Archetype A (detached house with good insulation)

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[9] The default value for discharge efficiency is 100%, meaning no energy is lost when the battery is discharged. Reducing this to less than 100% implies that a certain amount of energy is lost in the process, which was used in the model to represent the heat transferredto the material of the building.

The coefficients determined for each archetype are given in Table 8.

Table 8: Thermal mass adjustment coefficients determined for each archetype (used to determine discharge efficiency input I-02)

Archetype	Thermal mass coefficient a	Thermal mass coefficient b
DH-G	1	77
DH-P	1	85
SH-G	1	75
SH-P	1	79
MT-G	1	77
MT-P	1	83
FI-G	1	75
FI-P	1	79

3.2.3. Calibration versus set temperature operation

For the calibration model runs, Plexos was set up to match the half-hourly indoor temperatures from the building physics model results as closely as possible. For the baseline model runs the set temperature profile was used, which allowed the Plexos optimisation solver to determine the most efficient way to operate the heat pump to achieve the set temperature requirements.

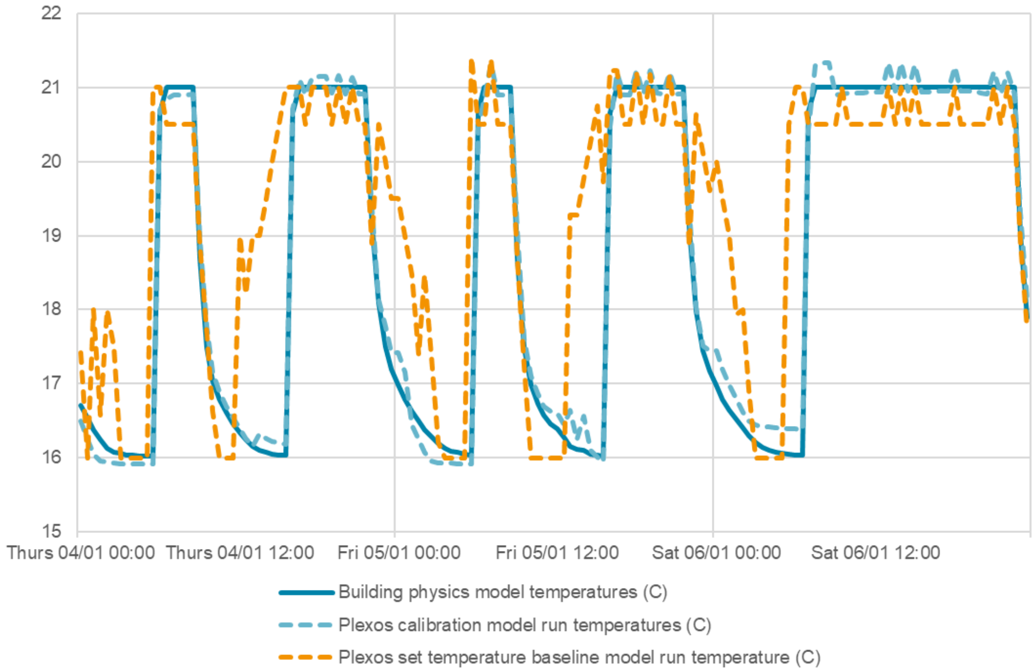

Figure 16 shows an example output for three modelled days comparing the temperatures predicted by the building physics model, the temperatures achieved in the Plexos model calibration, and the temperatures achieved with the set temperature profile requirements. In this example, with the set temperature requirements the Plexos optimisation solver elects to preheat the home ahead of the evening heating period in order to take advantage of warmer afternoon outdoor temperatures. It also maintains slightly higher temperatures after the evening heating period in order to avoid the heat pump operating as much to maintain the setback temperature in the early morning hours when outdoor temperatures are lowest. The same amount of heat is generated in total each day to maintain the desired temperatures in the different scenarios, just at slightly different times to maximise the efficiency of the heat pump and hence reduce the electrical input.

Sharp changes in temperature seen in the Plexos model outputs are as a result of the optimisation solver maximising the operation of the heat pump in half hourly periods when outdoor temperatures are highest. In reality heat pump control algorithms might be set to maintain more consistent temperatures, however it is not possible to force this type of smoothing in Plexos without changing the model inputs. This is a limitation at the individual house level, but it will not impact the overall conclusions at the network level.

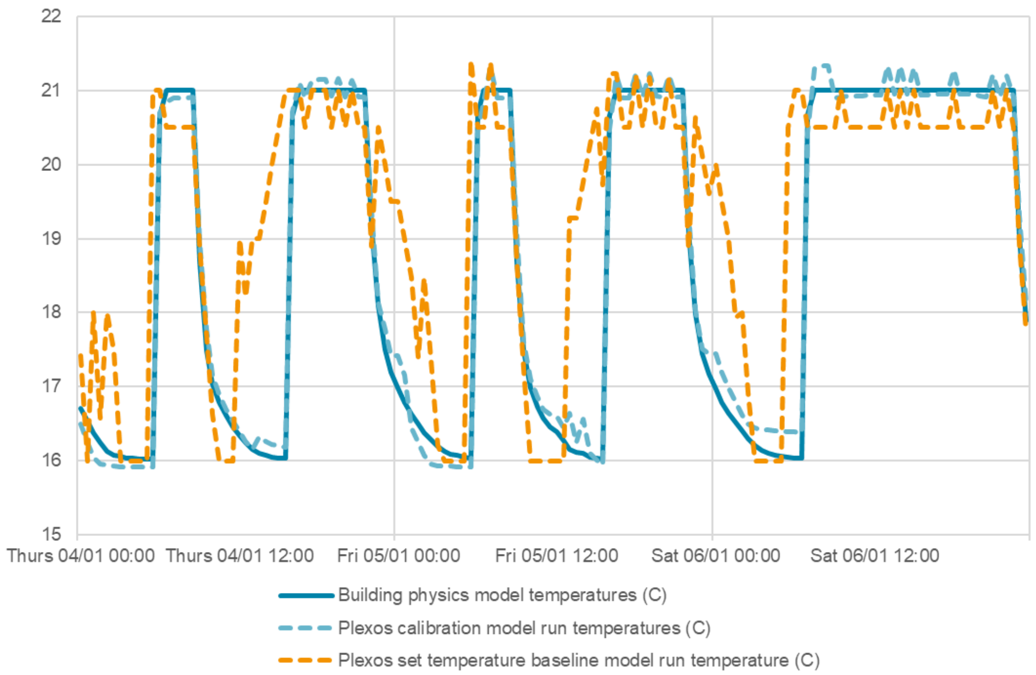

Figure 16: Indoor temperatures predicted by building physics model, Plexos model calibration and Plexos model run with set temperatures in Archetype A (detached house with good insulation) from Thursday 4 Jan to Saturday 6 Jan under cold weather conditions, day unoccupied

4. Generating house archetype hot water demand profiles

Hot water demand profiles were estimated for each archetype based on literature findings. Assumptions were made about hot water storage capacities and the hot water generation strategies used by heat pumps. These were input into the Plexos model to determine when heat pumps would be utilised to generate hot water.

In addition to space heating, the heat pumps modelled in this project were also required to generate hot water. This section details the assumptions made to generate the hot water demand and generation profiles.

4.1.1. Model inputs

Hot water usage profiles

Hot water usage profiles were determined based on findings in a 2008 survey of over 100 UK homes done by the EST[10]. From this research, daily hot water consumption in litres is estimated to be a function of the number of occupants in the house, which varies by archetype:

*Hot water consumption (litres/day) = 28 * Number of occupants + 40*

The energy required to generate hot water was determined to be 0.13 MJ/litre (0.036 kWh/litre) on average, based on average cold water inlet and hot water supply temperatures.

An average hourly hot water demand profile was also estimated from the research. This was used to generate the half-hourly hot water demand profile shown in Figure 17. This profile was used for each day for all eight archetypes.

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[10] 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

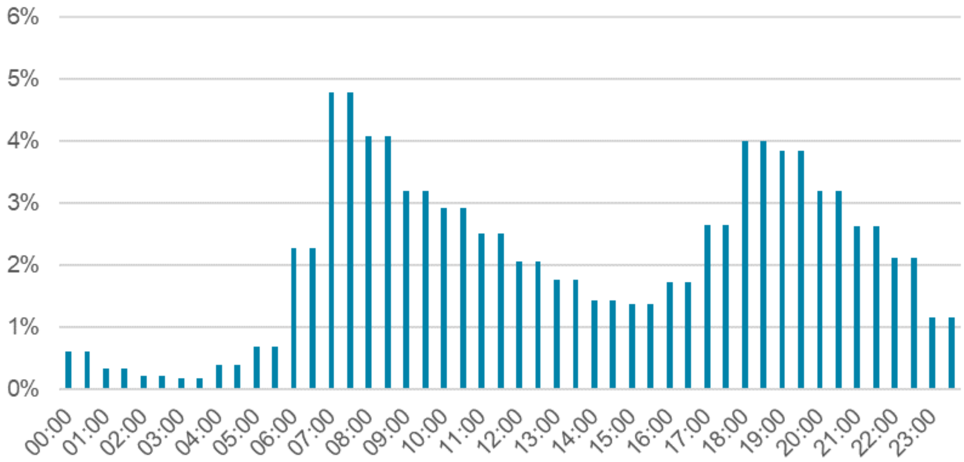

Figure 17: Average percentage of total daily hot water consumption in each half hour (used to determine input I-05)

Hot water cylinder sizing

Hot water cylinder sizes for each archetype were selected according to MCS guidance[11] based on the size of heat pump required and the assumed number of bedrooms and bathrooms given the property type and average number of occupants. Slightly larger cylinders were allowed for larger properties as heat pump installers tend to oversize cylinders, and from an electricity network perspective the additional storage capacity provides more flexibility. It was assumed that the hot water cylinders would not have electric resistance immersion heaters, which MCS recommends should be avoided as far as reasonably practicable[12].

Table 9: Hot water cylinder sizes assumed for each archetype (input I-06)

Archetype	Average number of occupants	Assumed number of bedrooms	Assumed number of bathrooms	Heat pump size (kW)	Cylinder size (litres)	Hot water demand (litres/day)
DH-G	3-4	3-4	2	17 kW	200	152
DH-P	2-4	3-4	2	20 kW	200	152
SH-G	2-4	3-4	1	12 kW	180	152
SH-P	1-3	3-4	1	14 kW	180	124
MT-G	1-4	2-3	1	8 kW	150	124
MT-P	1-3	2-3	1	9 kW	150	96
FL-G	1	1-2	1	6 kW	150	68
FL-P	2-3	2-3	1	6 kW	180	96

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[11] Domestic hot water cylinder selection guide, MCS, 2019: https://mcscertified.com/wp-content/uploads/2019/08/Domestic_HW_cyl_selection_guide.pdf

[12] Domestic heat pumps: A best practice guide, MCS, 2020: https://mcscertified.com/wp-content/uploads/2020/07/Heat-Pump-Guide.pdf#

Heat pump efficiency

A hot water delivery temperature of 55°C was assumed for all the archetypes. This is slightly higher than the average found by the EST[10] of 51.9°C because MCS recommends occasional heating to over 60°C to prevent bacterial growth. To heat hot water in the cylinder to 55°C a heat pump must heat the fluid running through the coil in the cylinder to 60°C according to MCS. The half-hourly heat pump efficiency for hot water generation based on the outdoor temperature and a flow temperature of 60°C was calculated using the same equation as for space heating (see Figure 10).

Heat pump capacity

The rate at which a heat pump generates hot water will depend on how hot the water in the cylinder is when the heat pump is set to generate hot water. If the water is far from its target temperature, the heat pump could operate at up to about 80% of its maximum electrical capacity in practice, depending on the size of the heat pump, though on average it will operate at a lower capacity. It is unlikely that a heat pump would operate at 100% capacity for hot water generation as it is limited by how fast heat can be transferred from the heat pump to the hot water cylinder via the heat exchanger coil. For hot water generation in the model the maximum electrical draw of the heat pump was limited to 40% of the maximum electrical draw applied for space heating (see

Table 6). At this capacity it takes between 30-60 minutes for hot water cylinders to be charged fully. It was necessary to apply this limit in Plexos to prevent the model using 100% of the heat pump capacity and recharging the cylinders in an unrealistically short amount of time.

Hot water cylinder losses

Heat losses from hot water cylinders are affected by several factors, including the cylinder age, cylinder size, hot water temperature and usage patterns. Based on findings from a 2013 study for DECC[13], a storage efficiency of 75% was assumed for hot water cylinders in all archetypes. Modern cylinders are likely to have improved efficiencies, but the value from the comprehensive report of 2013 has been taken as a conservative estimate. As a result the modelling has used a cautious approach to slightly over-estimate losses and consequently electrical demand. This was applied in Plexos by setting the discharge efficiency property of the hot water cylinder battery to 75%.

Hot water generation strategy

The hot water generation programme of a heat pump will be set by the installer based on occupant usage profiles. Some installers will recommend having two one-hour periods when hot water is generated, one shortly before the morning peak and one in the late afternoon ahead of evening demand. Others will recommend one three-hour period in the middle of the day when the heat pump is most efficient. If the customer has a time-of-use tariff with a low overnight price period, hot water will be set to generate then. Alternatively, the heat pump can be set to

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[13] Investigation of the interaction between hot water cylinders, buffer tanks and heat pumps, Kiwa GASTEC at CRE, 2013: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/198850/hot_water_cylinders_buffer_tanks_heat_pumps.pdf

generate hot water whenever the temperature in the hot water cylinder falls 10°C below the set temperature – in this case hot water will be generated multiple times throughout the day.

For hot water generation in the baseline scenario, hot water was set to be generated whenever the hot water cylinder battery state of charge fell below 80%, corresponding to about 10°C below the set temperature. This strategy was chosen to give more diversity across the houses than would be achieved by setting limited hot water generation periods. For scenarios looking at the amount of flexibility available from each house, hot water was allowed to be generated at any times during the day and no minimum temperature level was required to be maintained, provided hot water demands could always be met. Figure 18 shows the hot water generation profiles over three days in the baseline scenario with a minimum temperature requirement and the unlimited scenarios where the optimal generation periods are determined based on the heat pump efficiency and electricity price.

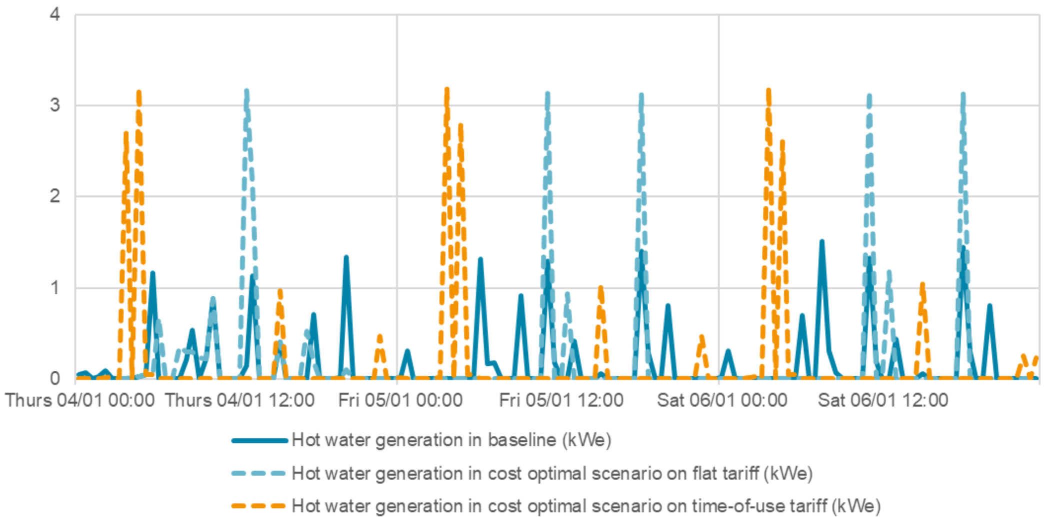


Figure 18: Hot water generation by heat pump in baseline scenario to maintain hot water temperature level and in cost-optimal scenarios with no minimum temperature requirement for Archetype A (detached house with good insulation) from Thursday 4 Jan to Saturday 6 Jan under cold weather conditions, day unoccupied

5.Generating house archetype non-thermal electrical demand profiles

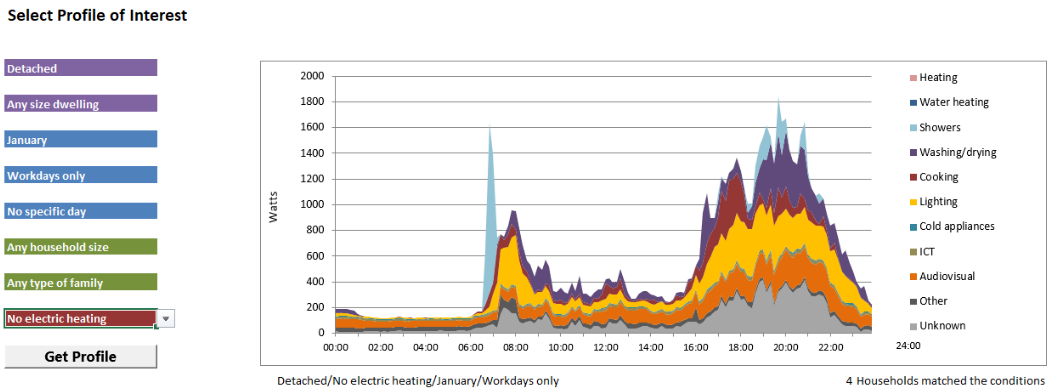
Non-thermal electrical demand profiles for each house archetype under different weather and occupancy conditions were based on findings from the literature.

5.1.1. Model inputs

Non-thermal electrical demand profiles were taken from the 2010/11 Household Electricity Use Survey conducted with 250 households[14]. Average daily profiles were extracted from the HES 24-Hour Chooser spreadsheet tool by:

- House type (detached, semi-detached, terrace or flat);
- Occupancy (workdays or holidays);
- Weather (average or coldest day); and
- Month (January or February).

Any electric space or water heating loads were excluded from the sample. An example profile from the spreadsheet tool is shown in Figure 19.



Select Profile of Interest

Detached
Any size dwelling
January
Workdays only
No specific day
Any household size
Any type of family
No electric heating

Detached/No electric heating/January/Workdays only

4 Households matched the conditions

Figure 19: Example non-thermal electrical demand profile from Household Electricity Use Survey spreadsheet tool (input I-13)

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[14] Household Electricity Survey, Department of Energy & Climate Change, 2013: https://www.gov.uk/government/publications/household-electricity-survey--2

Profiles for the two-month modelled period were then created for each of the eight archetypes based on the building type, occupancy, day of the week (weekday or weekend), month and weather. Days with an average temperature of over 0°C were classed as average while those below 0°C were classed as cold.

It was noted that profiles from the survey results for flats were the same for both workdays and holidays. There was also insufficient data available to generate the coldest day profile for detached houses and flats. Profiles for semi-detached and terraced houses showed that non-thermal electrical demands were around 35% higher on coldest days compared to average winter days. On this basis and for consistency across house types, coldest day profiles for all house types were assumed to be 35% higher than the average winter day profiles in every half-hour of the day. The resulting non-thermal demand profiles for each house type under the different occupancy and weather conditions are shown in Figure 20.

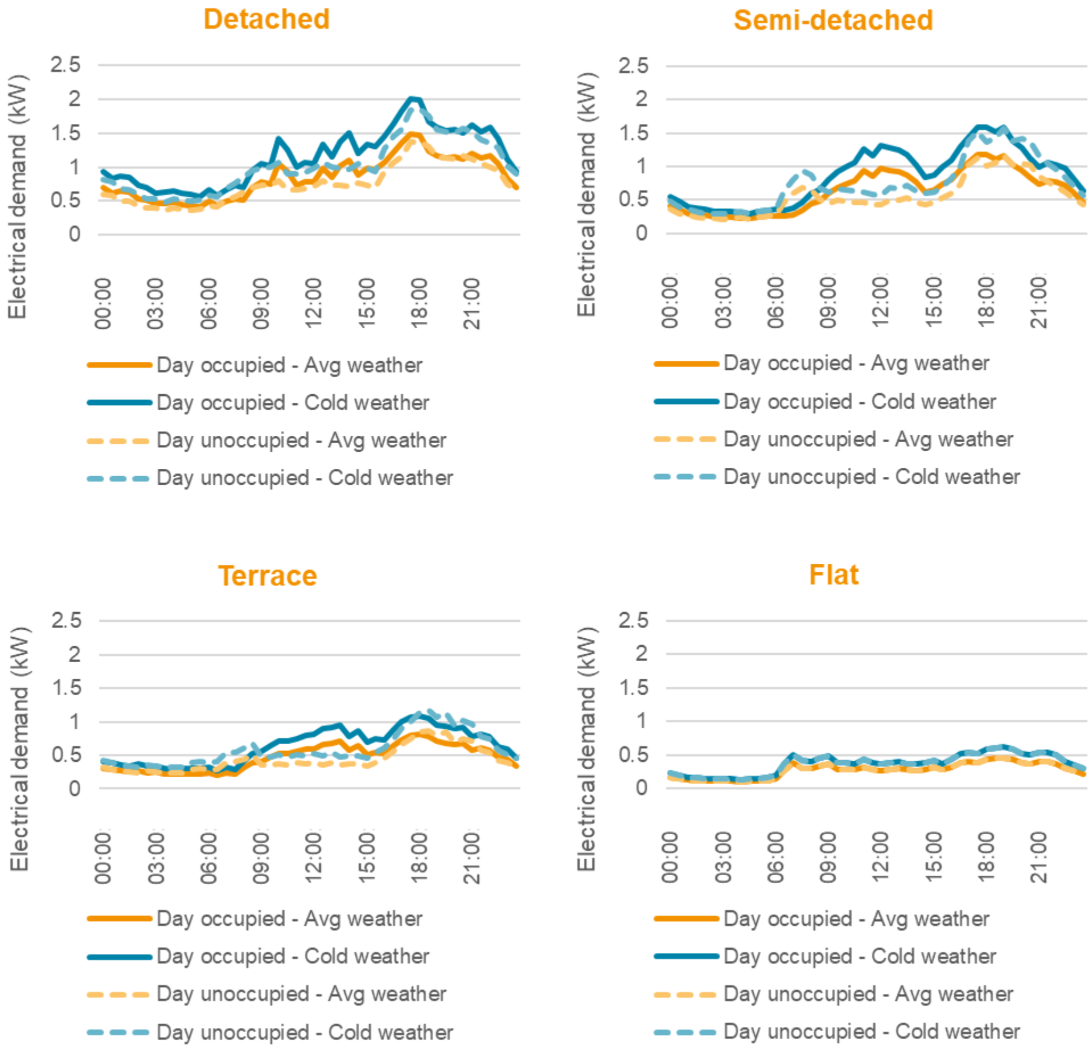

Figure 20: Non-thermal electrical demand profiles for each house type under different occupancy and weather conditions (average winter or coldest days)

6. Electricity price scenarios and control strategies

Plexos determines the heat pump demand profiles by finding the least cost solution that satisfies all model constraints. This section explains how the Plexos optimisation solver works and the electricity price assumptions made.

6.1. Cost optimisation in Plexos

Heat losses from the house to the environment and hot water consumed from the cylinder are inputs to the model set up in Plexos. The heat pump electrical demand profile required to meet the space heating and hot water demands are determined within Plexos using an optimisation solver, given all system constraints such as the temperature requirements, heat pump capacity, hot water cylinder volume and storage capacities.

The optimisation solver minimises the total system costs over a given calculation period. In the case that a house is on a fixed electricity tariff, that is done by operating the heat pump in periods when it is warmest outside and the COP is highest. If a house is on a time-of-use tariff, the solver will take into account both the heat pump efficiency and the cost of electricity.

Calculation periods of one day were used in the model starting at 00:00, meaning the optimisation solver knows the heat losses, hot water consumption, heat pump efficiencies and electricity costs for the following 24 hours and determines when to generate heat and store energy within that time. In practice this would mean a heat pump's control system knows what times heat will be required, which it does based on the temperature profiles and hot water programme set by the user. It also means the heat pump has the connectivity to receive weather and price forecasts. Heat pumps with the connectivity to receive forecasts are in the minority of installations today, but will become increasingly commonplace in future as connectivity costs come down and there are more incentives to optimise operation such as time-of-use tariffs. Since this project is looking at what the load impacts could be in 5-10 years, it is reasonable to assume that most heat pumps could be connected at this stage.

6.2. Time of use price scenarios

Two electricity price scenarios were used in the Plexos model runs: a flat tariff and a time-of-use tariff with higher prices during the evening peak and lower prices in the early hours of the morning. The time-of-use tariff profile was determined by taking an average of the Octopus Agile historical tariff rates over each day in January and February from 2018 to 2020 for South Western England[15]. This is shown in Figure 21.

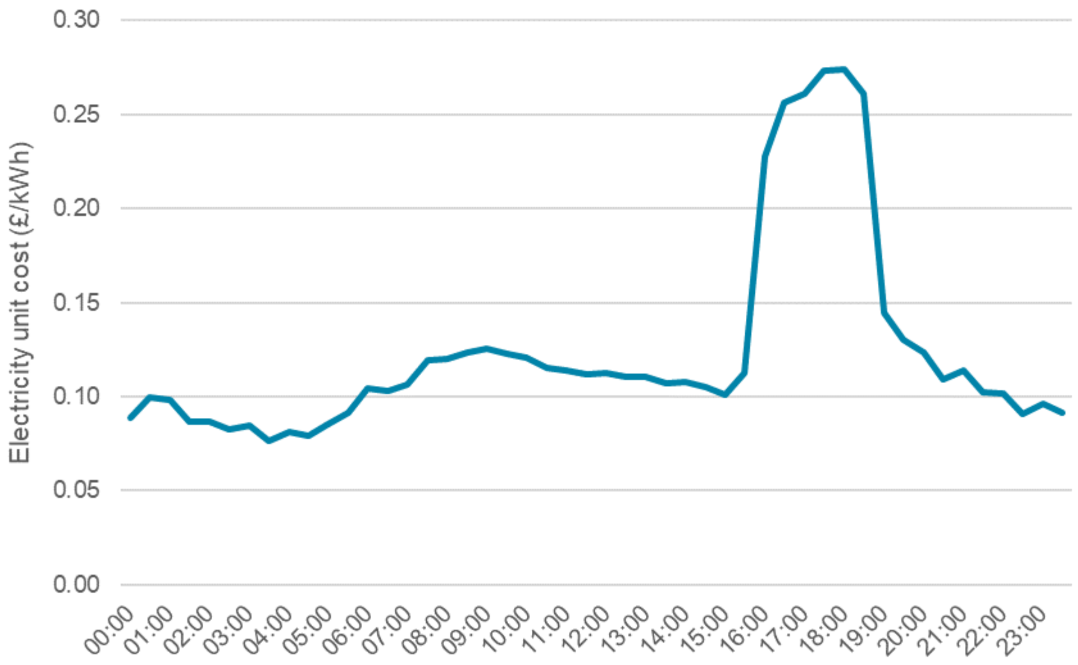

Figure 21: Daily time-of-use tariff profile used in dynamic price scenarios (input I-14)

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[15] Historical Octopus Agile pricing data can be downloaded from energy-stats.uk: https://www.energy-stats.uk/download-historical-pricing-data/

7. Additional storage devices

For scenarios with additional thermal or electrical storage included, assumptions were made for how much storage capacity to include in each house archetype. Storage capacities were chosen from literature values based on the property size of each house archetype.

7.1. Buffer tanks

7.1.1. Model inputs

Buffer tanks are used to allow heat pumps to continue generating heated water for space heating even when it is no longer required to achieve the desired indoor temperature. This prevents the heat pump from stopping and starting too frequently. Modelling of buffer tanks within Plexos is described in section 2.3.1. Storage volumes are relatively small compared to hot water cylinders, as they only need to provide relatively short-term storage. A more typical buffer tank size is around 40 litres, though tank volumes of around 100 litres can be installed in larger homes. The following buffer tank capacities were assumed for each of the house archetypes for modelled scenarios with buffer tanks:

Table 10: Buffer tank capacities used in scenarios with buffer tanks (input I-08)

Archetype code	Buffer tank volume (litres)
DH-G	100
DH-P	100
SH-G	40
SH-P	40
MT-G	40
MT-P	40
FI-G	40
FI-P	40

7.2. Electrical battery storage

7.2.1. Model inputs

Domestic scale electrical batteries can typically store between 4-14 kWh of charge[16]. Battery capacities and charge/discharge rates within this range were selected for each of the house archetypes based on the building size, assuming larger homes would have space to install larger batteries. Battery capacities used in model scenarios with batteries are listed in the table below:

Table 11: Battery capacities, charge rates and efficiencies used in scenarios with batteries (inputs I-09 and I-10)

Archetype code	Battery charge/discharge rate (kW)	Usable battery storage capacity (kWh)	Battery charge/discharge efficiency (%)
DH-G	7	13.5	90
DH-P	7	13.5	90
SH-G	5	10.0	90
SH-P	5	10.0	90
MT-G	3	5.0	90
MT-P	3	5.0	90
FI-G	3	5.0	90
FI-P	3	5.0	90

For the purposes of WP3 it was assumed that all house archetypes would have the necessary space to accommodate an electrical battery and/or buffer tank. WP4 will explore the impact of different uptake levels of storage devices at the network level, based on how suited each of the house archetypes are to having these installed.

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[16] Solar batteries and storage, Naked Solar, 2021: https://nakedsolar.co.uk/storage/

8.Results

Several scenarios were run in Plexos to determine the electrical demand profiles of each archetype under different conditions and with different flexibility measures applied. It was found that peak electrical demands were 3 to 6 times higher after the addition of a heat pump without any flexibility measures.

Allowing more flexible heating and adding thermal and electrical storage enables load to be shifted from high price to low price periods, if suitably incentivised. Flexible heat and hot water generation can enable 10-20% of demand to be shifted from the evening peak period, depending on the archetype. The addition of a buffer tank gives a further 5-15%, and an electrical battery can allow up to 100% of loads to be moved outside of evening peak times.

To test how much peak demands could be reduced rather than shifted with the additional flexibility sources, electrical supply limits were applied in the test scenarios. This showed that flexible heat and hot water generation can enable peak demands to be reduced by around 20-30%, buffer tanks by a further 10-20%, and electrical batteries by an additional 10-20%, depending on the archetype.

8.1. Modelled scenarios

To determine the average load profiles for homes heated by air-source heat pumps and the impact of flexibility measures on peak demand, ten scenarios were run in Plexos for each of the eight archetypes:

- 4 baseline scenarios with different weather and occupancy scenarios;
- 3 test scenarios with added flexibility measures applied to the unoccupied profiles in cold weather conditions:
    - Relaxed temperature requirements and no limitations on when hot water can be generated – this is the flexibility available without any additional thermal or electrical storage;
    - A buffer tank; and
    - An electrical battery.
- 3 test scenarios with the same added flexibility measures as above, plus a limit on the amount of electricity that could be drawn from the grid.

The input assumptions for each scenario are listed in Table 12. The baseline scenarios were run with a fixed tariff, while the test scenarios were run with a variable tariff to disincentivise electricity use during peak periods. Test scenarios were only run for cold weather and day unoccupied conditions as these result in the highest peak demands.

In the test scenarios without electrical supply limits, it was found that peaks were shifted to cheaper electricity periods but not reduced. Electricity supply limits were introduced to test how much peak demands could be reduced by with added flexibility measures. These supply limits were applied as a constraint within Plexos. Limit values were reduced in increments of 1kW down to a minimum of 3kW until electrical demands could no longer be met within the constraints, or the 3kW minimum was reached.

Table 12: Inputs for modelled scenarios for each archetype

No.	Scenario	Weather	Day occupancy	Electrical limit	Temperature profile	Hot water generation	Buffer tank	Electrical battery	Electricity price
1	Baseline	Cold	Unoccupied	None	Set	Maintain 80% charge	None	None	Fixed
2	Baseline	Cold	Occupied	None	Set	Maintain 80% charge	None	None	Fixed
3	Baseline	Average	Unoccupied	None	Set	Maintain 80% charge	None	None	Fixed
4	Baseline	Average	Occupied	None	Set	Maintain 80% charge	None	None	Fixed
5	Test	Cold	Unoccupied	None	Flexible	Flexible	None	None	Variable
6	Test	Cold	Unoccupied	Limit applied	Flexible	Flexible	None	None	Variable
7	Test	Cold	Unoccupied	None	Flexible	Flexible	Installed	None	Variable
8	Test	Cold	Unoccupied	Limit applied	Flexible	Flexible	Installed	None	Variable
9	Test	Cold	Unoccupied	None	Flexible	Flexible	Installed	Installed	Variable
10	Test	Cold	Unoccupied	Limit applied	Flexible	Flexible	Installed	Installed	Variable

8.2. Baseline scenario results

8.2.1. The impact of heating on peak electricity demand

Figure 22 shows the maximum total (thermal and non-thermal) electrical demands occurring in a half hour over the two-month modelled period for each archetype in the four baseline scenarios. Maximum non-thermal electrical demands are included for comparison. Total peak demands are typically higher in the day unoccupied scenarios compared to the day occupied scenarios because more energy is required to raise the temperature of the houses in the evenings, coinciding with peak non-thermal electrical demands.

Total electricity demand peaks are around 4 to 6 times higher than peak non-thermal demands, depending on the archetype. This confirms that peak loads on electricity networks would be significantly higher if a large proportion of homes were to switch from gas/oil/LPG heating to electrically-driven heat pumps.

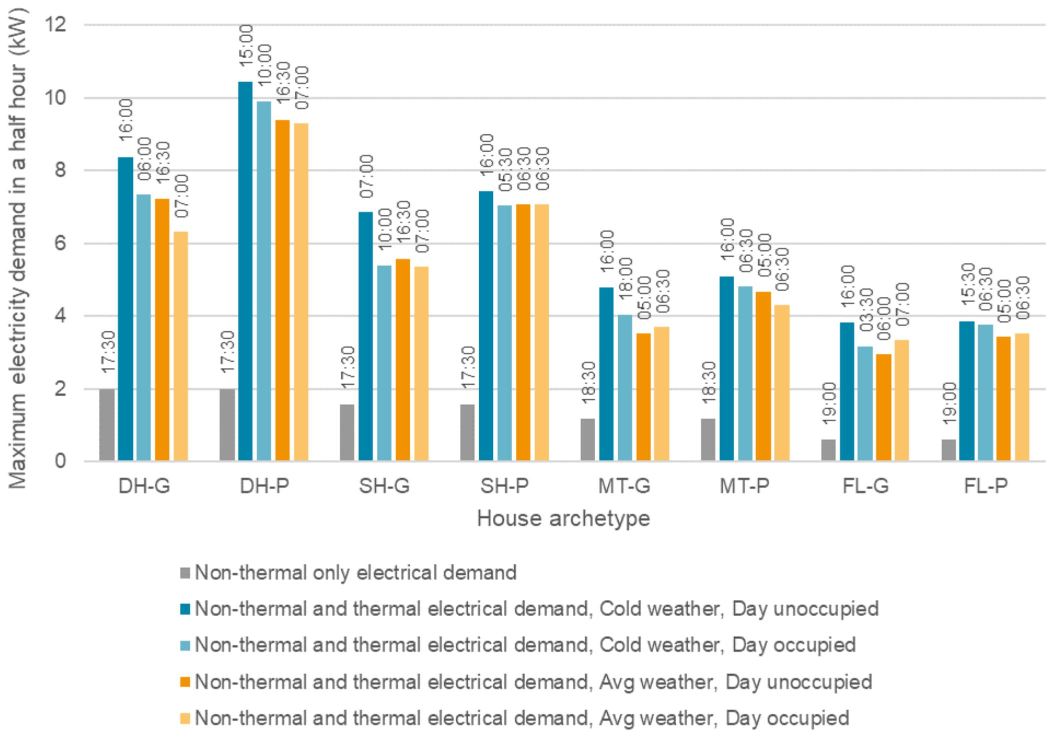

Figure 22: Peak non-thermal and thermal electricity demands in baseline scenarios with no flexibility measures; half hour in which peak demand occurs shown above bars

8.2.2. Average daily demand profiles for homes heated by heat pumps

Average daily winter electricity demand profiles were derived for each archetype by taking the average half-hourly results over the two-month modelled period, covering both weekdays and weekends. A weighted average of the two different occupancy profiles was then taken based on the occupancy characteristics determined in WP1 across the three study areas – for example, among DH-G archetype homes, about 50% are unoccupied during the day and 50% are occupied. Binary (yes/no) weekday occupancy characteristics were weighted by the total number of customers in each of the three study areas to determine these average occupancy estimates. The average profile for the DH-G archetype is broken down by thermal and non-thermal loads in Figure 23. The average total thermal and non-thermal electricity demand profiles for all archetypes are shown in Figure 24 and Figure 25.

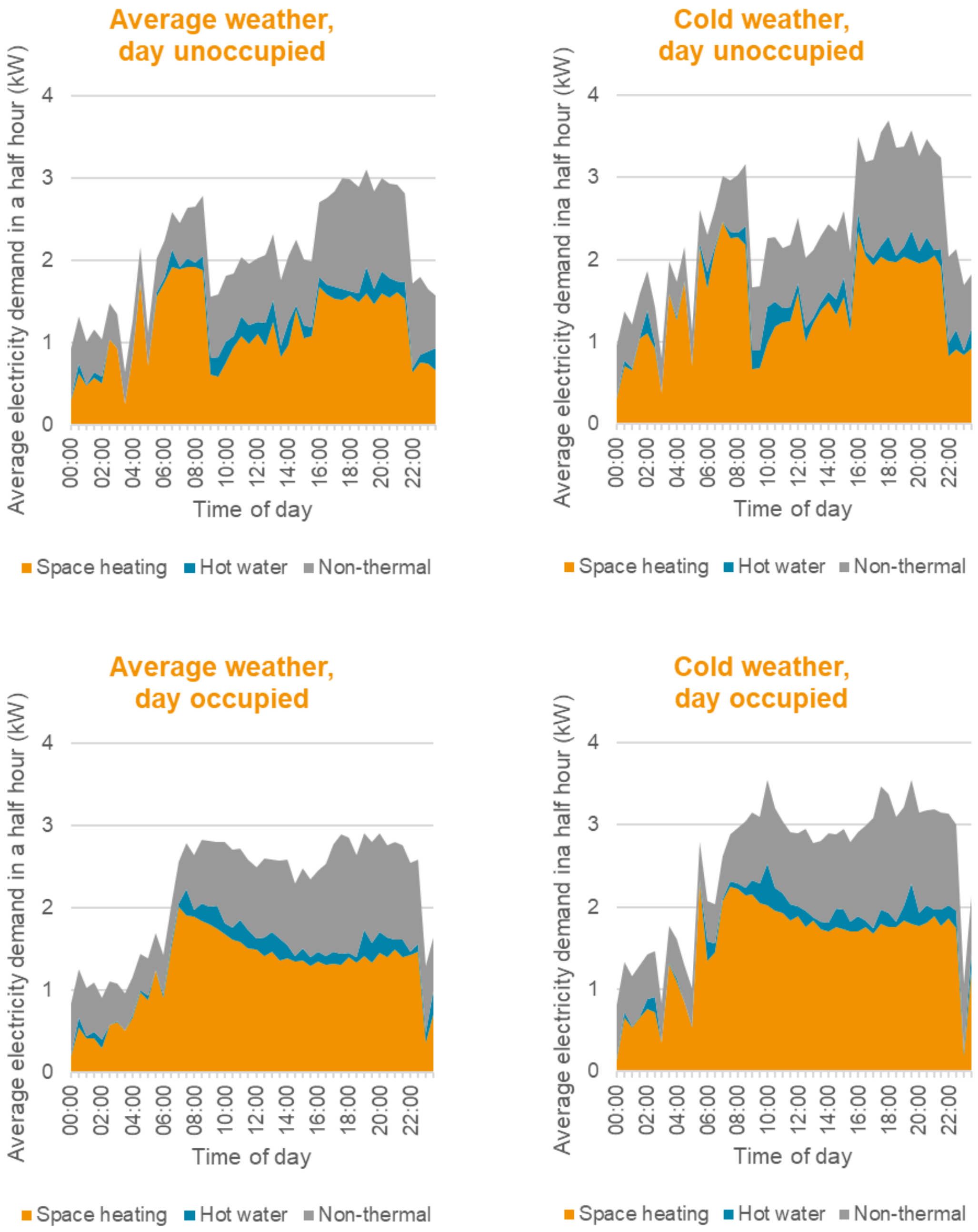

Figure 23: Break down of average daily electricity demand profiles over the two-month modelled period for DH-G archetype (detached house with good insulation) heated by an air-source heat pump with no flexibility measures; under average and cold weather conditions; day unoccupied or day occupied

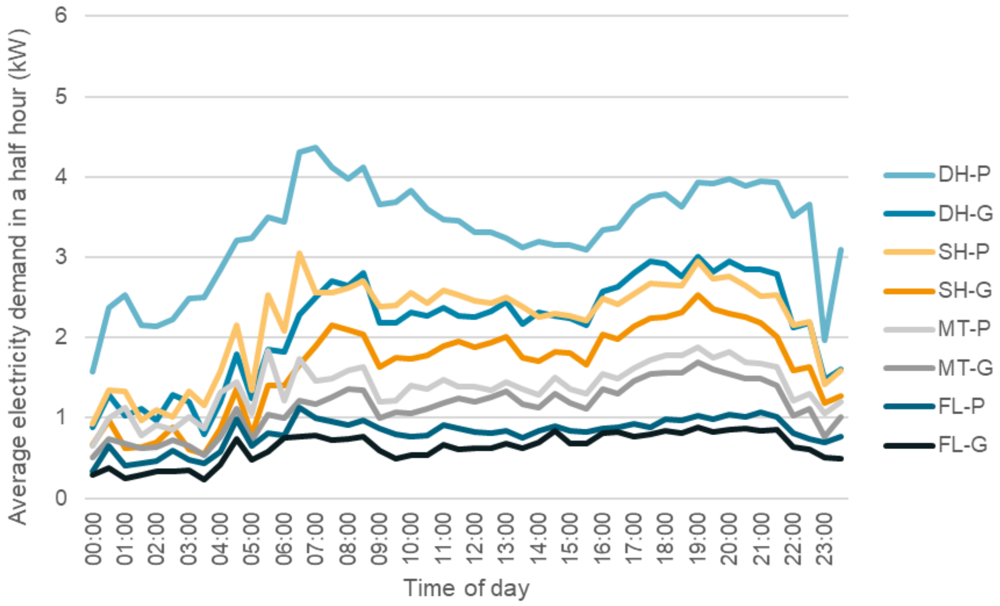

Figure 24: Average daily electricity demand profiles over the two-month modelled period for different house archetypes heated by an air-source heat pump under average weather conditions with no flexibility measures; based on weighted average occupancy characteristics per archetype

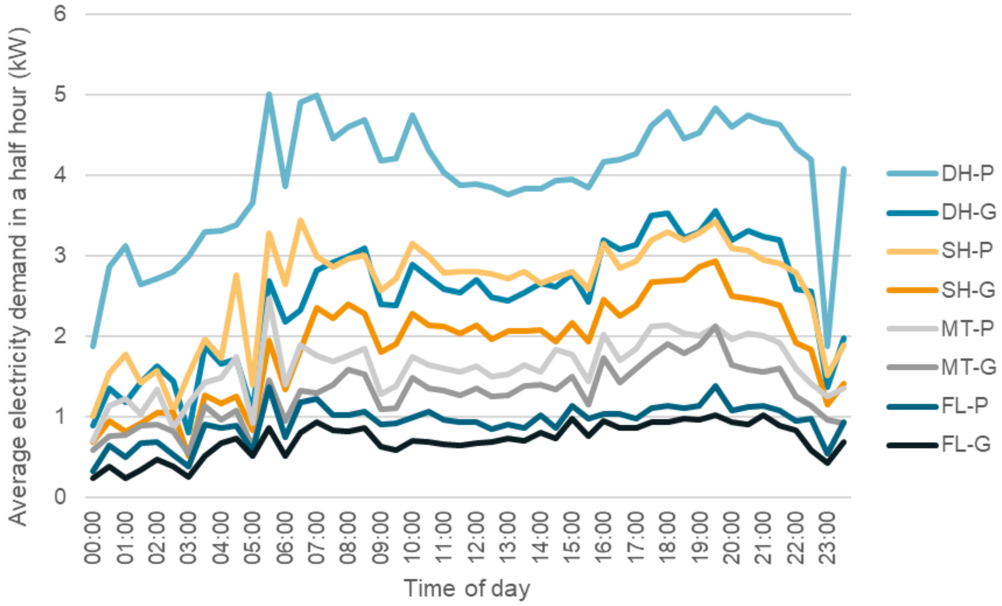

Figure 25: Average daily electricity demand profiles over the two-month modelled period for different house archetypes heated by an air-source heat pump under cold weather conditions with no flexibility measures; based on weighted average occupancy characteristics per archetype

The break down in Figure 23 shows that for the DH-G archetype (detached house with good insulation) space heating demand is highest in the early morning, when the house needs to be heated from its setback temperature to its set temperature and the heat pump is generally less efficient due to lower outdoor temperatures. Space heating demand is about 25% higher under cold weather conditions compared to average winter temperatures. Water heating accounts for a relatively small proportion of total heating demand as these profiles are for the middle of winter when space heating demands are highest. Peak electricity demand still occurs between 18:00 and 20:00, but with the addition of heating is about three times as high on average compared to non-thermal loads.

Figure 24 and Figure 25 show that total electricity demand is higher in larger homes and homes with less insulation. For most archetypes the average demand profile peaks between 19:00 and 20:00 in the evening. Morning peaks are also relatively high and occur between 4:00 and 09:00, with space heating loads coming on between 4:00 and 7:00 on average and non-thermal loads then picking up between 7:00 and 9:00.

8.3. Test scenario results

8.3.1. Impact of flexibility measures on peak demands at the individual house level

Test scenarios were run with added flexibility measures to determine how much these measures could reduce peak demands during cold weather conditions. Figure 26 shows the peak demand for each archetype over the two-month modelled period under the baseline scenario and different test scenarios. From these results it can be seen that:

- Switching to a variable tariff and allowing more flexible space heating and hot water generation (scenario 5) has a negligible impact on peak demand compared to the baseline (scenario 1). Heat demands are generally lower during periods when the electricity price is high, but peak loads remain the same as they are simply shifted outside of these hours.
- The addition of a buffer tank (scenario 7) also has little impact on peak demands. In fact, peak demands are slightly higher as a result of heat being generated and stored in the buffer tank ahead of high price periods.
- The addition of an electrical battery (scenario 9) increases peak demands by 50-80%, depending on the archetype. In this scenario peaks occur during the early morning hours when low electricity prices lead to the electrical battery charging at the same as the hot water cylinder or buffer tank are charged.

Although these measures result in peak-shifting rather than peak-reduction at the individual house level, they will likely have the desired peak-reduction effect at the network level when only a minority of homes have switched to electrically-driven heat pumps. Further modelling done in WP4 will confirm this. However, if eventually in future a majority of homes are equipped with heat pumps and storage devices and are all responding to the same price signals, the additional flexibility measures could actually have an adverse impact on peak demands by adding additional loads and shifting these peaks from high price periods to low price periods. New ways of incentivising diversity would then need to be introduced to avoid having all these intelligent, flexible loads coming on at the same time.

To test how much peak demands could be reduced rather than shifted with the additional flexibility sources, electrical supply limits were applied in each of the test scenarios. Limit values were reduced in increments of 1kW down to a minimum of 3kW until electrical demands could no longer be met within the constraints, or the 3kW minimum was reached. Scenarios 6, 8 and 10 in Figure 26 show the peak demand at the minimum viable limits for each archetype (to the nearest 1 kW, down to a minimum of 3 kW).

From this it can be seen that flexible heat and hot water generation can enable peak demands to be reduced by around 20-30%. Better insulated properties enable more flexibility as they lose heat at a slower rate and can be pre-heated further ahead of demand. Properties with larger hot water cylinders also offer relatively more flexibility – especially in smaller properties where hot water generation represents a higher share of total heating demand.

Buffer tanks appear to only enable significant reductions (10-20%) in peak demand in properties with good insulation, since heat released from the buffer tank to the building is then lost at a slower rate compared to homes with poor insulation. Greater peak demand reductions could be achieved by having larger buffer tanks, or more compact thermal storage devices.

Electrical batteries can enable an additional 10-20% reduction in peak demand, depending on the size of the battery relative to total electrical demands.

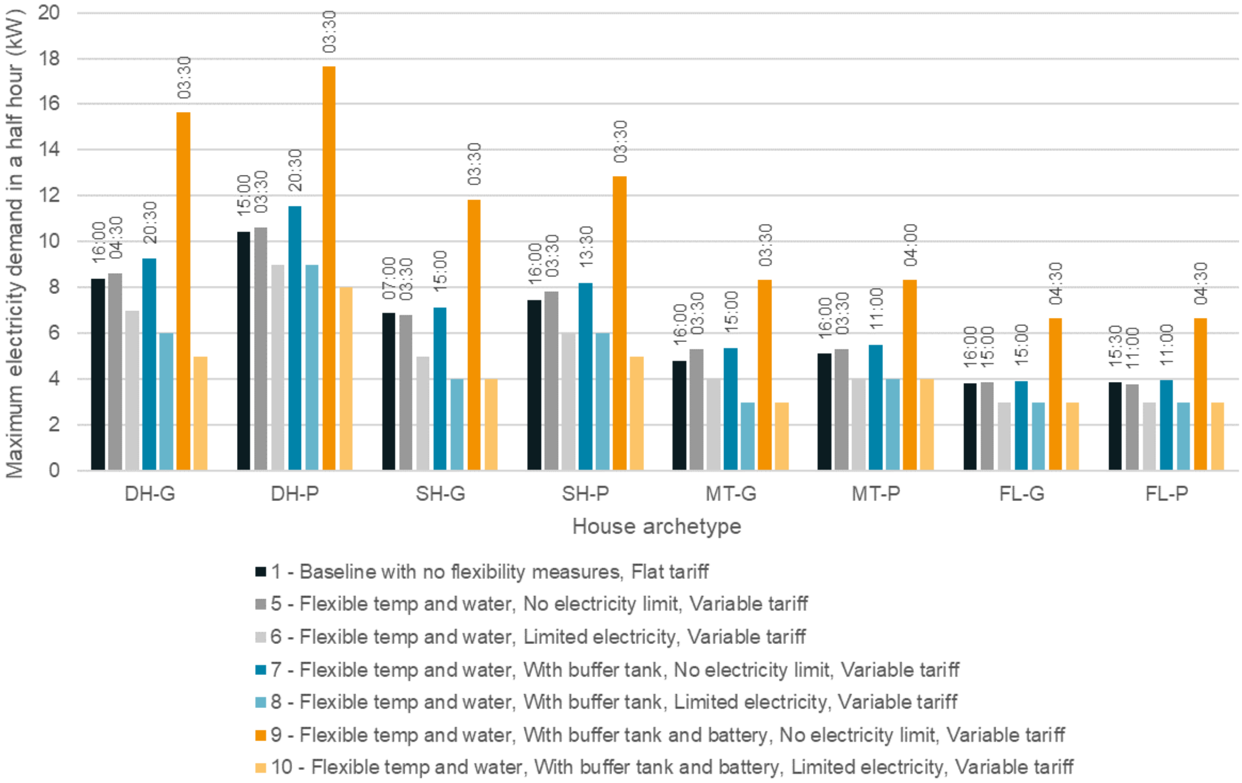

Figure 26: Peak electricity demands for each house archetype under scenarios (numbered) with added flexibility measures, a variable tariff and electricity supply limits; half hour in which peak demand occurs shown above bars (not shown for electricity supply limit scenarios as limit is reached multiple times in a day)

In practice it would be challenging to impose supply limits in the UK of around 3-9 kW as in the above scenarios, since the average home has a fuse limit of 60-100 amps (about 15-24 kW). However, this behaviour could potentially be incentivised with a load-dependent tariff structure facilitated by smart meters – for example as an illustration, having electricity costing £0.11/kWh when the total load is under 3kW, £0.15/kWh between 3-6kW, and £0.18/kWh above 6kW.

Alternatively, domestic loads might be aggregated and managed by a home energy management specialist as a service provided to network operators in exchange for some kind of reward/incentive. Simpler solutions to encourage diversity should also be considered, such as introducing a degree of randomisation in the timings of off-peak periods across households. These will be explored further in WP4 and WP5.

To illustrate the impact of adding flexibility measures with and without electricity supply limits on half hourly demand profiles, load profiles for the DH-P archetype on the coldest modelled day are shown as an example in the following figures. Figure 27 shows the baseline demand profile with no flexibility measures or electricity supply limits. Figure 28 shows the profile on a variable tariff with all flexibility measures added, but no electricity supply limit. Here the majority of demand is shifted out of the evening peak period but into the early morning hours when the battery and water stores are charged. Figure 29 shows how the system can be made to operate within a 5kW electricity supply limit to minimise peaks by spreading the charging of stores across the day.

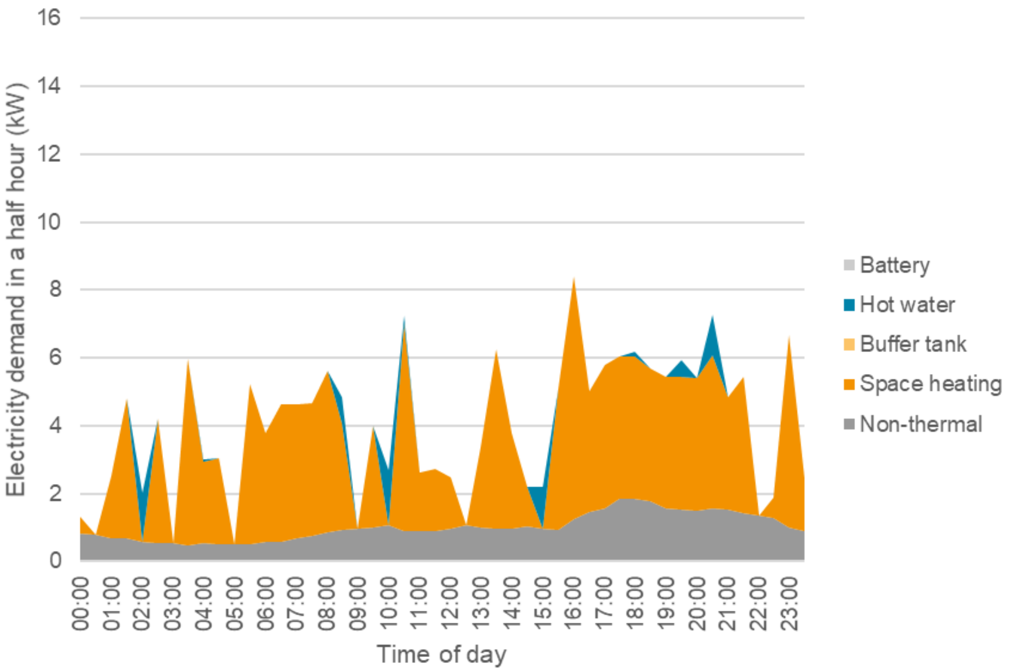

Figure 27: Coldest day (12 Jan) electricity demand profile for DH-G archetype (detached house with good insulation) in baseline scenario 1, day unoccupied, on a flat tariff, with no flexibility measures, no electricity supply limit

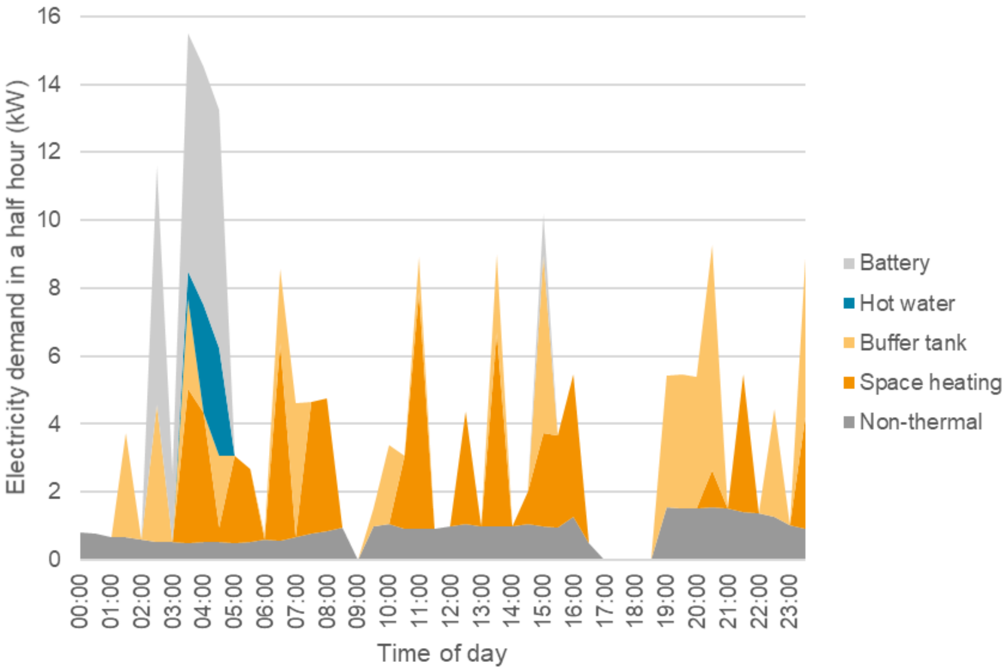

Figure 28: Coldest day (12 Jan) electricity demand profile for DH-G archetype (detached house with good insulation) in test scenario 9, day unoccupied, on a variable tariff, with all flexibility measures, no electricity supply limit

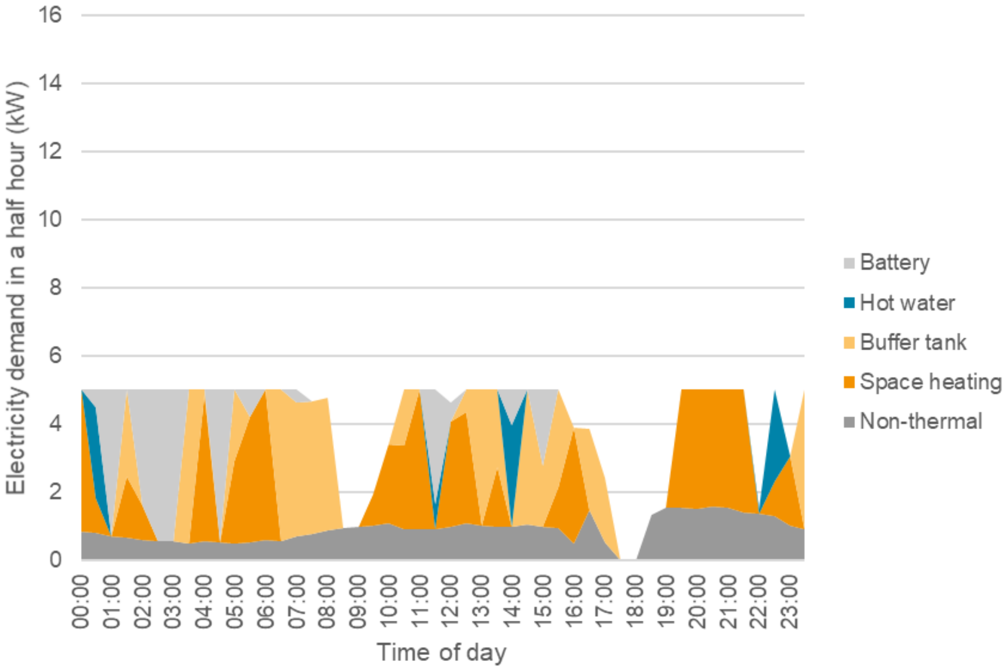

Figure 29: Coldest day (12 Jan) electricity demand profile for DH-G archetype (detached house with good insulation) in test scenario 10, day unoccupied, on a variable tariff, with all flexibility measures, electricity supply limit of 5kW imposed

8.3.2. Impact of flexibility measures during peak periods at the individual house level

As mentioned previously, shifting demands out of peak periods via some kind of incentives will still be beneficial for electricity networks when a minority of homes have electrically-driven heating – the impact of level of heat pump uptake will be explored further in WP4. This section looks at how much demand can be shifted outside of the daily peak period between 16:00 and 18:30. Figure 30 illustrates how much of each property's electricity demand from the grid can be moved with additional sources of flexibility, both on average over the two-month modelled period (shown by bars) and on the coldest day (shown by black markers).

It shows that flexible heat and hot water generation can shift 10-20% of demand outside of peak hours, depending on the archetype. The addition of a buffer tank can shift a further 5-15%. Adding an electrical battery can shift up to 100% of demand outside of peak hours for smaller properties. Even in a worst case scenario with 1 in 20 weather conditions, poor insulation levels or a relatively small battery, at least 55% of demand can be shifted.

Electrical batteries are clearly the most effective measure for shifting demand outside of peak times. However, even without installing an additional storage device, a significant amount of load can be shifted outside of peak times just by adjusting indoor temperatures slightly and timing hot water generation.

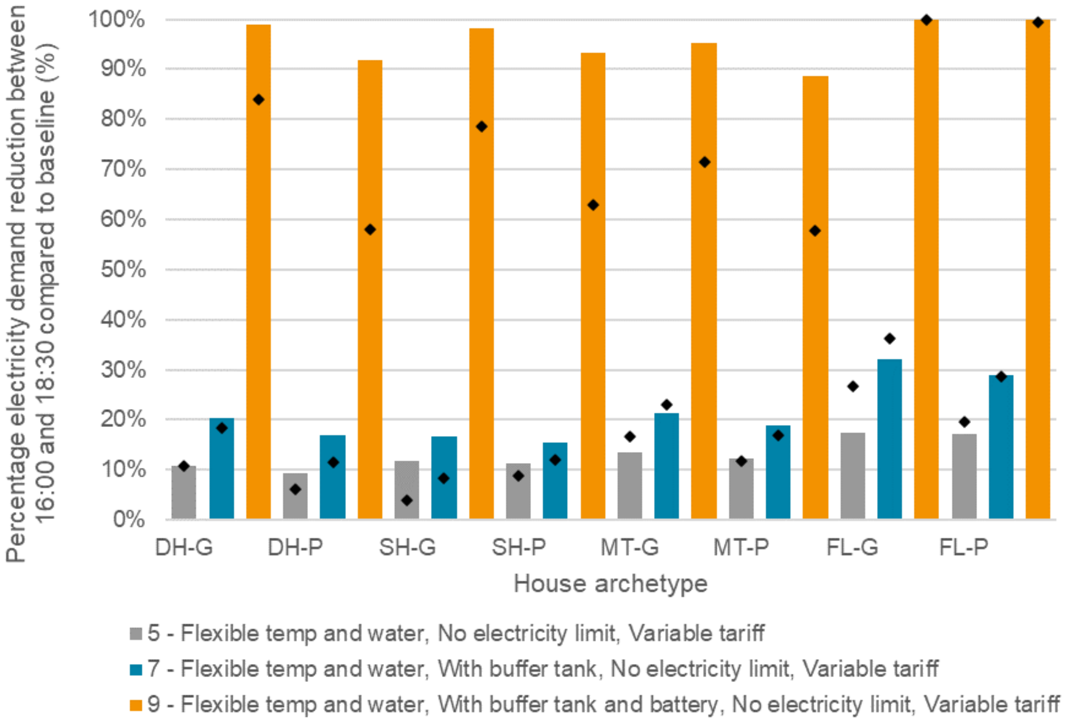

Figure 30: Percentage demand reduction during peak period between 16:00 and 18:30 compared to baseline under different flexibility scenarios, on average under cold weather conditions (shown by bars), and on the coldest day (shown by black markers)

8.4. Ground source heat pump operation

Because ground source heat pumps account for only a fraction of heat pump installations, baseline and test scenarios were run with air-source heat pump COPs. In WP4, a small number of detached homes will be modelled as being fitted with ground source heat pumps.

Figure 31 shows an example of how a ground source electricity demand profile differs from an air-source profile in the DH-G archetype (detached house with good insulation) on a weekday in January. Peak electricity demands are about 20% lower for the ground source heat pump on this day as it generates heat more efficiently than the air-source heat pump. The ground source heat pump load profile is also smoother in comparison to the air-source load profile, as the ground source heat pump COP is static, whereas for the air-source heat pump the Plexos solver optimises for half-hourly changes in outdoor temperature and hence COP.

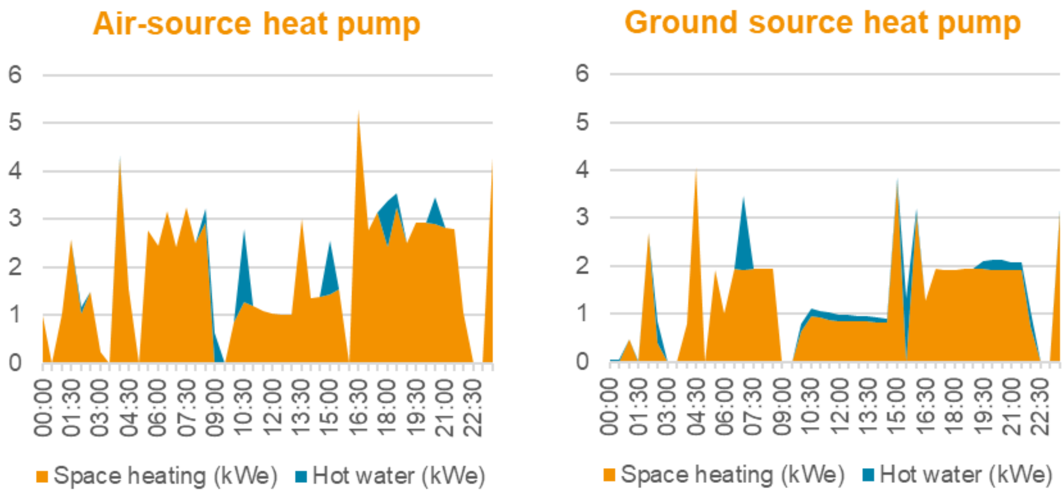

Figure 31: Air-source vs ground source heat pump electricity demand for space heating and hot water generation in DH-G archetype (detached house with good insulation), day unoccupied on Friday 8 Jan under cold weather conditions

8.5. Limitations of model assumptions

Numerous assumptions have been made in generating these results for the eight house archetypes in WP3. In view of how different the archetype load profiles might be from the modelled values in reality, the following are considered to be the main methodology limitations:

- **Building physics assumptions:** The physical properties of houses such as size and construction materials may differ from the averages assumed for each archetype based on EPC data and expert knowledge of the UK building stock. Stochastic heat loss profiles will be used in WP4 in effort to re-introduce some of the diversity that is lost by categorising thousands of different houses into just eight archetypes.

- **Model simplifications:** Both the building physics model and the house model created in Plexos are simplified representations of reality. This is evidenced by the fact that it was not possible to perfectly replicate the building physics model results in Plexos using the model of a house as a battery. The heat pump daily load profiles for individual house archetypes are judged to be sufficiently accurate on average over the two-month modelled period, but there is significant uncertainty associated with the estimates in any single half hour.
- **User behaviours:** The models rely on assumptions about what indoor temperatures are required and when, and do not account for any deviations in user behaviours such as opening windows, adjusting flow temperatures, or using far more hot water than average. The stochastic profiles introduced in WP4 will attempt to capture some of these deviations from the average at the network level.
- **Heat pump performance:** Poor heat pump performance as a result of product faults, installation issues or user behaviours are not accounted for in the COP values assumed, nor is the use of any electric resistive back up heating. In practice this would cause heat pump electricity consumption to be somewhat higher than estimated. However, given this project is considering likely impacts in 2030, it is fair to assume that poor performance will be the exception not the norm.
- **Optimisation algorithm:** The heat pump and storage device operation in Plexos is determined by its cost optimisation algorithm. This assumes that all devices in 2030 will receive and react to price, weather and perfect load forecasts, optimising only for cost with no limitations other than capacity. In reality there will still be some devices without the connectivity to do this, and these devices will not react to changes in electricity price or outdoor temperature. Estimates of how much load can be shifted out of peak periods should therefore be treated as maximum potential values rather than most likely results.

Appendix A: Building physics assumptions

Introduction

The building physics modelling used to simulate the archetypes requires a large number of assumptions to dynamically model the building performance in relation to the weather conditions.

We have highlighted some of the key assumptions in this section which drive the heating demands, primarily the type of fabric the building is constructed from and the resulting U-values. There are many additional assumptions which drove the building physics modelling which are not discussed here.

It should be noted that the focus of the modelling was to simulate the 'typical' archetype homes. Therefore in many cases the assumptions used are indicative and may not directly relate to a specific type of fabric, or to a specific reference dataset.

The assumptions used were based on the central case for each of the eight house archetypes. For example, the well-insulated flat (FL-G) archetype will include modern flats built within the last 20 years, but the most common age band for this archetype is 1950-1996. Input assumptions were made based on these average characteristics for each archetype. Diversity within archetypes will be accounted for using stochastic heat loss profiles in WP4.

U-value assumptions

U-values are used to describe the thermal conductivity of the building's fabric and are measured in watts per square metre per kelvin (W/(m²K)). The lower the U-value of an element, the more slowly heat is able to transmit through the fabric, and the better it performs as an insulator. For example, a poor performance double glazed window with a U-value of 2.8, for every degree difference in temperature between the inside and outside of the window, 2.8 watts will be transmitted for every square metre. A better performing window with a U-value of 1.4 will have half the heat loss.

The building physics modelling conducted by AECOM was based on a set of assumptions from Delta-EE including representative building archetypes (see Table 1: Archetype building and occupancy characteristics determined in WP1 (see WP1 report for methodology)), their key characteristics (such as property age, description of wall and roof insulation, type of windows, and typical floor area), as well as typical U-values to assume for different property elements. The U-values were based on analysis of the RDSAP Appendix S in the latest version of SAP (Version 9.92, BRE 2014) to be broadly reflective of archetype age and type of building construction within the study area[17]. These are outlined in the table below:

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[17] RDSAP is primarily used to produce EPC assessments on homes, and whilst there are more recent updates to the RDSAP dataset to produce more conservative assessments of EPCs and

Table 13. Delta-EE assumed U values for property elements

Characteristic	Description	Assumed U-value
Walls		
Solid wall, no insulation	Solid brick	2.1
Cavity wall, no insulation	Masonry cavity, as built	1.6
Cavity wall, insulated	Masonry cavity, insulated	0.4
Glazing		
Single	-	4.8
Double	-	2.6
Higher performance double (this aligns with ‘triple glazing’ in RdSAP (BRE, 2014)	-	1.8
Roof		
Loft insulation	250mm loft insulation	0.17
Thermal bridging		
Allowance for thermal bridging		0.15

These values were used as the basis from which the fabric specifications for each archetype, as used in AECOM’s building physics modelling (see below), were developed. The focus of this exercise was on creating indicative archetype specifications for both ‘poor’ performing and ‘good’ performing versions of each building type (archetype). Whilst some of the assumptions

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the benefits of different upgrade options, the original RDSAP dataset associated with the latest full version of SAP (9.92) was used to provide a more conservative assessment of peak loads.

don't necessarily represent a specific fabric type (as defined in RDSAP), they have been selected as 'typical' based on the archetype analysis [18].

As can be seen in Table 13 and 14, the main variables in determining poor and good variants of building types were external wall and external glazing U-values. These poor and good variants each make up distinct archetypes and will be mapped back on to their corresponding buildings in the wider network modelling in WP4.

AECOM building physics modelling fabric specifications

The following tables summarise the fabric specification for each of the building archetypes (summarised in section 3.1.1), which translates into the below tables on Opaque fabric and Glazed fabric parameter values for input into respective models.

Table 14. Opaque fabric specifications for each building archetype

	DH-G	DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P
Building element	**U-value (W/m²K)**							
External walls	0.4	2.10	0.40	1.60	0.40	2.10	0.40	2.10
Floor	1.60*							
Roof	0.17							
External doors (doors to flat)	2.20							

*Note: the exposed floor U-value has been predicted based on a 100mm concrete slab, 50mm cavity and 20mm chipboard flooring construction

The modelling assumed an adiabatic boundary with adjacent homes (no heat transfer between e.g. party walls), which is a mid-point scenario in terms of heat balance outside the thermal envelope of the building. This helps to not either underestimate or over-exacerbate the extent of heat load/demand for these modelled homes.

The Floor U-value of 1.6W/m²K was arbitrarily used to represent generally poor ground-floor floor thermal performance as a result of relatively poor insulation standards, ground coupling or the effect of suspended floors to capture worst case older buildings, as old as pre-1950s, which

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[18] This approach is common in housing stock analysis where simple archetypes are used to represent a broad range of housing types. Examples of 'averaging' include a U-value representing a house which is half double glazed and half single glazed, or a partial cavity U-value representing a mix of homes with cavity walls and solid walls. Whilst the resulting archetype does not represent a specific home, it can be indicative of a mix of homes.

is generally characteristic of the buildings under study. A single value was selected as there is a limitation on variation of range of U-vales of the various fabric elements to include in the small number of models run. The impact of this is seen to have generally resulted in 5-10% higher heat load compared to the upper range in (BRE, 2014), which should be within the margin of variation in heat load due to the variation in performance of other fabric elements including air leakage. For poor fabric models, the relative impact of this is tempered.

Table 15. Glazed fabric specifications for each building archetype

	DH-G	DH-P	SH-G	SH-P	MT-G	MT-P	FI-G	FI-P
Parameter	**U-value (W/m^{2}K)**							
External glazing U-value (W/m^{2}K)	1.80	2.60	2.60	2.60	2.60	4.80	2.60	2.60
g-value[19]	0.60							
Frame factor (% of window area that is frame)	FI-G and FI-P – 20% All others – 35%							

G-value pertains to solar gains and a value of 0.6 was selected based on modelling expertise to represent a situation where windows are not regularly cleaned (typical), and where windows are recessed with some self-shading (which is not picked up geometrically within the simplified building physics model). This means a marginally lower solar gain than would be achieved with the RDSAP g-value 0.68, but representing a more realistic outcome. It should be noted that the solar gains in the peak winter conditions modelled are very small and the impact of varying assumptions is negligible.

The frame factors were also based on modelling expertise and analysis of existing building physics models representing existing house types. The frame factors selected are typical for the stated age of the archetypes being modelled in this study. The RdSAP value of 0.7 (30% of the window area is frame) is a simple starting point and was refined in this project. The assumption of 20% of the window area that is frame was used for flats assuming these flats have slightly larger windows than houses, as the flat typologies were typically slightly older (50s/60s/70s) and this style of building often had large windows, but not to the extent of curtainwall type windows. For other houses, it was felt that the 70% glazed area (30% of the window area is frame) for non-flats was a little high considering many of the homes will have low cost UPVC windows (very poor frame factor), and also factoring in things such as curtains. Overall the frame factor is used for calculating solar gains and as described above varying assumptions will have

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[19] g-value is a measure of how much solar heat (infrared radiation) is allowed through a window

negligible impact on the peak loads in cold winter periods where there will be very low levels of solar gain.

Appendix B: Example calculations

Absolute COP values had to be converted into percentage equivalents to be input into Plexos as a battery charge efficiency property. To do this, all battery inputs, outputs and capacity values were divided by a maximum COP of 7.5. Example calculations without and with this adjustment are shown in Figure 32 and Figure 33 respectively. In both examples, the heat pump electrical draw from the grid and the impact on indoor temperature are the same.

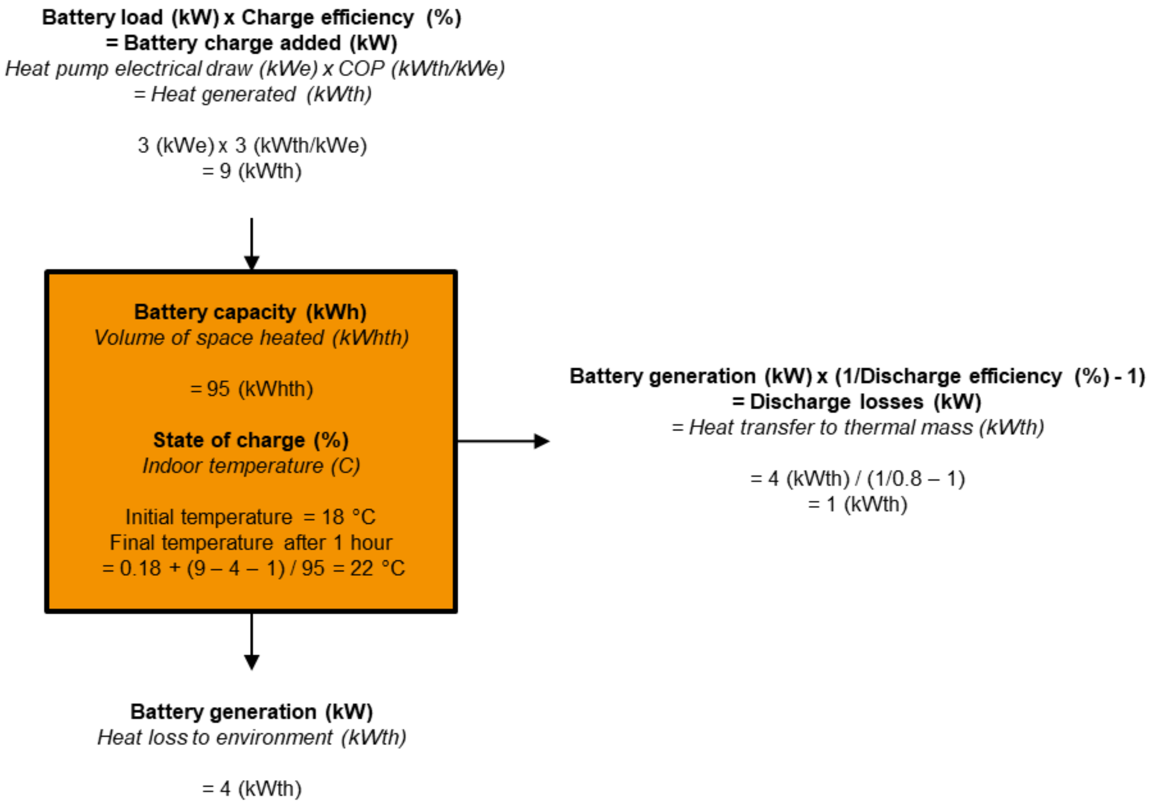

Figure 32: Worked example calculations for space heating without adjustment to convert COP to relative value

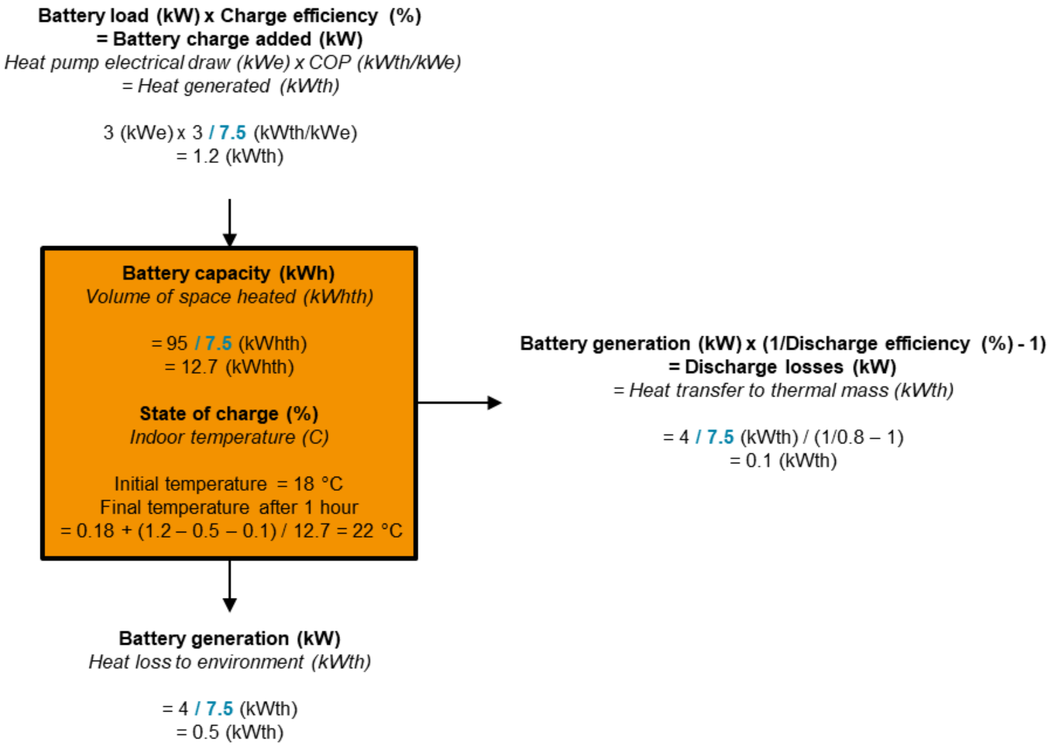

Figure 33: Worked example calculations for space heating with COP, battery capacity and battery outputs divided by maximum COP (7.5 – shown in blue) to convert COP to relative value