Net Zero Communities (NZCom)

WP7 – Reducing consumer energy costs with an innovative heat pump tariff and peak avoidance strategies

A strategy to mitigate the inevitable impact of heat electrification on distribution system costs which ultimately increase the cost to the consumer, while also, fairly billing heat pump consumption to incentivise their uptake and accelerate net zero carbon heating.

Version	Written	Released	Notes/Changes
1	Barnaby King	31/08/2022	Draft release
2	Barnaby King	05/09/2022	Final release
3	Barnaby King	14/09/2022	Consortium comments addressed
4	Barnaby king	23/09/2022	Additional considrations for vulnerable customers

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1. Executive summary

The NZCom project examines the impact of decarbonisation on the community residing within the Wadebridge and Padstow Network Area and offers solutions to ease that journey.

This work looks at the decarbonisation of heat with heat pumps and focuses on a strategy to reduce the consumer cost and network impact of mass heat pump uptake. This strategy has two elements, the first is a time-of-use tariff which excludes green levies from heat pump consumption and incentivises peak load reduction. The second element is several peak avoidance strategies which help consumers benefit from the proposed tariff and help reduce peak demand.

Computational modelling was conducted using TAS EDSL software for three typical dwellings for the area, a small flat, a terraced house and a large detached house. Each dwelling type was built with four typical constructions, pre 1950 solid brick, 1980 cavity wall, 2006 cavity wall, and 2021 concrete construction. Each combination of dwelling and construction type was simulated over the period of a year using a Plymouth weather data set. three peak avoidance strategies aiming to reduce peak demand and energy costs while maintaining thermal comfort were simulated as follows:

1. **Switch-Off:** the heat pump is switched off between 4-7 pm during weekdays.
2. **Thermal comfort:** the inside temperature is allowed to drop to (but not below) 18 degrees (from an initial setpoint of 20) between 4 -7 pm on weekdays.
3. **Buffer tank:** in addition to strategy 2, a buffer tank can be installed to eliminate 100% of the heat pump load during the 'red band' while still maintaining thermal comfort.

Strategy 1 demonstrates the most extreme action that could be taken, entirely switching off the heat pump. It's unlikely that many people, especially those vulnerable to cold would adopt this strategy, but it acts as a baseline by which other strategies can be compared. Strategy 2 demonstrates a 'moderate action' where consumers agree to drop their temperature by 2 degrees during peak times, thus experiencing some inconvenience in return for reduced energy bills (the high and low temperatures in this scenario could be different for different consumers). This may still be unacceptable for some customers, alternatively, scenario 3 provides a solution where peak load and energy bills are reduced without impacting the internal temperature of the dwellings. This is achieved by installing a type of thermal storage called a buffer tank which requires additional cost and space within the dwelling and reduces the annual bill savings due to the efficiency losses of the thermal store.

This simulation outputs the average inside air temperature and thermal heating load for each dwelling. The heating load is post-processed using a custom-built excel model which calculates electrical heat pump load and consumer energy cost for each dwelling, construction and peak avoidance strategy at hourly timesteps for the duration of one year.

Finally, given various heat pump uptake scenarios the heat pump load was aggregated and combined with substation load data to visualise the impact these strategies would have on the distribution network.

The bill savings were calculated using typical electricity prices as of August 2022. They should be updated regularly given the unpredictable nature of energy costs at present. Much of the report presents results in terms of temperature drop and peak load reduction. Thus, enabling the reader to easily calculate bill savings given different energy costs and tariff structures.

Summary of findings

- The tariff has the potential to save consumers up to 25% on their heat pump electricity bill.
- The majority of consumers can reduce and shift a percentage heat pump load during the ‘red band’ period between 4-7 pm. The amount of load possible to be shifted depends on the thermal properties of the house and the peak avoidance strategy employed.
- Peak Avoidance Strategy 1 results in the temperature dropping from 20 °C to as low as 12 °C in post-1980 dwellings and with 2006 dwellings as low as 16 °C, temperature drops of these magnitudes are likely to be unacceptable for many households, especially those containing medically vulnerable people. However, the dwellings built with the 2021 construction (equivalent to 2021 building regulations) rarely dropped below 18°C.
- With peak avoidance strategy 2, the heating load during a cold winter’s day can be reduced by 40-45% (1970 construction) to 70-80% (2021 Construction).
- The impact of such peak avoidance strategies on the distribution network was explored through further modelling. It is clear that the peak avoidance strategies can reduce ‘red band’ demand compared to a Business As Usual (BAU) scenario, however, it was also clear that these simple approaches to peak avoidance increased heat pump demand after 7 pm once the ‘red band’ period ended. Depending on the number of heat pumps taking this action this can cause a second higher demand peak at the substation level. Placeholder substation data has been used, therefore more detailed conclusions about the impact on the distribution network will be included in an addendum to this report once real substation data is available.

2. Introduction

The importance of rapid and global decarbonisation has never been clearer, the IPCC concluded earlier this year that we have to half emissions by 2030 to maintain a reasonable chance of keeping warming below 1.5^{o}C and preventing the worst and most dangerous impacts of climate breakdown.

However, the impacts of climate change are already evident and impact the most vulnerable people. For example, since 1961, crop productivity growth in Africa shrunk by a third due to climate change. In the UK, as we drive for net zero heating, transport and power we must ensure that we don't leave anyone behind and that the drive for net zero doesn't penalise the growing number of vulnerable people in our society.

One of the greatest challenges facing all domestic consumers in the bid to reach net zero by 2050 is decarbonising home heating and domestic hot water while maintaining a comfortable living environment and keeping energy costs affordable. Arguably one of the best ways to do this is via a heat pump. However, the high capital and running costs prevent many vulnerable and low-income consumers from purchasing heat pumps. One of the reasons that electricity is so much more expensive, is that it carries the burden of 'green levies' that pay for the policies promoting renewable energy.

Perversely, this means that if someone acts out of conscience to install a heat pump to access renewable heat energy, they pay significantly more towards the cost of promoting renewable energy. This means a lose/lose for those people making a significant capital outlay, just to be penalised by the very policies that promote renewable energy.

An additional consideration is the impact of the electrification of residential heat on the electricity networks. The networks already have to contend with high peaks of load at certain times of the day, the most intense being termed the 'red band', typically between 4 – 7 pm. Network reinforcements to cater for the increased supply capacity to meet heating loads will add to system charges which will further increase residential bills, notably, this is likely to increase everyone's bills including the most vulnerable people with the lowest capacity to pay.

This report introduces and analyses a strategy to reduce the cost of operating domestic heat pumps while simultaneously reducing the impact of heat pump uptake on the electricity distribution network, thus reducing inevitable future increases in consumer energy bills due to high systems costs.

In short, we are proposing a domestic electricity tariff which meters heat pump electricity consumption separately to the rest of the dwelling. Green levies are excluded from the heat pump tariff, saving the average consumer 12% on their heat pump electricity cost. This tariff is also 'Time of Use' meaning electricity costs vary throughout the day, encouraging consumers to reduce the use of their heat pump during the 'red band' time zone and further reduce their heat pump electricity cost. both actions combined can save a typical UK customer up to 25% on their heat pump electricity costs.

While this report is primarily concerned with the technical feasibility of providing such a service and quantifying the impact on dwelling temperature, the outputs from this work will inform a sandbox trial to understand how such a proposition would interact with consumer behaviour. therefore, it's crucial that this service provides consumers with an overall benefit and doesn't incentivise behaviours which may be damaging to the wellbeing of vulnerable consumers. This has been discussed in Appendix A, which sets out the challenges faced by vulnerable consumers and ways that the service will be designed to ensure all customers benefit from the service financially and otherwise.

3. Heat pump technology

Heat pump technology has been used to heat homes without access to mains gas in the US and Scandinavia since the 1950s. However, heat pumps are now widely recognised as being a key technology for the electrification and decarbonisation of space heating in the UK and globally.

Heat pumps use the vapour compressions cycle to extract heat from a thermal source and use this heat for space heating, water heating, or industrial processes. The thermal source, usually air, water or ground soil, is at a lower temperature than the heat output and therefore energy input is required to convert this low-grade heat into usable heat. Heat pumps consume electricity to do this, and for each unit of electricity, they can generate between 2 and 4 units of heat. The Coefficient of Performance (COP) is the ratio of electricity input to useful heat output and varies for different types of heat pumps, heating systems and external weather conditions.

There are many different types of heat pump and heat pump systems, each operating in different ways with different electricity profile shapes, COPs and thermal outputs. This section summarises some key differences between heat pumps and heat pump systems and states the technology assumptions made in this report. Before we discuss types of heat pumps it's important to understand the below components.

Compressor types

Compressors are the component which consumes the majority of power in a heat pump system, pumping the refrigerant through the cycle. Broadly speaking there are two types of compressors: Fixed speed compressors and variable-speed/inverter-driven compressors. Fixed speed compressors are 'on-off' appliances and regulate the thermal output by switching on and off at varying duty cycles. Meaning their profile shape has many peaks and troughs typically with a higher maximum power consumption than variable speed compressors. Variable speed compressors can regulate their speed and therefore heat output to match the heating demand. Therefore, their shape profile is smoother, typically just switching off once or twice a day. Because each compressor has a different load profile the impact on the network is different.

Depending on the heat pump design some compressors have a relatively short cycle life which can be as low as 5000 cycles, for such heat pumps peak avoidance strategies could reduce heat pump life and increase the lifetime cost of heating for the consumer.

Weather compensation

Weather compensation is often used as part of a heat pump control strategy, if correctly applied it increases the COP of the system and in the case of fixed-speed compressor machines, reduces or eliminates heat pump cycling. (1) Weather compensation varies the heating circuit flow temperature with outside air temperature, so during hotter days the heat pump can operate at a lower flow temperature and therefore higher COP and lower input power; fixed speed compressor machines can operate at a higher duty cycle, or a duty cycle of 1 (constantly switched on) if the weather compensation is perfectly set up. Many different weather compensation control strategies exist, and they may hamper peak avoidance strategies, as some weather compensation is designed to operate a 24-hour heating schedule and just provide enough heat to maintain temperature, therefore by changing the heat pump schedule the thermal comfort of the consumers may be compromised.

Thermal storage

Thermal stores are vessels that store heat usually in the form of hot water. Buffer tanks, a type of thermal store are sometimes used in heat pumps with single-speed or two-speed compressors to reduce compressor short cycling and to prevent heat pumps from switching on to meet small spontaneous loads. Depending on the buffer tank capacity they also have the potential to store heat to be used for space heating when the heat pump is off. Buffer tanks are not usually sized or configured for this application in the UK as suitable tariffs are not available. However, a buffer tank sized for this purpose may be well suited to respond to the proposed tariff in this report; this report will explore the potential for a buffer tank to store typical heating loads over the 'red band'.

Types of Heat pumps

There are three types of heat pumps commonly used in domestic UK dwellings:

Ground Source Heat Pumps (GSHP)

Ground source heat pumps use the ground at a depth of at least 1 metre as their thermal source. The temperature below ground is regulated throughout the year and typically changes much less than air. Therefore, the COP remains relatively constant throughout the year. Ground source heat pumps are more commonly used with single-speed compressors and therefore are commonly equipped with a buffer tank. However, this tank is not usually sized to provide meaningful heat storage.

Air source heat pumps (ASHP)

Air source heat pumps use outside air as the thermal source. Because of this, their COP varies significantly throughout the year and day, and because of this they are more commonly fitted with variable speed compressors and are therefore less likely to have a buffer tank. ASHPs, usually have a slightly lower COP for an identical source temperature when compared to GSHPs, due to the lower heat transfer coefficient on the source side.

It should be noted that due to Cornwall's temperate climate – the difference in performance between ASHPs and GSHPs is less significant than in the rest of the UK.

High-temperature ASHP heat pumps

High-temperature heat pumps are a variant of both ASHPs and GSHPs which are specifically designed to operate at similar heating circuit flow temperatures as traditional gas boilers, i.e., 60^{o} -80^{o}, therefore, they can be installed in homes with subpar insulation, and without changing the heating delivery system. However, the COP of such systems is significantly lower than more typical low-temperature heat pumps which operate at 35^{o} or 45^{o}. These heat pumps typically use inverter-controlled compressors and include a buffer tank in the system.

Technology assumptions

The modelling work in this report looks at the financial and network benefits of the proposed tariff on air source heat pumps across several dwellings. Whilst the type of heat pump impacts total annual energy consumption, the ability to shift load away from peak time is governed by the thermal properties of dwellings rather than the type of heat pump, and similar percentage reductions are observed regardless of heat pump type. Similarly, the size of the thermal storage tank required is not dependent on the type of heat pump installed. However, it's important to understand the variance in heat pump types and designs to understand the technical suitability of different heat pump types to achieve the peak avoidance strategies set out in this report.

The modelling work in this report assumes:

1. ASHPs with variable speed compressors, this is justified because while individual heat pumps with single speed compressors will have significantly different load profiles when aggregating numerous heat pumps together the resultant load profile of single speed and variable speed compressors are similar.
2. The heat pump systems do not include a buffer tank, as variable speed drive systems do not require one, and typically fixed speed compressors usually have a small buffer tank to eliminate short cycling and do not provide meaningful heat storage over the three-hour period studied.
3. The impact of an oversized buffer tank on the ability of consumers to respond to the proposed tariff has been indicated through the post-processing of modelling results.
4. Ground source heat pumps are shallow 'slinky collector type'.
5. A heating circuit flow temperature of 45 degrees has been assumed throughout the modelling unless stated otherwise – weather compensation has been excluded.
6. High-temperature heat pumps are modelled with a Heating Circuit and hot water flow temperature of 65 degrees.
7. Hot water heating has been excluded from the modelling – Hot water use is highly stochastic – and depends on individual behaviour patterns, furthermore, the hot water cylinders typically installed in heat pump systems provide 150-300 litres of hot water, which in most cases should provide the hot water demand between 4-7 pm. Therefore, it has been assumed that hot water demand can be shifted from the 4-7 period with little effort and need for modelling.
8. Unless stated otherwise the modelling in this report assumes a typical variable speed drive ASHP system with no buffer tank and no hot water heating. Such a system is shown in Figure 1.

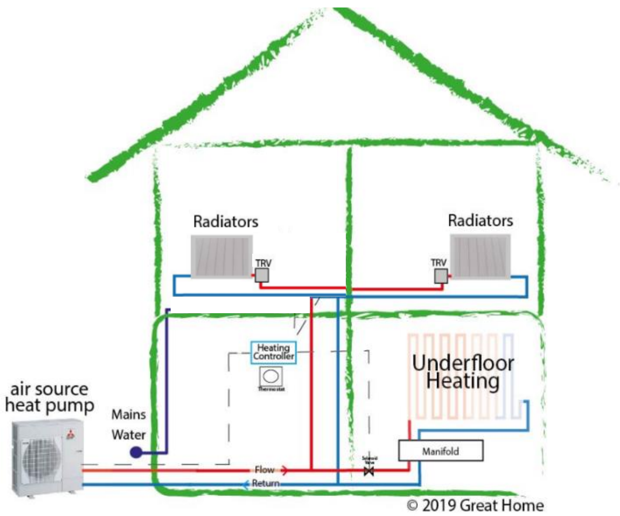


Figure 1 - heat pump system assumed for modelling

4. Literature review – Demand Side Response (DSR) with domestic heat pumps

Demand Side Response is the generic term given to electricity consumers responding to the needs of the electricity distribution and transmission systems by changing their electricity consumption. Either using more or less electricity than planned, usually in return for financial gain. Therefore, consumers who reduce heat pump consumption between the 'red band' are participating in DSR.

There have been several trials and studies in the UK which have looked at domestic heat pumps participating in DSR. Typically, these have looked at how the addition of a buffer tank (type of thermal storage) could shift heat pump load to off-peak times without any impact or interaction with the consumer, for example (2) calculates that a well-insulated semi-detached dwelling would require a 1000L hot water tank to shift all heat pump load to off-peak times as defined by the UK economy 10 tariff. While (3) states that an 800 litres tank would be required to shift 1 hour of load in poorly insulated dwellings. Similarly, network revolution (4) ran DSR consumer trials of heat pumps with appropriately sized thermal stores, these trials asked consumers to eliminate heat pump load for one-hour periods while using the thermal store to provide heating. Participants of these trials recorded little impact on thermal comfort and rarely overrode the automatic control.

Many studies including (5) document the impact on the electrical distribution network of such control strategies, and mention that care must be taken to ensure a net positive impact on the distribution network. For example (2) documented that if the buffer tank is heated up immediately before peak times, this introduced a new peak to the distribution network 50% higher than the previous peak (at 100% heat pump integration).

(5) documented a trial of an intelligent control strategy for heat pumps, which optimised heat pump operational cost against varying tariffs using only the building fabric as thermal storage. This study found that short-term load reductions of an hour could be achieved with little impact on the thermal comfort of trial participants, while longer duration shifting to optimise consumption alongside an Economy 10 tariff was more challenging, typically creating new network peaks before the off-peak period. This is partly due to consumer behaviour overriding the control system and preheating their home.

The work in this report builds on these studies to look at the inherent thermal storage in different types of UK dwellings and analyses the abilities of these dwellings to avoid the Distribution Use Of System 'red band' time zone between 4 pm and 7 pm during weekdays. We consider what the impact on the thermal comfort of consumers would be given different peak avoidance strategies, a study which is absent from most prior work which typically assumes that zero impact on thermal comfort is required. This report also looks at how these peak avoidance strategies would impact the distribution network at the primary substation level and analyses the heat pump uptake percentage where the introduction of secondary peaks in substation demand becomes significant, another piece of work lacking from previous literature.

5. Proposed tariff

This report proposes an innovative tariff to reduce heat pump operational costs for consumers and reduce their impact on the distribution network. This tariff is applied to electricity consumed by the heat pump, and not electricity consumed by the rest of the dwelling, therefore heat pump submetering is required which will add slightly to administrative charges.

The tariff has two substantial changes from the standard fixed rate tariff charged to most domestic electricity consumers.

1. It eliminates 'green levies' from the bill as a standard flat rate reduction, saving approximately 12% from the electricity cost of running a heat pump
2. Introducing a Time of Use (ToU) element which accounts for Distribution Use of System (DUoS) Charges. Electricity is significantly more expensive during peak, 'red band' periods, incentivising consumers to avoid using their heat pump during these times and becoming active participants in the electricity system. This can save up to 13% on a typical heat pump electricity bill.

This section first introduces and quantifies these charges on typical domestic consumption, then presents our proposed tariff along with the financial benefit this could have to heat pump customers.

Renewable Energy Levies (Green Levies)

'Green levies' make up approximately 12% of domestic UK electricity bills according to the default tariff cap level (price cap) for the period April 2022-September 2022 (6). According to the UK government, these levies are not predicted to change significantly by 2025 (7), however, the percentage of the total bill is likely to reduce as wholesale prices rise. Table 1 shows the various renewable energy, climate change and other policy costs which are included in domestic electricity billing in the UK. In this report, we exclude the Warm Home Discount (WHD) and Assistance for Areas with High Electricity Distribution Costs (AAHEDC) as they do not directly relate to renewable energy support. Therefore, renewable energy levies equate to a total of 3.7p/kWh on a typical UK electricity bill, charged as a flat rate on all consumption (note these charges are not locational)

Table 1 - Climate and policy tariffs on UK electricity bills – (8)

Policy tariffs	Key Driver	included?	Unit	Average UK Tariff
Renewable Obligation (RO) supplier obligation	Climate Change	Yes	£/kWh	2.5836
Contracts for Difference (CfD) supplier obligation	Climate Change	Yes	£/kWh	0.0094
Feed in Tariff (FiT) supplier levy	Climate Change	Yes	£/kWh	0.6034
Energy Company Obligation (ECO)	Climate Change	Yes	£/kWh	0.5395
AAHEDC (GB average)	Fuel Poverty	No	£/kWh	0.9626
WHD	Fuel Poverty	No	£/customer/year	0.0448

Distribution and transmission network charges

Distribution and Transmissions Network Use of System charges (DUoS and TNUoS respectively) are levies charged by the network operators to cover network O&M and upgrade costs. They are billed to commercial and industrial customers based on a blend of fixed and time-of-use tariffs, however, domestic consumers are charged on a per kWh basis, thus not providing a financial incentive for domestic consumers to shift their demand away from periods of network stress. As more domestic customers install heat pumps, it's widely recognised that a strategy which encourages domestic consumers to respond to system needs will be crucial to keep network costs low for consumers. Therefore, we are proposing that the time of use elements of network charges should be passed on to heat pump customers.

As part of Ofgem's targeted charging review (9), there were significant changes made to the way TNUoS is charged to customers, which significantly reduced the time of use element. Therefore, our proposed tariff does not include the ToU elements of these charges. However, a large percentage DUoS charges are based on a TOU tariff, with a strong price signal to avoid using electricity between 4-7 pm during weekdays. Therefore, this price signal is included in our tariff. DUoS costs vary significantly by region, the tariffs for the southwest are shown in Table 2.

Table 2 - Transmission and Distribution Costs for Southwest Consumers (10) (11)

DUoS SW	Red	Amber	Green
2022	16.37p/kWh	0.708p/kWh	0.044p/kWh

TNUoS SW	£/site/year	p/kWh between 5-7 pm
2022	0	8.7
2023 onwards	36.81	1.2

Our proposed tariff

We have calculated a number of tariffs which could be applied to heat pumps as below, in this report we suggest using the DUOS and Levy avoidance tariff highlighted in green in Table 3.

1. **Static BAU** represents a static tariff at the current price cap level
2. **Levy Avoidance** excludes the climate change levies from customer bills creating a lower flat rate tariff
3. **DUoS 'red band' avoidance** removes the standard flat rate DUoS tariff charged to most domestic consumers and replaces it with a time of use tariff indicated in Table 3. This tariff includes the 16.37p uplift during 'red band' times while equating the annual cost of electricity of a profile 1 customer with the static BAU tariff.
4. **DUOS and Levy avoidance** combines both the above tariffs to provide the most potential for consumer cost reduction and network benefit

Table 3 - Potential Heat Pump Tariffs

Tariff option	static tariff (£/kWh)	Off-peak Tariff (£/kWh)	Peak Tariff (4-7 pm) (£/kWh)
Static BAU (no change)	0.33		
Levy avoidance	0.29		
DNUoS avoidance		0.30	0.46
DNUoS and levy avoidance		0.26	0.43

The financial impact of the proposed tariff (assuming 100% 'red band' avoidance)

Given the typical dwellings set out in WP4, Table 4 demonstrates the cost of heat pump operation under the static BAU tariff indicated above and our proposed tariff, assuming consumers can shift 100% of the heat pump load from the peak time to off-peak time. These calculations have assumed a COP of 3 and an 18-hour heating day. These calculations have also assumed the total annual heating load is equal in both the static tariff scenario and the proposed tariff scenario. However, it is likely that by avoiding peak time use, the annual heat pump load will be reduced, further reducing energy costs. The actual electricity cost given different peak avoidance strategies is calculated based on modelled heat pump load in subsequent sections

Table 4 - Potential Cost Savings for Typical Dwellings

		Heat demand		Heat Pump electricity costs			
		Space heating kWh/yr	**Hot water kWh/yr**	**Static tariff**	**proposed tariff**		**potential savings**
A	Large house	13000	2103	£1,450	£1,156		£294
B	Large house	9100	1628	£1,032	£823		£210
C	Med house	9300	2103	£1,103	£879		£224
D	Med house	6510	1628	£789	£629		£160
E	Terr. House	5600	1628	£704	£561		£143
F	Terr. House	3500	1153	£455	£362		£92
G	Large flat	6400	1628	£779	£621		£158
H	Large flat	4000	1153	£502	£400		£102
J	Small flat	4800	1628	£629	£501		£128
K	Small flat	3000	1153	£408	£325		£83
L	Park home	4800	1628	£629	£501		£128

Why might the 'red band' not be avoided? Importance of thermal modelling, and real trials

Eliminating heat pump load during the 'red band' is the optimum financial result for consumers and the ideal outcome for the distribution network. However, the impact of switching the heating system off on the thermal comfort of the residence must be considered as maintaining thermal comfort is the sole purpose of a heating system. Therefore, the need to conduct an assessment of the thermal impact of various peak avoidance strategies arises.

6. Impact of Peak Avoidance Strategies on residents regarding heating load and thermal comfort.

Introduction

This section looks to quantify heat loss in terms of temperature reduction rate in UK dwellings. UK housing stock is varied and diverse and consequently, every home will have a different thermal performance. Furthermore, the thermal performance of a building, not only depends on the building fabric but the air permeability of the dwelling and the behaviour of residents. For example, the use of high-quality thermal curtains can significantly reduce heat loss, while by contrast, some occupants may open windows during the winter to circulate air and prevent mould growth significantly increasing heat loss. Note this was widely recognised advice during the COVID Pandemic, and there may still be a legacy of such behaviour. Furthermore, some occupants may take other actions to reduce their heating load, such as only heat-occupied rooms, while this doesn't change the thermal performance of the building it will significantly change the heating load and therefore impact the local distribution network.

Given the above caveats, this report considers three typical model dwellings (small terraced house, large flat, and large detached house) and four typical building constructions (Pre 1950s solid brick construction, 1970s cavity wall construction, 2006 concrete construction, and a modern 2021 construction). Each construction has been built in TAS EDSL building simulator and has thermal properties approximately equivalent to building regulations at the time, see Table 6 for full specifications. Each permutation of dwelling type and construction type has been modelled using TAS EDSL building simulator to determine the thermal impact to residents of the heat pump switching off between 4-7 pm each day. Further modelling has been conducted to understand what reduction in load could be achieved while maintaining a temperature of at least 18 degrees (from a setpoint of 20). And finally, an assessment was conducted of the potential for thermal storage to ensure buildings maintain thermal comfort limits while shifting their demand away from the 'red band' time zone.

Modelling methodology

- Using the TAS EDSL software several typical dwelling geometries have been built in the 3D Modeler,
- These houses have been simulated with 4 distinct construction types each with different levels of insulation: Building Regs 2021, Building regs 2006, building regs 1980s, and post-1950s solid brick construction - all dwellings have been assumed to have been retrofitted with 300mm of mineral wool loft insulation and double-glazed windows as a minimum.
  - The houses are assumed to be heated with radiators with a radiant proportion of 0.3 which is the default value for radiators set out in the TAS EDSL manual (12)
  - The infiltration values/Air Changes per Hour (ACH) have been assumed based on literature and current building regulations - Pressure test results at 50PA are divided by 20 to achieve an approximate ACH value under normal conditions (CIBSE guide part A).
  - Additional infiltration due to trickle vents, fireplaces or other such apparatus was excluded.
  - Windows remain closed during the wintertime. And blinds are used at night.
  - Heating gain from occupants and lighting and other equipment has been excluded. This may be significant in some cases, by excluding all thermal gains we are modelling a worst-case scenario. For example, a vulnerable and inactive person living alone and microwaving their dinner will experience very little heating gain, while an active family of five using an oven to cook a roast dinner will experience significant occupant and appliance gains.

Therefore when interpreting results in this report it's important to realise they represent this worst case, and in some scenarios temperature drop and heating load will be lower
    - Adjacent buildings, for example, adjacent terraced houses, or flats, were assumed to be heated to 18 degrees during the day and 16 degrees at night (12-6).
    - Nearby buildings were modelled around each dwelling to minimise the solar gain.
- Annual simulations for each building were run for one year with an hourly 2007 Temperature dataset from Plymouth.
- Peak avoidance or reduction was achieved by changing the setpoint schedule for the dwellings.
- The following outputs were recorded for each simulation; dry bulb air temperature, resultant temperature and hourly heating load for each room.

Results obtained from the modelling were validated through field studies conducted on UK dwellings during July. Only 2 validation tests were possible as the UK experienced a heatwave in July and therefore it was not possible to simulate winter conditions, however, the two tests successfully conducted acted as a 'sense check' on the ACH assumptions, confirming that they were realistic for the two dwellings tested. The following methodology was conducted:

- The dwellings were heated to 30 degrees centigrade and maintained at that temperature for 5 hours, during a period when the outside temperature was approximately 20 degrees.
- The heating was switched off between 12 midnight and 3 am.
- Easy Log EL-USB-1 temperature data loggers were used to record the inside and outside temperatures.
- Each dwelling was modelled in TAS EDSL using the outside temperature profile observed in the validation test, and the rates of temperature reduction are compared between the validation test and the EDSL modeming.
- The ACH used in the modelling was changed until the temperature drop observed in the test matched those observed in the modelling.

Model dwelling specifications

3 model dwellings have been modelled in this report- these dwellings have been modelled based on the Internal area of the terraced house, small flat and large house set out in WP4. Each dwelling has been.modelled with 4 different constructions. Table 5 shows the properties of each model dwelling, while Table 6 shows the thermal properties of each construction type

Figure 2 - 3d and Plan View of The Terraced House

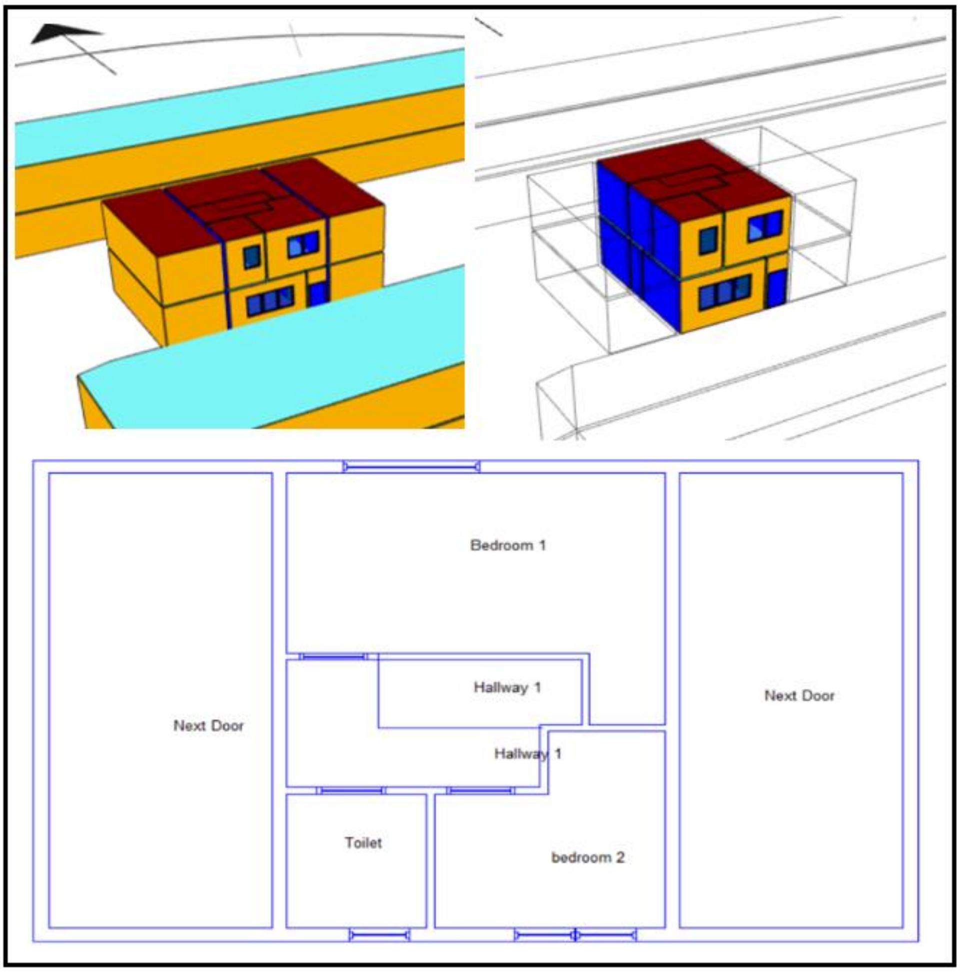


Table 5 - Specifications of the Dwelling Types

	Terraced house	Flat	Large house (detached)
External envelope Area (m^2)	179	96	263
Internal floor area (m^2)	70	60	130
Door and windows area (m^2)	12.7	6.8	24.3
Ceiling height (m)	3	3	3

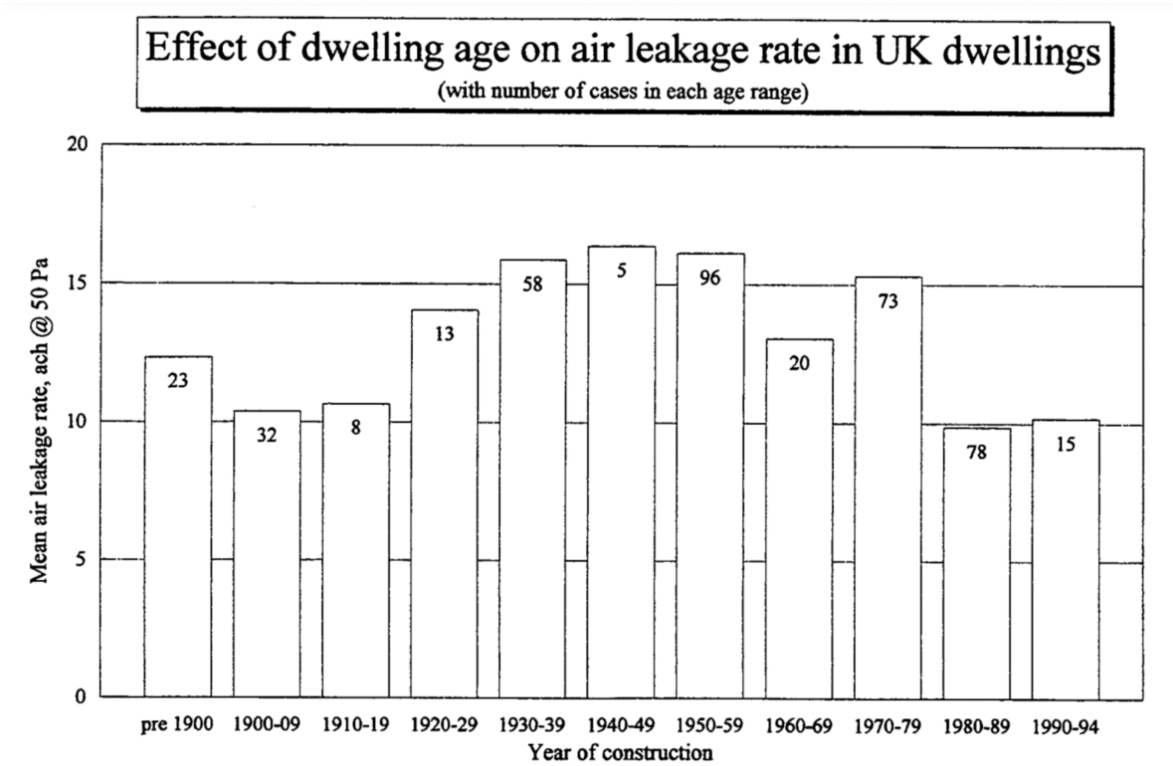
Table 6 - Specifications of the typical constructions used in the modelling

	External wall construction	Floor construction	Party wall/ceiling constructio n	Roof construction	Window type	Door type	ACH
Pre 1950s	**340mm Brick wall no cavity (U1.38)**	**Uninsulated solid concrete floor (U1.012)**	**Solid brick Wall 225mm**	**Insulated Pitched roof (U0.125)** • 9.5mm plasterboard • 300mm mineral wool insulation • Loft space, concrete roof tile	**Double glazing (U3.28)** • 4mm glass • 8mm air • 4mm glass	**Door (U2)**	0.6
1970 Cavity wall	**Insulated Cavity wall, (U0.57)** • 13mm Plasterboard • 100mm concrete inner leaf • 50mm air gap • 40mm mineral wool insulation • 100mm brick outer leaf • 20mm External render	**Solid insulated ground floor (U0.8)** • 50mm flooring screed • 10mm EPS • 100mm cast concrete • 25mm Brick slips. • Assumed sitting on clay	**Lightweight insulated wall (U0.6)**	**Insulated Pitched roof** U0.125 • 300mm mineral wool insulation • 9.5mm plasterboard • Loft space • concrete roof tile	**Double glazing (U3.28)** • 4mm glass • 8mm air • 4mm LE glass	**Door (U2)**	0.75
2006 Cavity wall	**Insulated cavity wall (U0.24)** • 13mm plasterboard • 25mm air layer • 100mm concrete • 140mm mineral wool insulation • 102mm brick • 20mm external render	**Solid insulated ground floor (U0.25)** • 50mm flooring screed • 120mm EPS • 100mm cast concrete • 25mm Brick slips. • Assumed sitting on clay	**Lightweight insulated wall (U0.6)**	**Insulated Pitched roof (U0.125)** • 300mm mineral wool insulation • 9.5mm plasterboard • Loft space • concrete roof tile	**Double glazing (U1.28)** • 4mm glass • 16mm argon • 4mm LE glass	**Door (U1)**	0.5
2021 Cavity wall	**Insulated cavity wall (U0.182)** • 12.5mm plasterboard • 100mm concrete • 108mm PIR insulation • Cavity 40mm • 100mm concrete • 20mmGypsum render	**Insulated suspended floor (U0.147)** • Chipboard 20mm • Unventilated cavity 50mm • Screed 50mm • Reinforced concrete 250mm • Insulation 232mm	**Lightweight insulated wall (U0.6)**	**Insulated Pitched roof (U0.125)** • 300mm mineral wool insulation • 9.5mm plasterboard • Loft space • concrete roof tile	**Double glazing (U1.28)** • 4mm glass • 16mm argon • 4mm LE glass	**Door (U1)**	0.25

ACH justification

1. Current building regulations have a target of 5 m3/hr/m2 @ 50 Pascals; therefore, this value has been assumed for 2021 construction (m3/hr/m2 has been equated to ACH in this report) – this is backed up by
1. literature [1], therefore a value of 0.25 ACH has been selected for the 2021 constructions
2. In 2006 typical buildings had an air tightness of 11.8m3 in Ireland according to [1] furthermore data from 1990-1994 at 10 5 m3/hr/m2 @ 50 Pascals, therefore a value of 0.5 was chosen at normal pressure
3. In 1970-1980 average values from Figure 3 shows a value of 15 m3/hr/m2 @ 50 Pascals therefore 0.75 was chosen
4. According to Figure 3, solid wall constructions have an ACH value at 50 pascals of approximately 12, therefore an infiltration of 0.6 ACH was assumed for Pre 1950 solid wall construction.

[1] In Ireland at the turn of the millennia, typical building was built with and ACH of 11.8 m3/hr/m2 @ 50 Pascals. - this has dropped to 3.7 in 2017 BER research tool for island, in addition data from ATTAMA shows average new UK building had an ACH of 5 in 2017 https://passivehouseplus.ie/magazine/guides/the-ph-guide-to-airtightness



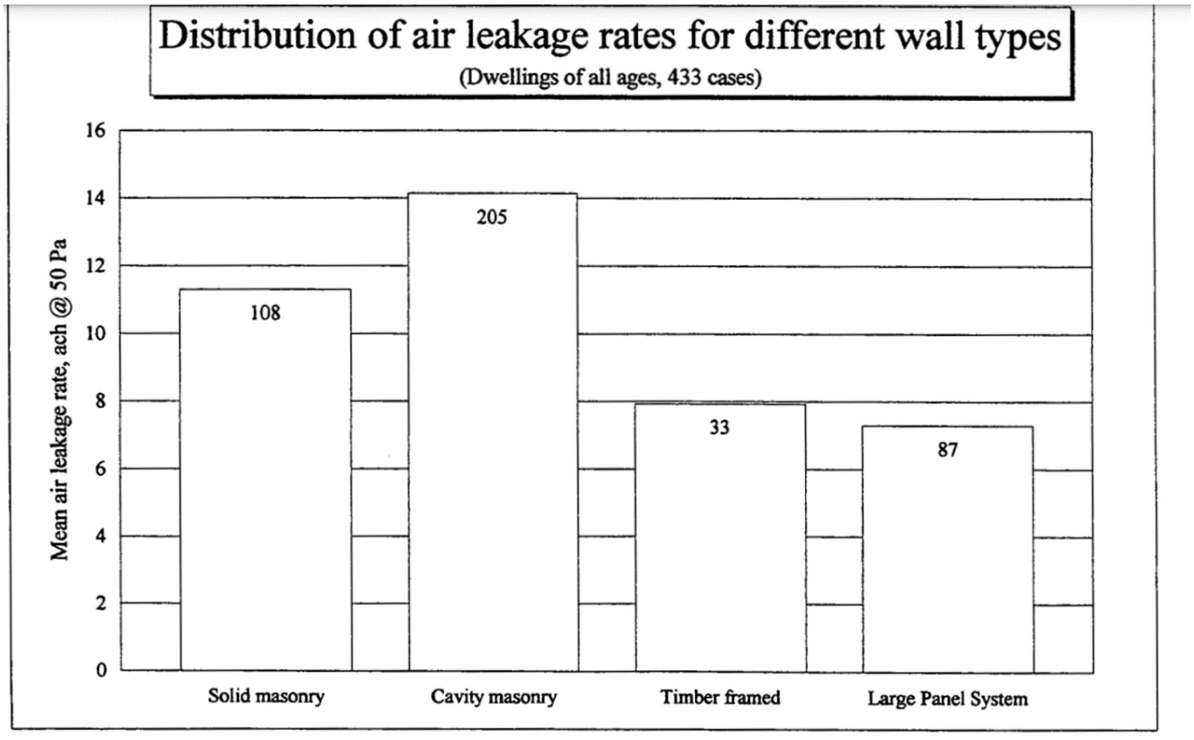


Figure 3 - Effect of Dwelling age and building fabric on Air leakage rate UK dwellings - Airtightness in UK dwellings: BRE's test results and their, significance - (12)

Peak Avoidance Strategy 1 - Switch Off: Switching the heat pump off during the 'red band'

The first scenario modelled across each house and construction type was to simply switch off the heating between 4 – 7 pm during weekdays. This was modelled throughout a typical year using Plymouth weather data, and for a worst-case day, where the outside air temperature was constant at 2°C. The inside temperature setpoint was 16°C at night, 20°C during the day, and 0°C during the 'red band'. The setpoint schedules including those used on weekends and for adjacent buildings are shown in Figure 4. Note the weekend setpoint schedule was also used to model a Business As Usual (control) scenario.

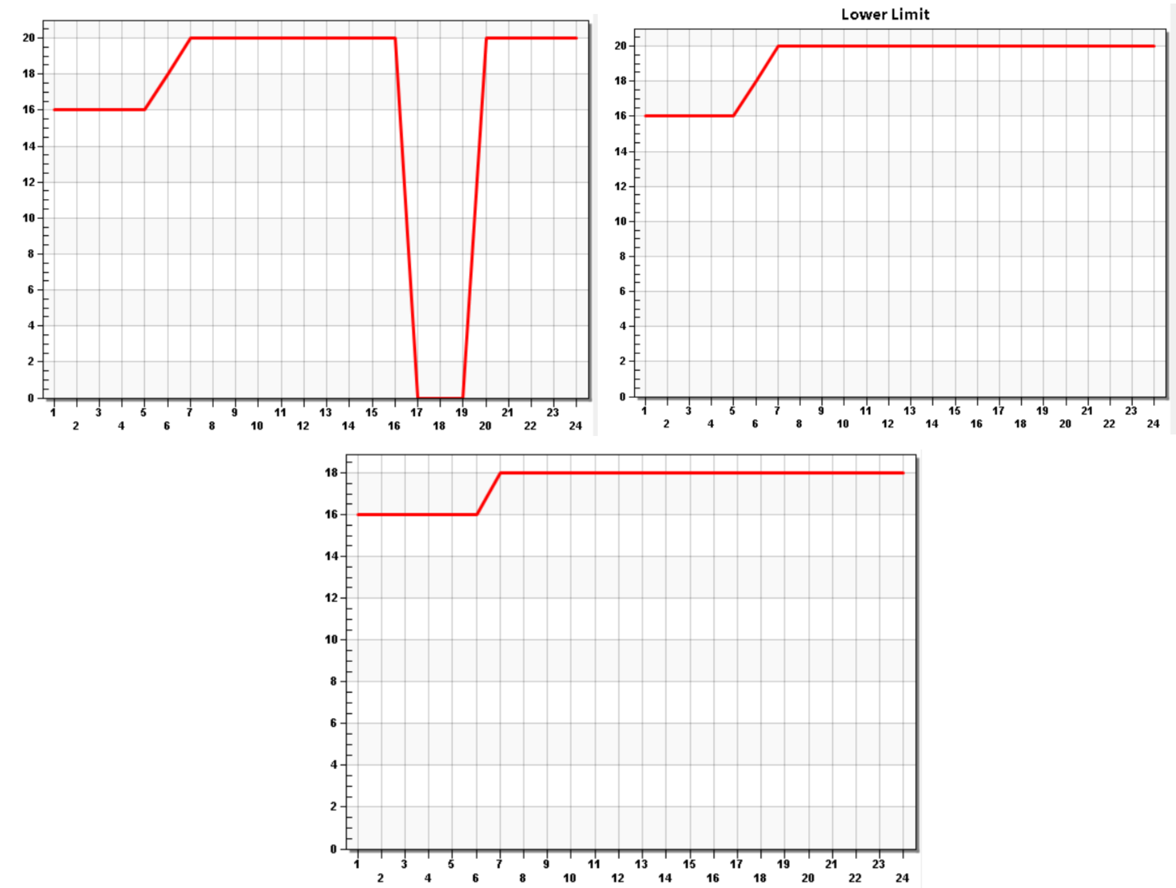


*Figure 4 – **(top left)** Setpoint schedule for Peak Avoidance Strategy 1- Switch heat Pump off Between 4-7 pm, **(top right)** BAU setpoint schedule, **(bottom)** next door schedule (x-axis hour of the day, Y axis inside setpoint temperature Degrees Celsius)*

Figure 5 shows the average temperature drop across all rooms in the terraced house during the worst-case day, where the outside temperature was constant at 2 °C. It shows the temperature drop between 4-7 pm is as much as 6 °C for the pre-1950 solid brick construction. While the 2021 construction built to current building regulations saw a temperature drop of less than 3°C, which may be considered unacceptable for some residents. However, this worst-case day is very rare in Cornwall. And for the majority of the year, the temperature drop is much less severe. For example, in the 2021 construction of the small flat and terraced house, the temperature rarely drops by more than 2°C. This can be seen in Table 7, which shows the average temperature drop by month, for each dwelling and construction type.

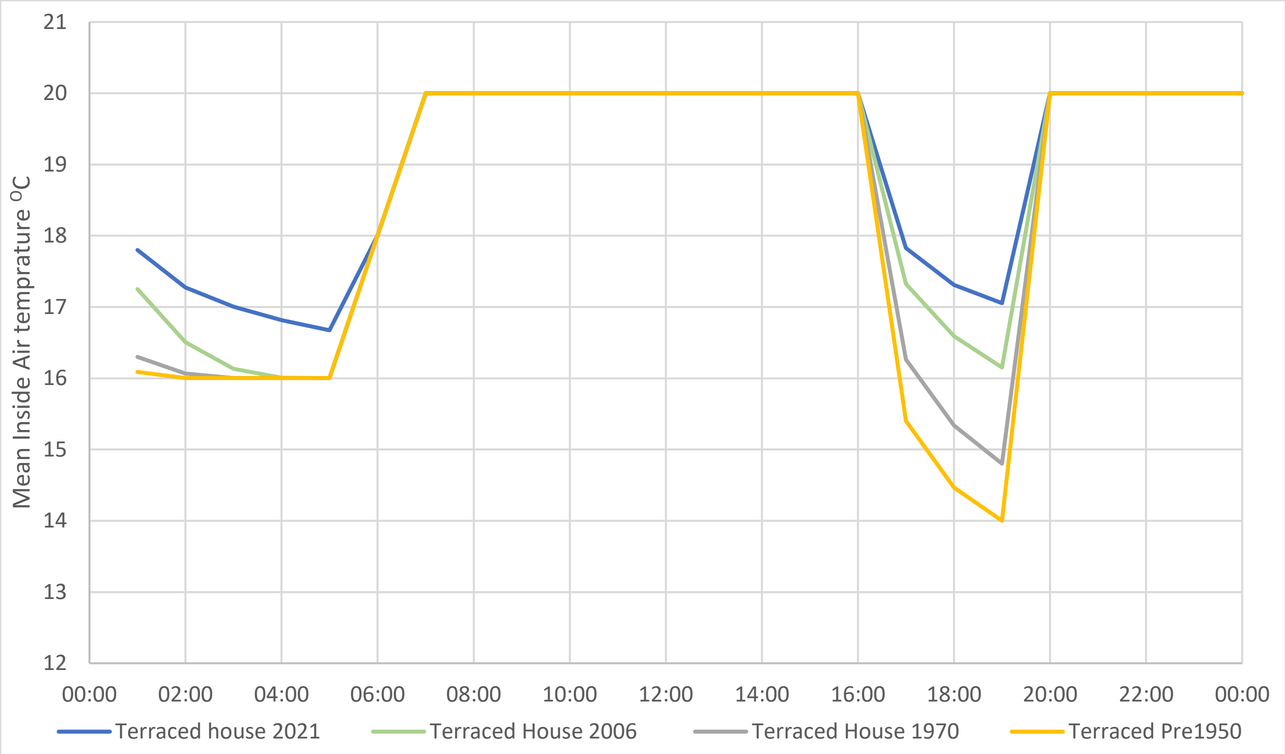


Figure 5 - Red Band Mean Temperature Drop for The Terraced House

Table 7 - Mean Temperature drop 4-7 pm for Each Dwelling and Construction Type – Starting Temperature 20 ^{O}C

°C	WCD	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Terraced Pre 1950	**6.0**	**3.7**	**3.5**	**3.3**	**2.9**	**1.6**	**1.5**	**-0.1**	**-0.2**	**1.5**	**2.4**	**3.7**	**4.2**
Terraced House 1970	**5.2**	**3.2**	**3.0**	**2.7**	**2.3**	**1.0**	**1.0**	**-0.5**	**-0.6**	**0.9**	**1.9**	**3.2**	**3.7**
Terraced House 2006	**3.8**	**2.3**	**2.1**	**1.6**	**0.9**	**-0.1**	**-0.1**	**-1.6**	**-1.6**	**-0.2**	**1.1**	**2.3**	**2.8**
Terraced house 2021	**2.9**	**1.8**	**1.7**	**1.5**	**1.2**	**0.5**	**0.4**	**-0.7**	**-0.9**	**0.3**	**1.1**	**1.8**	**2.2**
Large House Pre 1950	**7.7**	**4.7**	**4.5**	**4.4**	**4.0**	**2.0**	**1.8**	**0.0**	**-0.2**	**2.2**	**3.0**	**4.8**	**5.5**
Large House 1970	**5.7**	**3.5**	**3.3**	**3.2**	**2.8**	**1.2**	**1.1**	**-0.5**	**-0.5**	**1.5**	**2.2**	**3.5**	**4.1**
Large House 2006	**4.3**	**2.5**	**2.3**	**2.0**	**1.5**	**0.0**	**-0.2**	**-1.9**	**-2.0**	**0.4**	**1.3**	**2.5**	**3.0**
Large House 2021	**3.3**	**1.9**	**1.8**	**1.6**	**1.4**	**0.4**	**0.1**	**-1.1**	**-1.6**	**0.5**	**1.1**	**1.9**	**2.3**
Small Flat Pre1950	**5.2**	**3.5**	**3.4**	**3.2**	**2.8**	**1.6**	**1.5**	**-0.5**	**-0.5**	**1.5**	**2.4**	**3.5**	**4.0**
Small Flat 1970	**4.77**	**3.0**	**2.8**	**2.7**	**2.3**	**0.9**	**0.9**	**-0.7**	**-0.6**	**1.2**	**1.9**	**3.0**	**3.5**
Small Flat 2006	**3.44**	**2.2**	**2.0**	**1.7**	**1.2**	**0.0**	**-0.1**	**-2.1**	**-1.5**	**0.3**	**1.3**	**2.1**	**2.5**
Small Flat 2021	**2.63**	**1.7**	**1.6**	**1.5**	**1.3**	**0.5**	**0.4**	**-0.8**	**-0.9**	**0.6**	**1.2**	**1.7**	**2.0**

Peak Avoidance Strategy 2 – Thermal Comfort: reducing load while ensuring thermal comfort limits are maintained

This section seeks to understand the total load reduction that could be observed during the 'red band' while maintaining the thermal comfort of the dwellings and residents. Thermal comfort is a personal thing, and each consumer may have a different comfort level. In this report, we define thermal comfort as between 21-18 °C.

As shown above, the impact of switching the heating off for 3 hours between 4-7 pm can be significant, often dropping below the thermal comfort limit of 18°C and for many residents, this will not be acceptable. The second piece of modelling was conducted to determine what reduction in thermal heating load, and electrical heat pump load is possible while keeping the average air temperature above a nominal thermal comfort limit of 18°C. This was achieved by modelling the below two thermostat schedules and comparing heat pump load for each permutation of dwelling and construction type.

1. **Peak Avoidance - Thermal Comfort:** this schedule is designed to reduce heat pump load while keeping within thermal comfort limits of 18°C. The schedule is shown in Figure 6, during weekends the BAU schedule is used (Figure 7).
2. **Business As Usual (BAU):** as with scenario one it's necessary to model the Business As Usual (BAU) Scenario assuming that no action is taken to avoid the 'red band' the setpoint schedule for this scenario is the same for weekends and weekdays Figure 7.

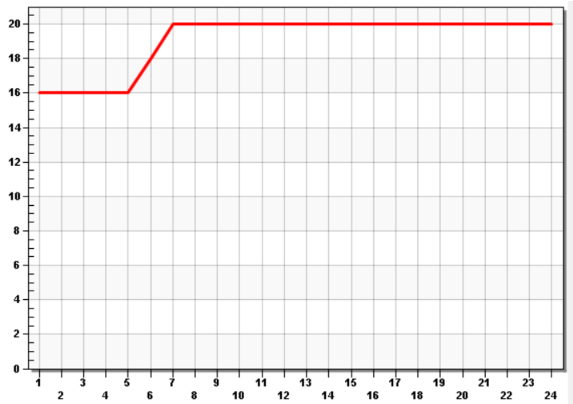


Figure 7 - BAU Setpoint Schedule and Weekend Schedule

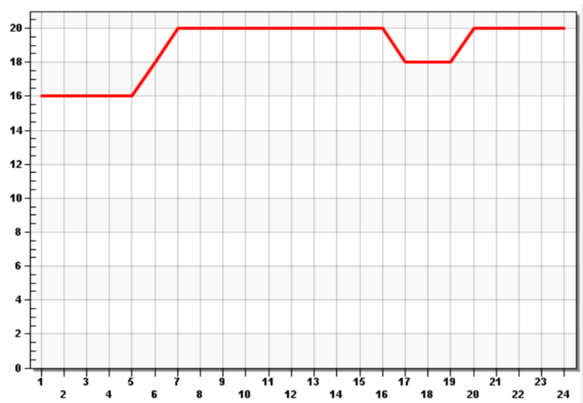


Figure 6 - Peak Avoidance - Thermal Comfort Weekday Setpoint Schedule

Hourly heating load data generated through modelling both scenarios in TAS was post-processed using a custom built excel model, which calculates the heat pump electrical load given the thermal heating load, source temperature (outside air temperature) and COP data linearly extrapolated from Table 8 which also shows other heat pump system and sizing assumptions. Note heat pumps have been nominally sized choosing the most appropriate typical rated power.

Table 8 - Heat Pump Modelling Assumptions

	Heating circuit flow temperature °C				
Outside air temperature °C	**35**	**40**	**45**	**50**	**55**
-5	**3.72**	**3.47**	**3.18**	**2.36**	**1.707**
0	**4.04**	**3.78**	**3.47**	**2.56**	**2.05**
5	**4.38**	**4.1**	**3.78**	**2.79**	**2.39**
Hot Water temperature (degC)	**45**				
heating Delivery system efficiency	**0.95**				

Heat pump specifications	**heating capacity**	**Power consumption**
Small Flat	4kWth	0.9kWe
Terraced house	5kWth	1.1kWe
Large house	7kWth	1.6kWe

Figure 8 shows the average daily heat pump load for each month, alongside the Worst Case Day (WCD) heat pump load for the 2006 Terraced House, it shows that the heating demand can be more than halved during the WCD. However, this day is rarely observed in Cornwall, and more typical peak load reductions throughout the year are between 80-95%. Table 9 shows the total annual peak load reduction that can be achieved in each dwelling and construction type and the annual bill reduction that represents. Note the pre-1950 solid brick construction has been excluded from this modelling as the thermal performance is so poor a significant load reduction would not be observed.

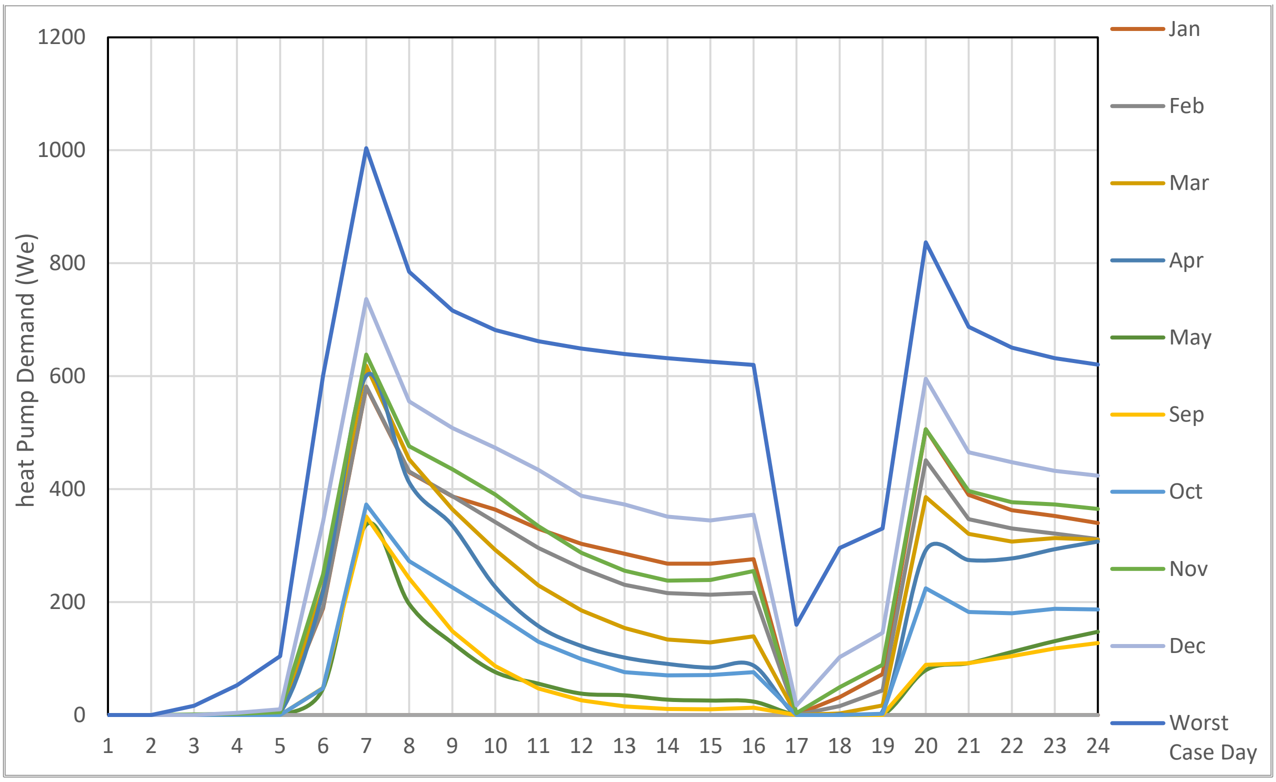


Figure 8 – Heat Pump Load- Peak Avoidance Strategy 2 - Terraced House 2006

Table 9 - Peak Load Reduction - Peak Avoidance Strategy 2

	Annual Peak-Load Reduction		WCD Peak load Reduction		Annual Bill Savings	
2021 Terrace House	97kWh	97%	1.1kWh	74%	£78	24.2%
2006 Terraced House	99kWh	89%	1.0kWh	56%	£95	24.0%
1970 terraced House	153kWh	74%	1.3kWh	43%	£162	23.1%
2021 - Large House	189kWh	97%	2.1kWh	69%	£144	24%
2006 - Large House	198kWh	86%	2.0kWh	53%	£181	23%
1970 - Large House	318kWh	70%	2.6kWh	41%	£336	23%
2021 – Small Flat	66kWh	99%	0.7kWh	79%	£56	24.6%
2006 – Small Flat	70kWh	92%	0.7kWh	62%	£69	24.4%
1970 – Small Flat	103kWh	76%	0.8kWh	45%	£111	23.5%

For the majority of the year, the 2006 and 2021 constructions can reduce peak time heating load by 100% while maintaining thermal comfort within the dwelling, however, during the coldest times of the year, this is not the case. As can be seen in Table 9, which shows the peak load can be reduced by between 50-70% for the 2006 constructions during the WCD. Periods of electricity network stress also often occur during cold weather. Therefore, this value is likely to be of more importance to the DNO that the annual peak load reduction. The pricing signals do not reflect the increased importance of wintertime 'red bands', and therefore changes to the tariff could be considered which provide a higher financial incentive to avoid these periods.

Table 10 demonstrates this. The cost savings between Peak Avoidance Strategy 1 (Switch-off) and Strategy 2 (Maintain Thermal Comfort) are negligible, while the impact on the distribution network during the red band is significantly greater for strategy 2 as explained above. Interestingly for post-2006 constructions, higher bill savings are achieved with strategy 1. This is caused by an interesting phenomenon specific to air source heat pumps. While the thermal heating load of Scenario 1 is less than Scenario 2, the electric heat pump load is higher. This can be explained because in scenario 1 - all the 'red band' heating is shifted to 7-9 pm when it's colder and the Heat pump is operating a lower COP. While in scenario 2 heating occurs more evenly throughout the evening, so the average COP of the heat pump is higher.

Table 10 - Bill Savings of different peak avoidance strategies on the large house

	Annual Bill Savings compared to BAU	
	Scenario 1: Switch off	**Scenario 2: Maintain Thermal Comfort**
1970 -Large House	24%	23%
2006- Large House	23%	24%
2021- Large House	22%	24%

The potential for thermal storage to further eliminate peak heat pump load

Thermal storage could support the efforts of a consumer to reduce their heat pump load during the 'red band'. Many heat pump systems include a thermal buffer tank which is designed to reduce short cycling and maintain minimum flow rates through the heat pump, these buffer tanks could be used to store thermal energy during off-peak times and release this energy during peak periods, hence reducing peak load. however, these buffer tanks are not sized to shift electricity consumption from one time of day to another.

This section estimates the thermal buffer size that would be required to reduce 'red band' electricity consumption to zero while ensuring the inside air temperature does not drop below 18 ^{o}C. It should be noted that this scenario relies on control of the heat pump system rather than the setpoint, therefore, to implement this scenario, the heat pump must have associated control capabilities.

A simple modelling methodology was employed. The total thermal heating load for the WCD was extracted from modelling scenario 2. Which gives the total thermal energy in kWh needed to maintain thermal comfort between 4-7 pm. The buffer tank volume which satisfies this demand was calculated using the assumptions in Table 11.

Table 12 shows the suitable buffer tank size for each dwelling and construction type. For post-2006 constructions, the required buffer tank size seems feasible in most cases, ranging from 71 litres for the 2021 flat to 678 litres for the 2006 large house. However, this incurs additional capital cost and space requirements and retrofitting such systems would be unlikely to make financial sense.

It should be noted that the addition of a buffer tank in the system increases the total annual heat pump load and therefore increases annual energy costs compared to Peak Avoidance Strategy 2. This has not been quantified in this report because it's highly variable, it depends on the insulation of the tank, the time of the day the tank is charged, and the location of the tank.

Table 11 - Buffer Tank Assumptions

Stratification ratio	0.30	Amount of Stored Heat which mixes with cold water and therefore is lower than the target temperature
Max hot percentage	0.80	Maximum percentage of the tank which can be used to store hot water
HP Outlet Temperature	50.00	
HP Return Temperature	40.00	

Table 12 – Required buffer Tank Size for Different Dwellings

	WCD thermal load – 'red band' (kWh_{th})	Required buffer tank size (litres)
2021 - Terrace House	1.1	147
2006 - Terraced House	2.3	309
1970 - terraced House	5.0	670
2021 - Large house	2.8	378
2006 - Large house	5.4	728
1970 - Large House	11.1	1,462
2021 - Small Flat	0.5	71
2006 - Small Flat	1.2	167
1970 - Small Flat	2.9	388

Examples of housing stock variation

The results demonstrated through modelling in section 6 have assumed typical UK dwellings, however, as mentioned previously UK housing stock is significantly varied and there are many types of properties which are not well represented by the modelling; this section seeks to demonstrate that by discussing different types of UK dwellings

For example, the typical constructions modelled in this report are lightweight and do not have significant thermal mass. a stone cottage with the same U value as the 2006 construction, but significantly more thermal mass would obverse a much lower temperature drop of approximately 2.3 ^{O}C during the WCD (Table 13). Table 13 also demonstrates that relatively small differences in the heating of neighbouring properties can have a significant impact on the rate of temperature drop observed.

Table 13 - Examples of Temperature Drop for Variations in Dwelling Construction and External Conditions.

House Type	WCD 4-7 Temperature drop (^{O}C)
2006 Terraced House	3.8
Terraced House - Externally Insulated Stone Cottage	2.3
2006 Terraced House (where neighbours heat their house to 22 degrees)	3.2
Terraced House 2006 Terraced House (where neighbours heat their house to 16 degrees)	4

Different types of heat pumps

The thermal load during the 'red band' is a function of the thermal properties of the dwelling, the inside temperature setpoint/s, and the behaviour of the residents. The type of heat pump does not impact this. However different types of heat pumps will be more or less efficient at providing that thermal load due to variations in the COP.

Because of this, modelling with different heat pumps is not beneficial to this piece of work, as heat pumps with higher COPs will still observe a similar percentage reduction in heat pump load and therefore energy bill, but from a smaller or larger annual load.

There are some caveats to this, for example, high-temperature heat pumps are often installed in poorly insulated houses as a straight swap for electric or gas-powered central heating, therefore in most cases, high-temperature heat pumps would not be able to take advantage of price signals such as those set out in the proposed tariff. Heat pumps with a low cycle life may want to avoid conducting DSR of this type as it will reduce their operational life. Finally, heat pumps with certain weather compensation control strategies may struggle to recover the dwelling temperature quickly after a period of peak avoidance. To mitigate this the control system may need to be changed which would likely reduce the overall COP of the system. Therefore, bespoke analysis must be done to ensure there is an overall financial benefit to the consumer.

It is also worth mentioning the subtle difference between the operation of ASHPs and GSHPs when responding to this tariff, ASHPs COP is a function of outside air temperature, which usually drops significantly at night, thus ASHPs at night operate at a lower COP than during the day, which reduces the financial benefit of responding to our proposed tariff as more heating is shifting to the colder periods where the Heat pump is less efficient. However, GSHPs COP is a function of ground temperature which does not drop during the night, and this phenomenon does not exist. The impact of this on electrical load is low, when comparing ASHP and GSHP with the same average COP, a difference in energy bill of just 1% is observed.

7. Impact of heat electrification on the distribution network

Introduction

The impact of heat electrification on distribution and transmission networks is projected to be significant. The UK government recently announced a plan to encourage the installation of 600,000 heat pumps each year by 2028. DSR strategies are likely to play a big part in minimising system costs for consumers

Based on the previous section there are several peak avoidance strategies that may be used in response to the proposed tariff. Some consumers in thermally efficient dwellings may switch their heating off completely, while others in less efficient houses, or with more stringent thermal comfort levels may just turn down the heating during this time, reducing but not eliminating their heat pump load. Finally, some may choose to install thermal storage to eliminate their 'red band' heating load while still heating their home via thermal storage. The modelling completed in this section looks at what impact these strategies would have on the electricity shape profile at the primary substation level.

Modelling methodology

Real data from an equivalent substation has been requested from WPD however it is delayed; as a placeholder, profile 1 data has been scaled to represent the number of houses included in the study (13,406), this excludes any commercial or industrial load and therefore an interpretation of the result should not be considered accurate. An addendum to this report will be published once this data is available.

The heat pump load calculated for all three scenarios, BAU, thermal comfort and Switch-off, in the previous section has been scaled to match the heat pump uptake scenarios shown in Table 16. These aggregated loads are superimposed on the substation data, thus, enabling an assessment of the impact of various peak avoidance strategies on the substation shape.

The heat pump uptake scenarios have been modelled based on the 2026, 2031 and 2036 projections from WP4. Heat pump profiles for the 2006 medium house have been scaled according to their Gross Internal Area (GIA) from the modelling outputs for the large house. While the large flat and park home heat pump profiles have been scaled from the modelling outputs for the 2006 small flat. It has been assumed that all dwellings with heat pumps have the higher level of thermal efficiency as set out in Table 15. Therefore, Modelling results from the 2006 constructions have been used throughout. The results from the 2006 construction most closely align with the annual heating demands of these dwellings set out in WP4 and Table 15 (+/-10%). The 2006 construction is also the best representation of a typical house with a heat pump, it could represent a modern house built in the 2000s or older houses which have been thermally retrofitted.

The rated power of the heat pumps impacts the rate at which dwellings recover temperature and their maximum power consumption, while this has little importance for individual consumers, it impacts the heat pump load profile after peak avoidance action has been taken, and therefore, bears more weight in this section. Typically, 3,4,5,7, and 9kW heat pumps are available on the market. For each dwelling type, the heat pump chosen is the smallest heat pump which meets hourly demand throughout the year (Table 14).

Table 14 - Heat Pump Rated Power assumption for each dwelling

	heating capacity	electrical capacity
Small Flats, large flats and park homes	4kWth	0.9kWe
Terraced house	5kWth	1.1kWe
Large and medium house	7kWth	1.6kWe

Table 15 - Typical dwelling specification, as set out in WP4

		Large house		Medium house		Terraced house		Large flat		Small flat		Park home
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**J**	**K**	**L**
GIA	m^2	130	130	93	93	70	70	80	80	60	60	60
Occupants	Qty	3	2	3	2	2	1	2	1	2	1	2
DHW demand	KWh/yr	2,103	1,628	2,103	1,628	1,628	1,153	1,628	1,153	1,628	1,153	1,628
Heating (fabric efficiency)	kWh/m^2/yr	100	70	100	70	80	50	80	50	80	50	80
Heating demand	kWh/yr	13,000	9,100	9,300	6,510	5,600	3,500	6,400	4,000	4,800	3,000	4,800
Unregulated electricity	kWh/yr	4,300	4,300	2,900	2,900	1,800	1,800	2,900	2,900	1,800	1,800	1,800
Total electrical heating load	kWh/yr	15,103	10,728	11,403	8,138	7,228	4,653	8,028	5,153	6,428	4,153	6,428
Total electricity use	kWh/yr	19,403	15,028	14,303	11,038	9,028	6,453	10,928	8,053	8,228	5,953	8,228
number of properties	Qty	419	417	4096	4099	1252	1252	88	88	753	753	189

Table 16 - Heat pump uptake scenarios modelled at substation level

		Number Of Dwellings With heat pumps											
			Large house		Medium house		Terraced house		Large flat		Small flat		Park home
Year	**Percentage of dwellings with heat pumps**	**Total**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**J**	**K**	**L**
2026	**10%**	1282	0	81	0	795	0	243	0	17	0	146	0
2031	**27%**	3570	0	226	0	2213	0	676	0	47	0	407	1
2036	**47%**	6225	0	394	0	3860	0	1180	0	83	0	709	0

Modelling outputs – Indicative DNO substation Shapes

Figure 9 shows how the different peak avoidance strategies influence the hourly substation profile during the WCD, each graph shows three lines, current load (2022) which shows the current substation load (estimated using 13,406 multiples of profile class 1), BAU which shows the current substation load superimposed with heat pump load where no peak avoidance strategy was implemented, and peak avoidance which is the current substation load superimposed with heat pump load where a peak avoidance strategy is employed.

3 graphs, 1 for each heat pump uptake scenario, are shown for both peak avoidance strategies, switch-off and thermal comfort. (Note the buffer tank strategy has the same peak load impact as thermal comfort, as the buffer tank would be recharged during off-peak times).

It's clear that both strategies are effective at reducing 'red band' demand, reducing peak demand by between 5 and 15%. However, the increase in heating load observed after the 'red band' period, which is required to get the dwellings back up to temperature, causes a new, higher substation peak between 7-8 pm when heat pump integration goes above approximately 25%. It's also clear that the peak avoidance strategy 2: thermal comfort causes a smaller peak between 7-8 pm compared to the peak avoidance strategy 1: Switch-off and therefore a higher heat pump integration percentage can be observed without increasing peak demand.

The size of this second peak is determined by the thermal heating load required by the building, and the rated power consumption of the heat pump. Therefore, heat pump selection heavily influences the size of the second peak. The higher the rated capacity of the heat pump, the larger the thermal output at maximum capacity, therefore directly after a peak avoidance action dwellings recover lost temperature faster and the electrical demand is higher, thus creating a higher peak between 7-8 pm. Therefore, any tariff or other DSR incentive for heat pumps must take this into account.

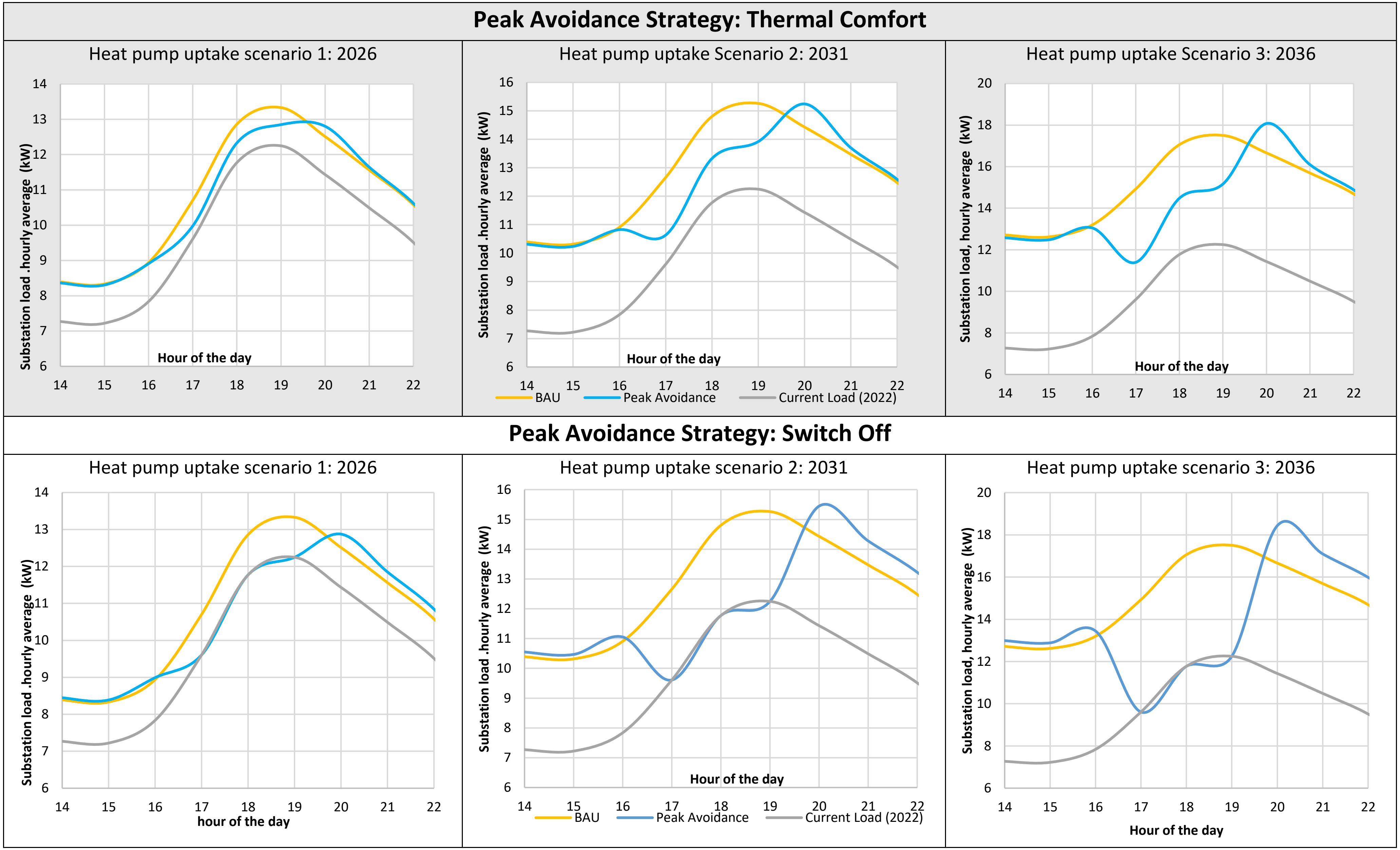


Figure 9 - Impact of Peak Avoidance Strategies on substation shape given different heat pump uptake scenarios

Fixed speed Compressors

The modelling completed in this report has assumed variable speed (inverter driven) compressor heat pumps throughout. This is justified because the aggregated profile of numerous single-speed compressors is similar to that of variable-speed compressors. In addition, many ASHPs and GSHPs on the market are currently variable speed compressor driven. However, in reality, many heat pumps still use fixed-speed or 2-speed compressors, and therefore operate differently to the modelling due to their higher start-up current, and modulating electrical load.

Modulation

Heat pumps with fixed-speed compressors achieve the required heat demand through two methods:

1. **Modulation**, i.e., a 5kWe heat pump operating at a COP of 3 will produce 15kW of heat output, if just 7.5 kW of heat output is required, the heat pump will operate with a duty cycle of 0.5, the frequency of the duty cycle is determined by the heating delivery system, building fabric and the thermostatic control range.
2. **Weather compensation** of heating circuit flow temperature to match heating demand. This reduces or eliminated heat pump cycling by closely matching steady-state heat pump output with demand.

Heat pumps using method 1 above, have the potential to create short-term spikes in demand which are not represented by the hourly average demands presented throughout the modelling. While it can be anticipated the impacts of this modulation will average out at substation level under normal operation. Under the proposed tariff, many heat pumps are likely to ‘cycle on’ simultaneously at 7 pm, which is likely to create a front-loaded demand peak in the 7-8 pm timestep.

The impact of this during winter is low as heat pumps are usually sized to have a duty cycle close to one during cold winter days. This can be observed in Table 17, which shows if 47% of dwellings are heated using modulating heat pumps, a peak power of 10% above average is observed, 7-8 pm WCD. However, in Spring and Autumn where heat pump output is much greater than heating demand, this impact is much more significant. A peak 46% higher than the 7-8 pm hourly average is observed in March and up to 62% in October. Table 17 shows the worst-case impact of this modulation, assuming all heat pumps are fixed speed modulating heat pumps, and they all switch on simultaneously at 7 pm.

This impact is significant, and synchronising duty cycles of modulating heat pumps should be avoided, therefore excluding such heat pumps from accessing this tariff may be advised.

Table 17 - Impact of heat pump modulation on substation power peaks between 7-8 pm

Year	Heat pump integration	Average Substation power - 7-8 pm (MW)	Peak substation power 7-8 pm (caused by heat pump modulation)
WCD			
2026	10%	12.8	13.2
2031	27%	15.2	16.5
2036	47%	18.1	20.2
March			
2026	10%	9.3	10.5
2031	27%	10.6	13.7
2036	47%	12.0	17.5
October			
2026	10%	9.9	11.4
2031	27%	10.6	14.6
2036	47%	11.4	18.4

Start-up current

Start-up currents for inverter-driven compressors are less than the typical running currents, However, this is not the case with non-inverter-driven (fixed speed) compressors. Research into the start-up current of heat pumps without variable speed drives has shown that typical start-up currents for both ASHP and GSHPs are approximately 2.3 times their nominal operating current at a given flow temperature. Some older heat pumps without any soft start have larger start-up currents ranging from 4-6 times standard operating current, however, as these are uncommon in domestic properties they have been excluded.

Assuming all heat pumps are modulating heat pumps with a start-up current 2.3 times their nominal operating current, Table 18 shows the transient (10-second) current that would be observed at the substation level during the worst-case day. Similar increases are observed throughout the year unlike the effect of modulation, so this has not been displayed.

Table 18 - approximate peak transient current observed at the substation due to simultaneous heat pump start-up

Year	Heat pump integration	Average substation current 7-8 pm (KA)	peak transient current 7-8 pm - 10 seconds (KA)
WCD			
2026	10%	56	70
2031	27%	66	88
2036	47%	79	116

8. Indicative Data solution for a Future Field Trial

Introduction

If the work in this report was to progress to a sandbox trial, it would require a data solution to separately record half-hourly heat pump data and dwelling-wide electricity data, process this data and display the resulting energy cost to the consumer. Trust Power Limited, creators of the household energy-saving mobile application, Loop, are aware of this project and have expressed an interest in providing such a data solution for any resulting trial. Below is a summary of the solution that has been discussed.

Smart meter data

Half-hourly smart meter data is obtained remotely via the DCC and ingested into Loop’s cloud-based platform. Loop’s solution supports all meters enrolled into the DCC including most SMETS1 and all SMETS2 meters.

Heat pump data

Heat pump installation will include a measurement and monitoring solution that provides remote third-party API access or on-site programmatic access to data (e.g. via an MBUS interface). If only on-site access to data is possible, additional hardware will be installed alongside the heat pump to make heat pump data available remotely to Loop (e.g. using OpenEnergyMonitor designs). At a minimum half-hourly energy usage data will be accessible from the heat pump. Ideally, data is more granular and includes:

- Heat output
- Outside temperature
- Multi-point internal temperature
- Flow rates
- Out and return temperatures
- Heating schedule
- Hot water status

Heat pump data is ingested into Loop’s cloud-based platform either via API or on-site hardware.

Consumer-facing solution

The customer creates an account with Loop via a webapp. The customer provides consent to Loop to collect both smart meter and heat pump data. The customer’s tariff is entered - standard and time of use tariffs are supported. The user sees their smart meter and heat pump data presented to them via graphs on the webapp, and summaries including usage and cost. The link between external temperature, thermostat settings and running costs is clearly explained to the user. Reports are sent via email weekly. Forecasting future costs based on the weather forecast, tariff and heating schedule is provided to enable users to consciously reduce their heat pump running costs.

9. Conclusion

Summary of findings

- This report proposes a heat pump tariff which passes on Time of Use (ToU) Distribution Use of System (DUoS) charges to incentivise domestic consumers to avoid using their heat pump during periods of network stress. The tariff also eliminates ‘green levies’ from the bill.
- The tariff saves consumers up to 25% on their heat pump electricity bill, with 12% of these savings coming from the elimination of ‘green levies’ from the bill and up to 13% coming from peak avoidance strategies which reduce the use of more expensive ‘red band’ electricity.
- The majority of consumers can reduce and shift a percentage heat pump load during the ‘red band’ period between 4-7 pm. The amount of load possible to be shifted depends on the thermal properties of the house and the peak avoidance strategy employed.
- Peak avoidance strategy 1 simply switches the heat pump off entirely during the ‘red band’. temperature drop over this time varies significantly depending on both dwelling type and construction type, but ranges from 2.5^{O}C for a modern flat, to 7.8 ^{O}C for a 1970s-built detached house. This may not be acceptable for many consumers, however, for other consumers, this may be seen as a small price to pay to a 25% reduction in heating bill.
- If consumers want to ensure their dwelling stays within thermal comfort limits, then peak avoidance strategy 2 can be employed (20-degree setpoint dropping to 18 during ‘red band’ times) with this strategy heating load during a cold winter’s day can be reduced by 40-45% (1970 construction) or 70-80% (2021 Construction). It should be noted that these temperatures are average temperatures throughout the house, and consumers' zonal temperature control could heat areas of their house to higher temperatures and allow others to drop lower.
- The impact of such peak avoidance strategies on the distribution network was explored through further modelling. It is clear that the peak avoidance strategies can reduce peak ‘red band’ demand compared to a BAU scenario, however it was also clear that these simple approaches to peak avoidance increased heat pump demand after 7 pm once the ‘red band’ period ended. Depending on the number of heat pumps taking this action this can cause a second higher demand peak at the substation level. Placeholder substation data has been used, therefore more detailed conclusions about the impact on the distribution network will be included in an addendum to this report once real substation data is available.

Impact of consumer behaviour

While the results presented in this report show typical values are given typical consumer behaviour and external conditions, consumer behaviour has a large impact. For example, if consumers only heat-occupied areas of their house during the ‘red band’ time, peak load can be significantly reduced. While in the case of peak avoidance strategy 2, if consumers install non-invasive thermal curtains and secondary glazing peak load can be significantly reduced. While consumer behaviours such as opening windows during cold days and leaving curtains and blinds open significantly increase peak when implementing Peak Avoidance Strategy 2, such behaviours will also increase the magnitude of the 7-8 pm peak observed at a network level.

Because responding to such a heat pump tariff can become complex it's likely that consumer engagement with the electricity system and education in heating and energy conversation would be beneficial to the successful implementation of these strategies.

Differentiating between winter ‘red band’ and other ‘red band’ times

The proposed tariff does not provide a strong financial signal for consumers to avoid heat pump use during winter peaks. Most of the year the heat pump can entirely avoid ‘red band’ heating with little impact on thermal comfort. However, this is not true during cold winter days which represent a very small portion of the year. Because the proposed tariff does not change seasonally, consumers are able to get the majority of benefits from the tariff by avoiding ‘red band’ time during temperate months. If consumers then chose to ignore the price signals during colder months and heat their dwelling as usual, the positive impact on the distribution network will not be observed. The cost of using more expensive peak time energy during the coldest 5% of days only represents less than 1% of the total energy bill.

Further work should look at other tariff structures which accurately cost peak consumption during different periods. This work would benefit from being done alongside further work explained in the following section.

Avoiding Additional Peaks

It has been well documented in previous studies and trials such as (5) that heat pump DSR must take care not to introduce new network peaks at different times. The outputs of this work also show that this is a major concern when incentivising heat pump DSR.

Several previous publications have suggested that model-based predictive control algorithms could be used to mitigate this, by optimising heat pump consumption within fixed thermal comfort parameters and a dynamic electricity tariff. This would require that a third party, in effect, take control of a consumer's heat pump 24/7. Due to the significant lack of trust between consumers and energy suppliers this option could prove unpopular, particularly given the current ‘per unit’ model by which suppliers sell energy, which incentivises the sale of as many units as possible regardless of how efficiently this energy is used. A switch to an Energy as a Service (EaaS) business model, whereby customers pay a service fee for their heating needs regardless of how many units are used, might reduce this trust barrier, as suppliers are then incentivised to use energy efficiently, and customers have more certainty on energy bills. The willingness of customers to relinquish control of their heating system given differing supply arrangements could be explored further through community engagement.

Several simple static strategies could be employed to reduce the creation of additional network peaks including:

1. Staggered ToU tariff: tariff participants would have staggered three-hour periods during which electricity cost was higher, this would smooth out the 7-8 pm peak, as well as the impacts of modulation and start-up current demonstrated above.
2. Peak capacity charge: the addition of a peak capacity charge would disincentivise high heat pump power usage at any time, thus disincentive the problematic 7-8 pm peak.

Further assessment of the above strategies using the same modelling approach implemented in this report is recommended to inform the design of trials of such a tariff. In addition, further assessment of the various heat pump control methodologies used by leading manufacturers is needed to understand how they would achieve the peak avoidance strategies modelled in this report.

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11. Appendix A: Considerations for vulnerable consumers

Throughout the duration of this project, some concerns have been raised about how providing financial incentives for heating peak avoidance may impact vulnerable customers. This paper is primarily concerned with the technical feasibility of such a proposal and the impacts that this has on internal temperature given various dwelling types. We hope to use the outputs of this paper to inform the design of a Sandbox trial which must ensure that vulnerable customers can be protected through such a scheme; therefore these concerns must be addressed. This appendix is the starting point for addressing these concerns.

The challenge regarding vulnerable customers

The 'red band' period exists as a product of societal behaviours. Higher electricity demand patterns correspond to the time when children come home from school, and people return home from daytime work. At that point, a large proportion of the population wants to be assured their homes are warm as they settle into evening activities and start preparing the evening meal. Levels of energy demand are accordingly high at these times and seeking to shift heating demand away from this peak period presents several challenges. While the proposals outlined in this paper are technically feasible, the reality of achieving at-scale demand shifting needs careful consideration.

While heat pump technology is mature, historic uptake has been low so far in the UK, and as such, there is low awareness amongst the general public of how these heat pump systems can be used efficiently and effectively. Furthermore, public acceptance of the technology has not yet been proven. In addition, the suggestion that a domestic heat pump should be turned down, or switched off during key periods of the day, or that households need to plan when heat is available, will require significant engagement with the consumer, as historically heat has been available at a flat rate. Therefore, there is a risk that offering time-of-use tariffs won't be perceived by the public as an incentive for good behaviour, but as a form of rationing. This, therefore, requires appropriate and careful communication management, as it's likely to be met with resistance unless the benefits are very clear.

From the perspective of vulnerable consumers, that is, those less able to interact with the energy market, there are additional concerns about the red band proposal:

- Where low or fixed incomes are a root of vulnerability, it is also a reality that many people in this position also live in properties that are thermally very inefficient. Unless effective fabric upgrades are made, the roll-out of electrified heat will face major challenges; estimates of EPCs in Cornwall suggest 70—75% homes are EPC D and below. There is growing concern that many households are managing rising energy costs by deliberately underheating and self-disconnecting. In this context, trying to encourage behaviours that shift demand requires significant preparatory work, outside the scope of the DNO.
- Knowledge of using heat pump technologies is limited. Project partner, Community Energy Plus, already has evidence of situations where social housing tenants have had their property upgraded to air-source heat pumps and have subsequently switched them off because of the perception of higher running costs (either real or imagined).
- Since the first draft of this paper, the Government has announced their intention to move the burden of 'green/social' levies into general taxation. While welcome in terms of alleviating pressure on energy costs for low-income households, this restricts the ability to offer reduced tariffs and there is a question of whether the tariffs discussed are sufficiently attractive to prompt the desired behaviours.

Ensuring benefit for vulnerable customers

a sandbox trial is proposed which will provide a financial incentive similar to that proposed in the main body of this report, to 25 homes with heat pumps. This trial will likely have a representative mix of houses, including affluent households, vulnerable households and those in between. Therefore, the sandbox trial must ensure such an incentive will provide benefits to all, especially the most vulnerable.

The details of the trial are not yet confirmed; however, it will be designed with the following considerations:

1. The trial would seek to increase awareness and education about heat pump systems, how they work, and how much they cost. For example, this could be through a Heat as a Service model such as the paying for 'warm hours' a HaaS model trialled by Energy Systems Catapult. This makes it clear to customers how much an hour of heating costs in each room of the house, thus enabling simple decision-making for customers on when and how to heat each space. This approach led to increased trust among consumers and energy suppliers. Also, many customers primarily concerned with heating costs chose a fixed schedule of warm hours in return for a cost reduction. While almost all trial participants chose to only heat certain rooms at certain times, an approach which provides both a heating load reduction and optimal thermal comfort.
2. This trial would ensure a significant reduction in total annual heating system cost, therefore allowing more heating hours throughout the week for the same cost, albeit in return for a reduced setpoint between 4-7 pm on weekdays. For example, for vulnerable customers, this could mean they can afford to heat their house throughout the day where they weren't before if they are prepared to reduce their internal setpoint by 2 degrees between 4-7 pm.
3. The proposed trial will be intended only for houses with appropriately installed heat pumps, that is low temperature heat pumps installed in houses with appropriate insulation. These dwellings have significant inherent thermal storage and therefore can benefit from tariffs such as these with lower impact on thermal comfort. This provides additional financial incentives for houses which are properly insulated and improves the business case for improving thermal insulation encouraging high uptake. Houses with high-temperature heat pumps or heat pumps installed in inappropriately insulated houses would not be eligible for the trial.
4. This trial will likely include zonal control of heating as a prerequisite (installing zonal control for vulnerable consumers will be considered), to demonstrate how zonal control could be used to provide DSR without reducing thermal comfort in occupied rooms. This will therefore provide further financial benefit to installing zonal heating controls, hence improving the business case for the energy-efficient technology which has significant potential to reduce energy costs for vulnerable consumers.

In addition to the above considerations which ensure vulnerable customers are protected in the short term, this project is also aimed at keeping electricity prices low into the future. We all collectively pay for the cost of operating the distribution and transmission network through network charges on our bills. If heat electrification is undertaken at scale without peak avoidance strategies such as that represented in this report, hundreds possibly thousands of primary transformers up and down the country will need to be upgraded, with untold costs ultimately being passed on to the consumer through network charges. These costs will hit vulnerable customers the most and would likely increase fuel poverty and intentional underheating, therefore research on how this can be prevented is especially in the interest of vulnerable customers.