April 2022

DSR flexibility for domestic heat pumps

PART 2

Home thermal modelling and potential for DSR control of heat pumps

Vaillant and geo white paper

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Executive summary

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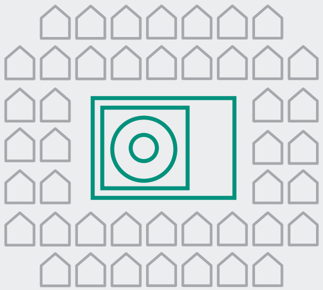
In April 2021, the UK Climate Change Committee's (CCC) sixth carbon budget[1] recommended that 21 million existing homes should be fitted with heat pumps as part of a low-carbon heating strategy for every home.



21 million
existing homes will need to have a heat pump fitted

Consumers are increasingly aware of the need to change their behaviour and reduce their carbon emissions and are looking for low-carbon heating solutions.

This paper sets out the case for mass deployment of domestic heat pumps as an integral part of the UK's net zero strategy.

The paper discusses that appropriate insulation, not just of existing housing stock, but also of new build properties, is prerequisite for such a deployment.

It also demonstrates that utilising the flexibility that heat pumps can offer is critical to managing the significantly greater peak demand that electrification of heat creates alongside the increased adoption of EVs.

The UK Government has announced plans to have 600,000 heat pumps installed per year by 2028. We believe this objective should go further and faster.

This paper identifies that the additional electricity demand from heat pumps (although individually relatively small) when applied to a significant proportion of the 21 million homes already built, would have a major impact on the adequacy of our Low Voltage (LV) electricity networks without the mitigations we propose.

Low voltage networks will be significantly impacted without DSR solutions

For this reason, we have examined smart grid technology which allows better control of heat pumps at the grid edge to manage the peaks of supply and demand to alleviate that stress. This technology offers the potential to save billions of pounds in electricity network infrastructure reinforcement.

The electricity network has been using Demand Side Response (DSR) flexibility for centrally managed large-scale grid batteries and controlling commercial and industrial loads, for several years already.

While residential DSR trials have taken place, much of the technology necessary to enable mass-market adoption is still in R&D labs and the lack of standardisation between manufacturers is a barrier to deployment.

Lack of standardised smart energy protocols between devices needs to be solved by industry

We have sought to address these challenges, and in developing an understanding as to how these systems could work, have produced a series of recommendations for a cross-section of stakeholders including government, consumers, media, house builders, energy retailers and those working in the heat pump sector.

#1

Low voltage networks may become overloaded when 10-20% of the existing 21 million homes have heat pumps fitted to them.

- While heat pumps can be made to be flexible with smart protocols (to reduce demand at peak times), the amount of flexibility is dependent on good insulation and thermal properties of homes.
- Additional thermal storage or battery storage will be needed to offset the impact of adding heat pumps to homes.

#2

Enabling Demand Side Response (DSR) control of Energy Smart Appliances is hampered by a lack of agreed protocols between manufacturers.

- We propose that industry adopts a set of existing standards (EEBUS, Matter and OCPP) with a flexible architecture supporting EV chargers, vehicle-to-grid (V2G), heat pumps, solar PV, battery storage and white goods.

#3

The GB smart metering system can help to enable domestic DSR, by providing core data to support peak load control in the home, base-lining data for DSR service and providing LV substation monitoring information to DNOs.

- Existing smart meters can share real-time power readings with home energy management systems, and avoid costly additional metering, which is currently needed for DSR services.

#4

The UK Government sponsored, PAS1878 for Energy Smart Appliances (ESA) has moved industry forwards, but the authors consider that it is insufficient for manufacturers to adopt.

- We propose that an industry consortium of willing stakeholders including DNOs, energy retailers, DSR Service Providers (DSRSP), Customer Energy Manager (CEM) and ESA manufacturers is formed to develop mass-market solutions capable of adoption in the UK and in international markets.
- This industry consortium should be responsible for selecting and developing the interoperable protocols and mass-market solutions with a "DSR ready" trust mark that enables consumer confidence when purchasing equipment.
- These solutions should be proven in large-scale, real-world trials centred around single substations to demonstrate the impact of additional load on the LV portion of the network and how best to mitigate it.

#5

The idea of allowing multiple CEMs per home proposed in PAS1878 may have undesirable outcomes including potentially safety issues.

- Multiple CEMs will encourage competition and innovation between vendors.
- Further work is needed to understand the practical implications of such a scheme at a system level.

Scope

This white paper is the second in the series of three which are the output from a joint project conducted by Vaillant and Green Energy Options (geo).

During our research into the topic of Demand Side Response (DSR) control of heat pumps, we uncovered a wealth of learnings which will help governments and industry to align around best practice and identify key steps towards decarbonisation of domestic heating, which represents around 15% of the UK's energy use and 21% of carbon emissions[10].

The subject areas cover commercial, procedural as well as technical barriers which need to be resolved to make a mass market heat pump deployment viable.

Paper 1 – Review of market, policy and situation today:

- The current situation in the heat pump and DSR markets
- The potential impact of heat pumps on low voltage networks
- The need for scale
- The need for technical standards and interoperable protocols
- The need for a code of practice
- Recommended next steps

Paper 2 (this paper) – Home thermal modelling and potential for DSR control of heat pumps:

- Building models, impact of insulation and heat losses
- Pre-heating homes and hot water to take advantage of Time of Use (ToU) tariffs
- Heat pump flexibility options
- Simulation results

Paper 3 – Smart home protocols and DSR:

- Use cases for EV, heat pump, solar PV & battery storage
- DSR control of in-home Energy Smart Appliances (ESAs) & PAS1878
- Review of standards and protocols
- Recommended architecture for smart home DSR solutions and heat pump

Introduction

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Heat pumps & domestic DSR

In the first white paper we covered the market situation for DSR control of domestic heating.

This second white paper covers the thermal modelling of homes and the operation of heat pumps which at scale can be used flexibly to avoid overloading the LV networks at peak times of day.

In particular we discuss the key differences in homes heated by oil or gas boilers, and how the situation of heat pump heated homes is different.

We cover the need for good insulation, thermal storage and some of the typical features of a modern heat pump that allows its heat output to be modulated relatively quickly making it suitable for DSR.

Our thermal models presented here take into account factors such as heat losses based on building fabric U-values, heat pump sizing and impact of stored energy in the building structure (thermal mass) and we examine how these impact grid flexibility.

Background

In the UK, the department for Business Energy and Industrial Strategy (BEIS) has funded the development of ***PAS1878*** (Publicly Accessible Standard) focused on kick-starting the domestic DSR revolution by defining an architecture for ESAs.

PAS1878 focuses on the minimal set of requirements to satisfy the UK Government's concerns around: ***interoperability, data privacy, grid stability*** and ***cyber security***. Its scope is broad and covers a range of domestic loads which can offer flexibility such as EVs, HVAC and battery energy storage systems.

In other markets around the world, DSR technologies already exist which can call on air conditioning to reduce its power demand, or solar PV inverters to reduce their generation output. These have traditionally involved a relatively simple 2-wire analogue control signal that ultimately provides the control, but does not allow a bi-directional conversation.

Newer technologies can call on the ESA to make flexibility offers (e.g. it would be possible to switch off for 20 minutes, and save 1kWh without significantly impacting user comfort). They can also call on the smart heating system to forecast how much power it is likely to need in the next few hours.

These forecasts may be based on a combination of pre-set desired temperature, the outdoor temperature, weather forecast, building thermal model and electricity tariff.

By using the extensive data available inside these intelligent systems, it is possible to provide far more accurate energy forecasts to energy retailers, national grid and DNO/DSOs.

This in turn will allow those operators to plan more effectively, reducing the degree of grid reinforcement required and allowing better matching of renewable energy supply with household demand, minimising costs and CO_2 emissions.

The UK Government (BEIS and OZEV) has sponsored the development of two Publicly Available Specifications (PAS). PAS1878[4] focuses on ESAs and PAS1879[5] focuses on the DSR - Code of Practice.

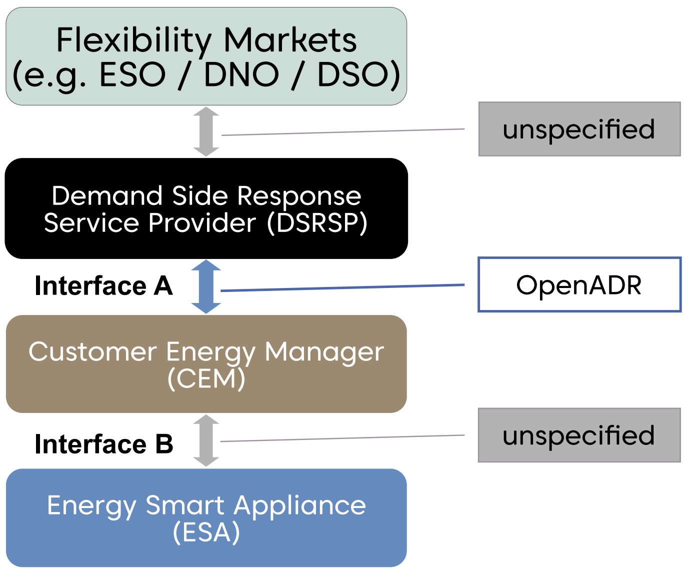


Figure 1 - PAS1878 high-level components and interfaces

Both PAS documents were first published in May 2021 with the aim of kick-starting and standardising the control of energy smart appliances on the electricity network.

The PAS1878 architecture is shown in Figure 1, with the four main actors and the defined interfaces between them: flexibility markets, DSRSP, CEM and ESA.

Notably, only Interface A has been specified in PAS1878, with OpenADR being recommended. The flexibility markets in the USA (where OpenADR was initially developed) allow network operators to request service to their DSRSPs using OpenADR. In the UK, DNOs may not be aware of the standard and may be looking at building their own proprietary implementations.

> The key challenge for enabling mass-market control of a range of ESAs is the lack of an agreed interoperable protocol (Interface B) between a CEM and a variety of ESAs (be they EV chargers, heat pumps, solar inverters, battery storage or white goods).

The lack of a common standard means that CEM manufacturers today have to develop partnerships with many different manufacturers, gain access to their proprietary protocols and build bespoke solutions.

By buying a CEM from a given manufacturer, consumers may then unwittingly get locked into a specific set of brands of supported equipment (e.g. one type of EV charger with one type of solar inverter and one type of heat pump).

The cost for CEM manufacturers to develop, maintain and support a range of compatible devices, for example supporting heat pumps from several different manufacturers, starts to become prohibitive in this scenario.

The alternative of an industry-led open standard for allowing communication between the CEM and a variety of ESA types from many different manufacturers would help enable competition and reduce costs, in turn driving the much needed uptake of Domestic DSR. It would also enable greater flexibility for users to choose their ESAs from different brands and swap them out over time, avoiding lock-in.

The myths around heat pump flexibility

Myth 1 - Heat pumps cannot be flexible

The traditional view is that heat pumps should be left alone and are always left on, needing to consume energy throughout the day, meaning that they cannot be flexible. This is not the case - heat pumps can play an important role in domestic demand flexibility

When choosing a heat pump, the installation engineer will need to calculate the required heat pump output that is appropriate for the heat loss of the property. This output power needs to be sized for the coldest day to ensure that consumer comfort levels are met, implying that on the coldest days the heat pump may need to be on maximum output for a continuous period.

Since not all days are extremely cold, then the opposite is true, that is to say heat pumps are not running at maximum output all the time, and in fact do switch off or reduce power output once the home has reached its temperature set point. This rather simple assessment leads to the basic conclusion that there is some degree of flexibility on the majority of non-extreme days.

Myth 2 - Switching heat pumps on and off can damage them

Some argue that turning heat pumps on and off will damage them. That may be true of older style fixed speed compressor systems, but most modern heat pumps have inverter-controlled compressors which can have their heat output set between 20-100%.

Thanks to this variable output, DSR can request that the heat pump increases or reduces its electrical power consumption without damaging the system.

> modern heat pumps have inverter-controlled compressors

While a heat pump heats the home much more slowly than a gas boiler, there is evidence to show that a heat pump with an inverter-controlled compressor can be used as a flexible asset.

In this section we compare and contrast the key differences between homes heated with oil or gas and homes heated by heat pumps.

There are many possible combinations and variations in domestic heating systems to consider. Here we consider the key components needed in a typical heat pump home which provides heating and hot water and the in-home communication needed to optimise the behaviour of those components (e.g. between thermostat, heat pump control, heating diverter valve etc.).

Typical heating & hot water deployments today

In the UK today there are over 26 million hot water based (wet) central heating systems. The majority of heating systems are gas combination boilers (15 million), with around 9 million system/regular boilers (with DHW cylinder)[11].

Heat pumps currently only contribute a further 250,000 homes to this overall number, but with the challenge of net zero carbon and energy efficiency, this number is set to rise.

The UK Government has set targets for the installation of 600,000 heat pumps per year by 2028, which will represent one third of the annual heating installation market.

The market is divided into new homes (roughly 180,000 new homes are built each year in the UK) and retrofit to existing housing stock.

From 2025 gas boilers will be more difficult to fit under the new Future Homes Standard regulations. Some house builders are already fitting heat pumps as standard. This is enabling them to get ahead of the curve as customers are increasingly looking for eco-friendly homes that do not require as much heating due to the more modern airtightness and insulation requirements in the current building regulations.

However, the larger retrofit market presents a significant challenge. Persuading homeowners to undertake the significant building work (e.g. installation of underfloor heating) and to cope with the time and inconvenience that work will impose, is a significant hurdle for heat pump providers and installers to overcome. This means that many consumers will naturally opt for a replacement gas boiler when their current one breaks down.

The UK Government is seeking to incentivise the retrofit market with the Boiler Upgrade Scheme (BUS) from April 2022 with up to £6,000 vouchers available to homeowners to help make it easier to replace existing gas boilers with heat pumps.

Gas & combi boiler systems today

Retrofitting existing homes requires an examination of the predominant heating systems already in homes. The large majority of heating systems today have a single zone heating circuit which is heated via radiators and has a single heating programmable thermostat, usually installed in a hallway as a reference point for the entire home. Individual thermostatic radiator valves may also have been fitted in order to influence temperatures in specific rooms.

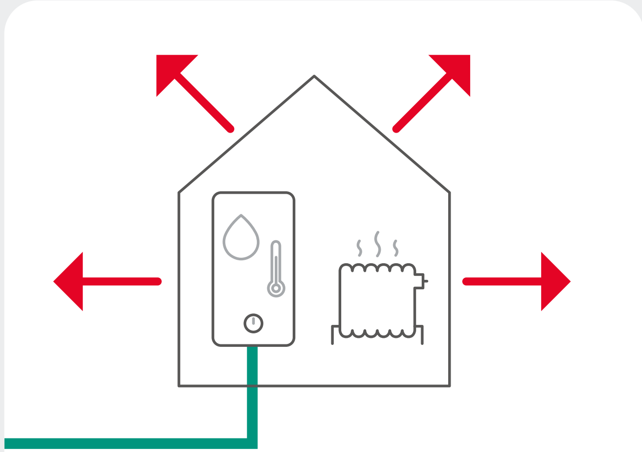
Properties over 120m^2 will likely have two heating circuits. In this case usually the upper floors will be heated via radiators and the ground floor will be heated by radiators or underfloor heating. Programmable thermostats are typically installed in a hallway on each floor of the building, operating as two separate reference points for each individual circuit for consumer comfort.

It is evident from this initial overview that heat pump systems are significantly more complex to plan and install than their less climate-friendly gas or oil-powered equivalents. To drive a significant increase in the pace of change, the full benefits of heat pumps need to be clearly and easily realisable for the overwhelming majority of households.

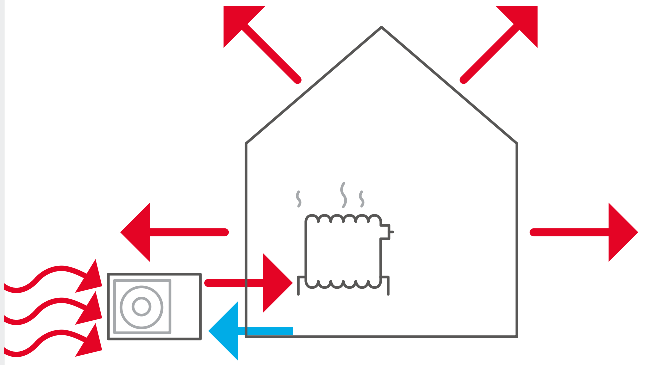
Heat pump efficiency & COP (Coefficient of Performance)

Understanding heat pump operation

Oil, gas, and direct electric or storage heaters produce new heat energy by burning fossil fuels, or passing electric current through a heating element. That heat energy escapes from our homes to the outside and is lost.



"heat pumps can be 300-400% efficient..."



A heat pump is fundamentally different in that it effectively recycles the existing heat in the ground or ambient air and pumps it back into our homes at higher temperatures.

The heat will still escape back into the atmosphere eventually (which is why good insulation is important).

This process still works when it is cold outside (even at temperatures down to -20°C) although it becomes less efficient in air source heat pumps as the temperature drops below 0°C. This is where ground source heat pumps which extract energy using pipes buried deep below the ground can be more efficient, but are more costly to install.

The process to pump the existing heat energy into our homes is similar to how a fridge works (but in reverse).

The heat pump uses electricity to drive the compressor and motors to generate much more heat output than the equivalent amount of electricity would have produced from direct electric heating.

The heat pump's efficiency ratio depends on the ambient external air temperature. This efficiency factor is referred to as its Coefficient of Performance (COP). In the UK climate, heat pumps can have a COP of 3.0-4.0 (i.e. can be 300-400% efficient). This is because the heat pump is scavenging the free heat energy from the air or the ground and so can be more than 100% efficient (in a similar way that a solar panel extracts free electricity from the sun). It requires 1kWh of electricity (running the fans and compressors) to produce 4kWh of heat output.

At very cold temperatures (-15°C or below) the COP can drop below 1.0 such that the heat pump uses more energy than it produces. Under these extreme cold temperatures, some heat pump manufacturers also have back-up heating elements (immersion heating).

Heat pump based systems

Figure 2 shows a heat pump system which is used to heat a home and DHW. The fan unit and compressor (1) is outdoors, and the extracted heat energy is transferred through pipes using a mix of water and antifreeze, to the indoor unit (2). The indoor unit comprises of a heat exchanger and expansion tank and may have an electrical back-up heating element.

The indoor unit then uses hot water to transfer the heat at the output of the heat exchanger into either a central heating buffer tank (3) or a DHW cylinder (7) using a controllable diverter valve. The buffer tank is used to store some heat before pumping it around the radiators (5) or under-floor heating (6) circuits.

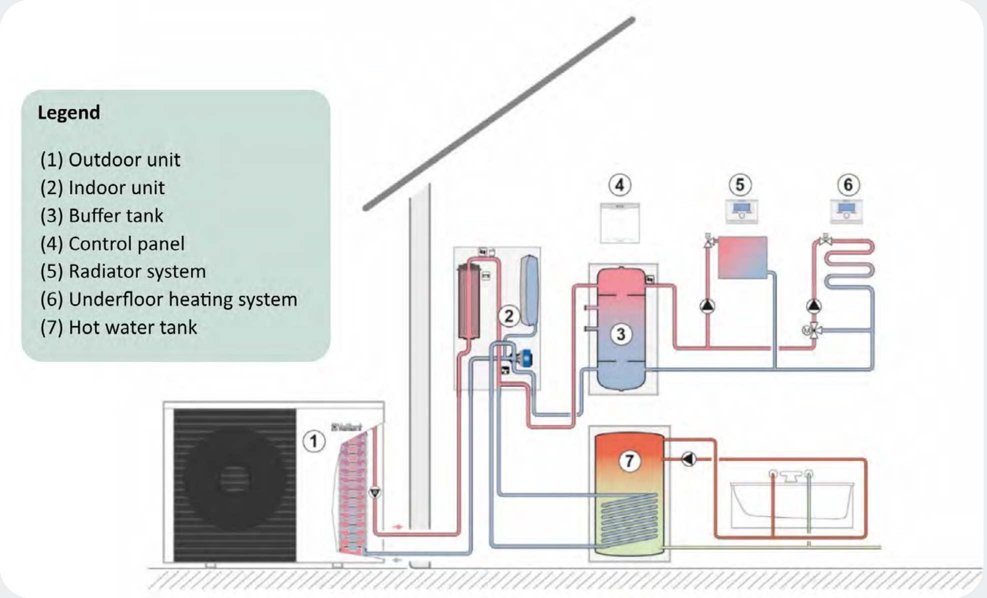


Figure 2 - Heat pump components

Note that this schematic shows all potential components - (2) and (3) are not always required.

Key differences between heat pumps & traditional boilers

One of the key differences when heating homes with heat pumps compared to gas boilers is the relatively lower water flow temperatures (typically 55°C). In a traditional boiler the output temperature of water can be as high as 75°C, which when pumped around radiators or underfloor heating means that consumers can feel the effect of this heat quickly.

Since heat pumps produce lower temperatures in the flow to radiators, radiators do not get as hot and so do not create the chimney effect that makes air flow circulate into the room. In addition, the heat transfer into the home is generally slower due to the relatively smaller temperature differential between the ambient air and the radiator temperature.

This means that heat pump based systems need to utilise correctly-sized radiators (with double panels) to radiate the same amount of heat energy from the heat pump system. Feeding the radiators with heat requires higher flow rates which normally means larger pipe sizes are needed. Some older homes may have larger pipes, but more modern buildings are built with 8-10mm microbore pipes which are more flexible to build with but have lower flow rates. As such, more modern homes may still need to replace both pipes and radiators (even though they are generally better insulated).

This is why heat pump based systems sometimes use underfloor heating in place of radiators on the ground floor, in effect using the concrete slab as a massive heat store. This can be installed in major renovation projects or new builds but is often impractical for retrofit projects.

Buffer tanks for flexibility

Flexibility requires the ability to store energy for later use. In a simple model, a battery can store energy – so it can be charged up when there is surplus energy on the grid and discharged when the grid is under stress.

Well-insulated hot water tanks also store heat energy much like a battery and can be pre-heated to a higher temperature when there is low demand on the grid.

In the UK, these buffer tanks are typically relatively small in size (45 Litres), but it is possible to fit larger buffer tanks to provide extra thermal storage which would provide some level of flexibility.

In continental Europe, large buffer tanks (up to 500 Litres) are often installed, but in the UK (largely due to lack of space) are not commonplace.

Table 1 shows the amount of energy that can be stored in a hot water tank based on its size (assuming that the water is heated to 60°C).

Thermal storage solutions using phase-change materials are another option, which due to their relative smaller size are sometimes a more attractive solution. On average these store three times more energy than an equivalent sized cylinder.

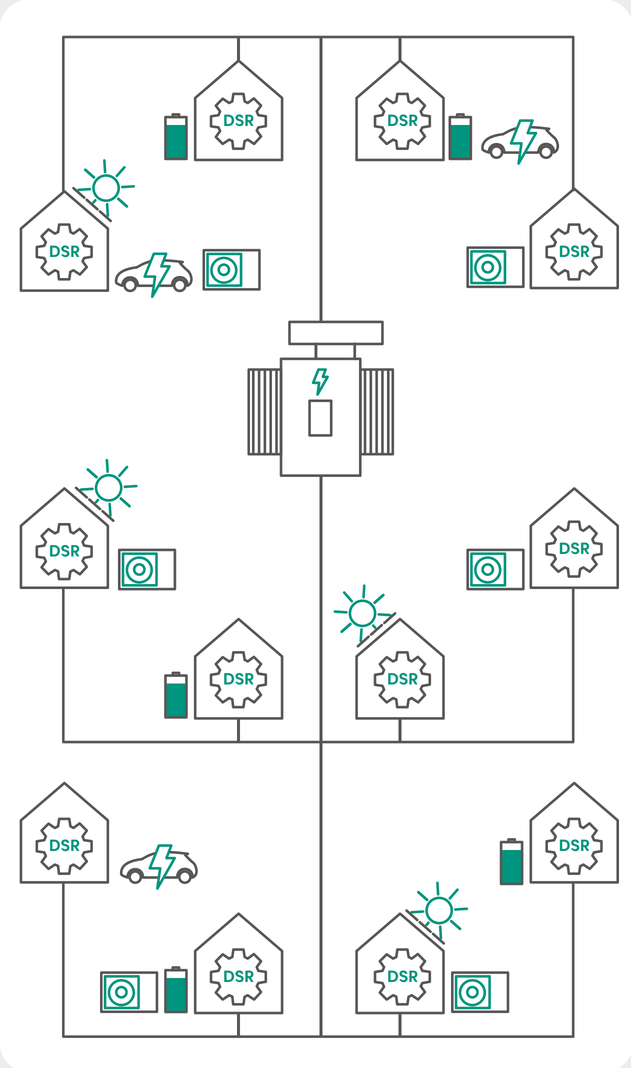
Tank size (Litres)	Temp. Incoming Cold (°C)	Temp. Hot (°C)	Temp. Difference (°C)	Stored Energy (kWh)
45	15	60	45	2.35
80	15	60	45	4.18
100	15	60	45	5.23
150	15	60	45	7.85
200	15	60	45	10.46
250	15	60	45	13.08
300	15	60	45	15.69

Table 1 - Impact of buffer tank size to stored energy

Domestic hot water energy storage

Older hot water cylinders do not have suitably sized coils to transfer the heat (at lower flow temperatures), and it is typical that in 80% of retrofit heat pump installations, the DHW cylinders will need to be replaced with newer heat pump ready designs which include larger coils.

Heat pump flexibility benefits the grid with thermal storage



Variable heat output using variable speed heat pumps

DSR aggregators would be able to pool many thousands of homes to relieve pressure on the grid if, rather than just cutting the power to the heat pump, they were intelligently controlled using IP networking protocols to adjust the heat output modulation level that is available in variable speed compressor systems.

A 5kW thermal rated heat pump operating with a COP of 3.0, when operating at 100% heat output, would consume 5/3 = 1.6kW of electricity. Asking the heat pump to drop its power to 20% for a short period of a few minutes would see a net electrical power reduction of 1.3kW.

By requesting a temporary drop in power from 100 to 20% output spread over 10,000 homes, represents a reduction of 13MW of power demand.

If the heat pump power is not restored at some point, the heat losses in the home would eventually mean that the home cools down to a point where the consumer feels uncomfortable.

The calculations to determine how long a heat pump can be turned down for are subject to heat losses and thermal storage capacity. This is examined in more depth in later in this paper.

In reality, most heat pumps will not be operating at 100% all of the time (once the home has reached the set point temperature). The heat pump will back off to circa 50% output, and so the potential savings by dropping from 50% to 20% may be smaller in reality.

The variable power is more likely to be useful to ask the heat pump to increase output power (say from 50% to 100%) in the hours before the peak time, enabling heat to be stored in the building mass itself, or in buffer tanks or thermal storage.

If there is sufficient thermal storage, then the heat pump could potentially be switched off completely during peak periods on the grid for 1-2 hours. This could help alleviate the stress caused by installation of new heat pumps on the older stock of LV transformers.

Thermal models

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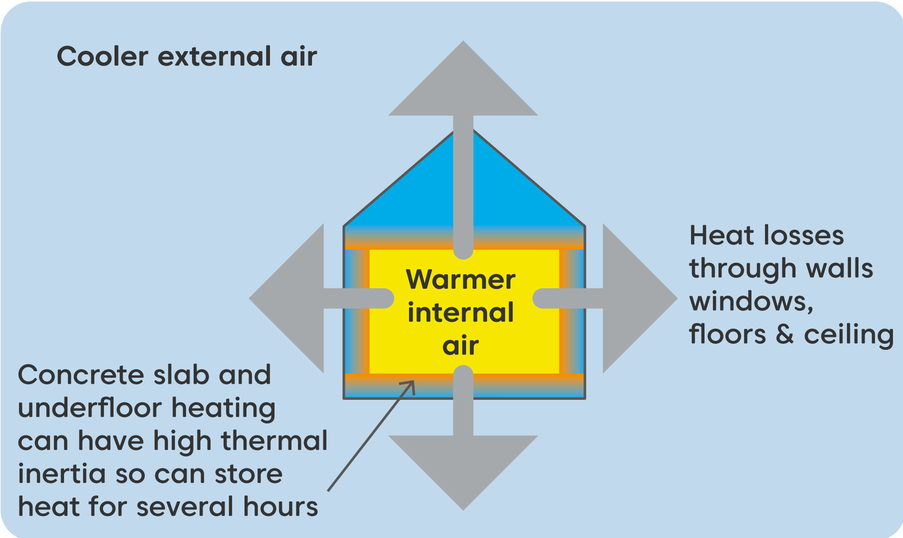

Figure 3 - Understanding heat losses in a building

Modelling the thermal behaviour of a building is complex as there are many variables to consider, but it can be broken down into two key elements:

1. Net heat losses.
2. Stored thermal energy.

Heat loss equations

The heat flow through a building is a function of heat input from the heat source, less the heat lost through the building fabric and draughts.

The external building fabric and internal structures act as barriers or insulators which have different heat transfer rates.

Different building materials will have different thermal conductivity values. By knowing the thickness and material type we can calculate the material's U-value.

Finally, by knowing the area of each wall and by calculating the temperature difference between the inside and outside of the walls, we can compute the heat loss in Watts.

Stored thermal energy in the building's thermal mass

It is also necessary to consider the thermal mass of the property for example in the wood, insulation, bricks, stones and concrete used in its construction.

Buildings with a high thermal mass will take longer to heat up, but will also retain their heat for longer.

Older homes typically have higher thermal mass than their more modern counterparts.

Heat loss calculation in Watts

As a worked example, it is possible to build a simple model of a home as a 3D box, which has specific floor, walls and ceiling areas.

This 3D box may then have doors and windows added to it. All of the components (wall, floor, ceiling, doors and windows) will have some 'U-value' that can be used in our simple model.

In our model, we can then assume a simple temperature difference between the external ambient air and the internal temperature. If the outside temperature is 0°C and the internal temperature is 20°C, that equates to 20°C difference.

If we model a 2-storey home which we assume is 5m high, and 6m x 6m floor area, we can calculate the total exterior wall area (less windows and doors which we will assume is 25m^2) as 95m^2.

We can also calculate the ceiling area and floor area are 36m^2 (note we ignore the pitched roof loft area since we assume that is uninsulated to the outside).

Using the typical U-values from a 1970's home[7], we can see that with a 20°C temperature difference that the heat losses are around 7.38kW.

	Area (m^2)	U-value (W/ m^{2}K)	Temp difference (K)	Heat Loss (W)
Walls	95	1.6	20	3040
Ceiling	36	1.5	20	1080
Floor	36	1.2	20	864
Doors & Windows	25	4.8	20	2400
			TOTAL	**7384**

Table 2 -Heat loss model for 1970's (unmodified home)

Contrast this with a home built more recently to 2010 building regulations. This has much lower (better) U-values which would only have 1.87kW heat-losses:

	Area (m^2)	U-value (W/ m^{2}K)	Temp difference (K)	Heat Loss (W)
Walls	95	0.3	20	570
Ceiling	36	0.2	20	144
Floor	36	0.22	20	158
Doors & Windows	25	2	20	1000
			TOTAL	**1872**

Table 3 - Heat loss model for 2010's home

Heat loss = U-value x Area x Temperature difference

This difference in U-values clearly shows the need to try to bring older properties up to date with good thermal insulation before fitting a heat pump.

Calculating the electrical load

Gas boilers can produce more than 25kW of instantaneous heat so can heat homes quickly (and then switch off), in comparison to a heat pump which may only provide 7kW of heat output (and so need to stay on for longer).

The calculation shows that to maintain the temperature difference of 20°C, a 1970's home would need a heat pump continuously outputting around 7.38kW of heat energy. If the temperature difference increased, then more heat input would be needed.

Since the external temperature also impacts the heat pump efficiency, when the outside temperature is at 0°C the heat pump may be operating with a COP of 4.0; meaning that the electrical power needed would be 7.38kW/4.0 = 1.85kW to maintain the home temperature.

In order to increase the temperature, for example if the consumer increased their set point by 1°C, then it would need even more heating power input and therefore more electrical power.

Ventilation heat loss

Buildings also lose heat through ventilation heat losses. If we consider our previous house example of 6m x 6m x 5m height, then the volume of air in the home is 180m^3.

Depending on air-tightness (older buildings tend to be more draughty, partly due to chimneys) then there will be more air-changes per hour.

Building category	Description	Air changes per hour
Category A	Older building (pre-2000)	2.0
Category B	Modern building (2000 or later) with double glazing and regulatory minimum insulation	1.5
Category C	New building (after 2006) complying to all current building regulations	0.5

Table 4 - Air changes per hour by building category

The air has a specific heat capacity and density so will absorb some heat.

We can calculate these heat losses using the number of air changes per hour and air temperature difference using the Standard Assessment Procedure (SAP) formula:

Heat loss = 0.33 x number of air-changes x volume x temperature difference.

Therefore the ventilation heat loss for a Category A home is:

Heat loss = 0.33 x 2.0 x 180 x (20 - 0) = 2376W

This means that in addition to the heat losses from the building fabric, there is an additional 2376W loss from air ventilation.

The heat pump in the 1970's home (Category A) therefore needs to produce 7384 + 2376W = 9760W to maintain the temperature.

It is vitally important to draught-proof homes as well as insulate them, but in doing so may cause ventilation issues (such as mould, damp and condensation).

To help combat ventilation heat loss, whilst maintaining air quality, homes can be fitted with Mechanical Ventilation Heat Recovery (MVHR) solutions that use heat exchangers to extract the heat from the stale air before it is expelled from the house and transfer this extracted heat back into the fresh incoming air as it enters the property.

Other sources of heat gain

Whilst the heating system is the principle source of heat in the home, other devices in the home will also generate heat.

Cookers, dishwashers, washing machines, electrical appliances, hot water, lighting as well as humans all produce heat, and can help to maintain the background temperature in a well-insulated home.

The energy in hot water used in showers, washing machines and dishwashers will tend to escape down the drain unless waste water heat recovery units are installed.

Smart metering data can help to understand where additional energy gains are coming from.

In the future, it will be increasingly important to provide consumers and heat pump installers with a heat pump readiness indicator using data collected from smart thermostats and smart metering. Similar studies have been performed in the UK BEIS SMETER project.

The data from smart thermostats and smart meters can assist in planning the necessary insulation and draught-proofing improvements that may be needed before installing a heat pump. They may also provide a means to financiers to understand which improvements offer best value to homeowners.

Thermal mass

The building itself will also have thermal mass which will depend on the materials used.

For example, a brick-built home will have a higher thermal mass than one built from wood. Similarly concrete has a higher thermal mass than brick. This means that homes with a concrete floor that has good insulation between the slab and the ground can absorb and store heat, releasing it back into the home for several hours after the heating has been switched off.

It should also be noted that during summer months, underfloor heating is likely to be off and as a result, less thermal energy will be stored than in winter months.

In summer the home is heated using solar gain (not via the heat pump), so the heat energy may not get absorbed into the concrete slab, and so will cool down more quickly once the sun goes down.

Thermal battery

The thermal mass of the home allows it to store energy, so the larger the thermal mass, the more energy can be stored. The home can therefore be thought of as a thermal battery which can be charged up, and which will discharge over time.

The higher the thermal mass, the more thermal energy the building can store.

The energy consumption national statistics show more modern buildings have a lower thermal mass due to the differences in construction materials[9].

Consider an older style home which has a wall made with 200mm brick and 13mm 'wet' plaster. This may have a poor (high) U-value of $2W/m^2K$, but a relatively high thermal mass of $169kJ/m^2K$.

In contrast a newer home with 100mm brick, 150mm mineral wool-filled cavity, 100mm aerated concrete block and 13mm plasterboard dry lining on 10mm dabs will have a (good) low U-value of $0.19W/m^2K$ but a poor thermal mass of just $9kJ/m^2K$.

Improving thermal mass in modern building construction

Changing the dry-lining to 13mm 'wet' plaster can increase the thermal mass to $60kJ/m^2K$, without impacting the U-value.

Increasing thermal mass can help slow down cooling in winter, but also helps to avoid overheating homes in summer, creating DSR flexibility for air conditioning as well as heat pumps.

DSR Scenarios

Substation sizing & impact on the local electrical grid

Substation diversity factors

DNOs use diversity factors to calculate a 'After Diversity Maximum Demand' (ADMD) per home so that they can determine the required substation capacity.

This ADMD figure is then multiplied by the number of homes to enable the DNO to choose the appropriately sized substation for those homes.

The diversity factors take into account that not every heating element, washing machine etc. is switched on at the same time in every home.

For a typical 3 bedroom gas heated home it is assumed that maximum (peak) demand after diversity is taken into account is approximately 1.7kW.

Electrically heated homes (using direct electric heating) assume that the heating appliances cycle on/off, so on average they collectively may have an average maximum power demand of 20% of the total maximum heating load from all panel heaters.

For example, 5 x 2kW direct electric heating panels would potentially need 10kW instantaneous power (if they were all on concurrently), but once at set point they would start to switch off and on at different times.

With a 20% diversity factor, this would mean that the average peak load from all of the electric panels would be 20% of the 10kW potential peak load = 2kW. This would be added to the baseline 1.7kW.

3 bed-room property	Baseline peak load (ADMD)	Additional electric heating load (coincidence x power)	Total ADMD
Gas heated home	1.7kW	0	1.7kW
Direct Electric heating	1.7kW	0.2 x total heating (e.g. 5 panels @2kW = 10kW)	(+2kW) 3.7kW
Heat pump heating	1.7kW	1.0 x 50% of HP electri-cal power (1.8kW)	(+1.8kW) 3.5kW

Table 5 - 'After Diversity Maximum Demand' per home

However for lighting and heat pumps, DNOs assume that all devices are on simultaneously, since a heat pump may be constantly operating, in all of the neighbouring properties.

Consumers are also likely to ditch their gas hob and switch to electric induction hobs, further increasing the ADMD figure.

In their sizing calculations DNOs assume 50% of the electrical load of the heat pump.

For example, a 11kW heat output heat pump running (with COP 3.0) requires a peak electrical load of 11/3 = 3.6kW. The DNO would assume 50% of this (1.8kW) in its ADMD figure.

This can more than double the 'After Diversity Maximum Demand' (ADMD) for the home which was previously gas heated to (1.7 + 1.8) = 3.5kW.

Substation modelling results

In our modelling, we used the baseline ADMD figure of 1.7kW (for gas or oil heated homes) applied to 250 homes. Our spreadsheet model can be easily adapted for a different number of homes, and appropriately sized substation transformer.

This results in a peak load (see Figure 4) on the transformer of 425 kVA, which for a 500kVA transformer represents 85% of its capacity. This means there is a 15% (75 kVA) head room left for growth or unusual peak demand.

If these existing homes were retrofitted with a 11kW heat pump, then potentially each additional home will add 11kW (heat) with a COP 3.0 = 3.6kW peak electrical load. Assuming this is running at 50% (1.7kW), It only takes 43 homes out of the 250 homes (19%) to consume the 75kVA head room.

If 15kW heat pumps were fitted, then it only takes 30 homes of the 250 homes (12%) to use up the 75kVA head room.

We used this model to examine the potential impact DSR could have if heat pumps could draw power from the grid or solar PV earlier in the afternoon, in order to reduce the peak load in the 4-7pm window.

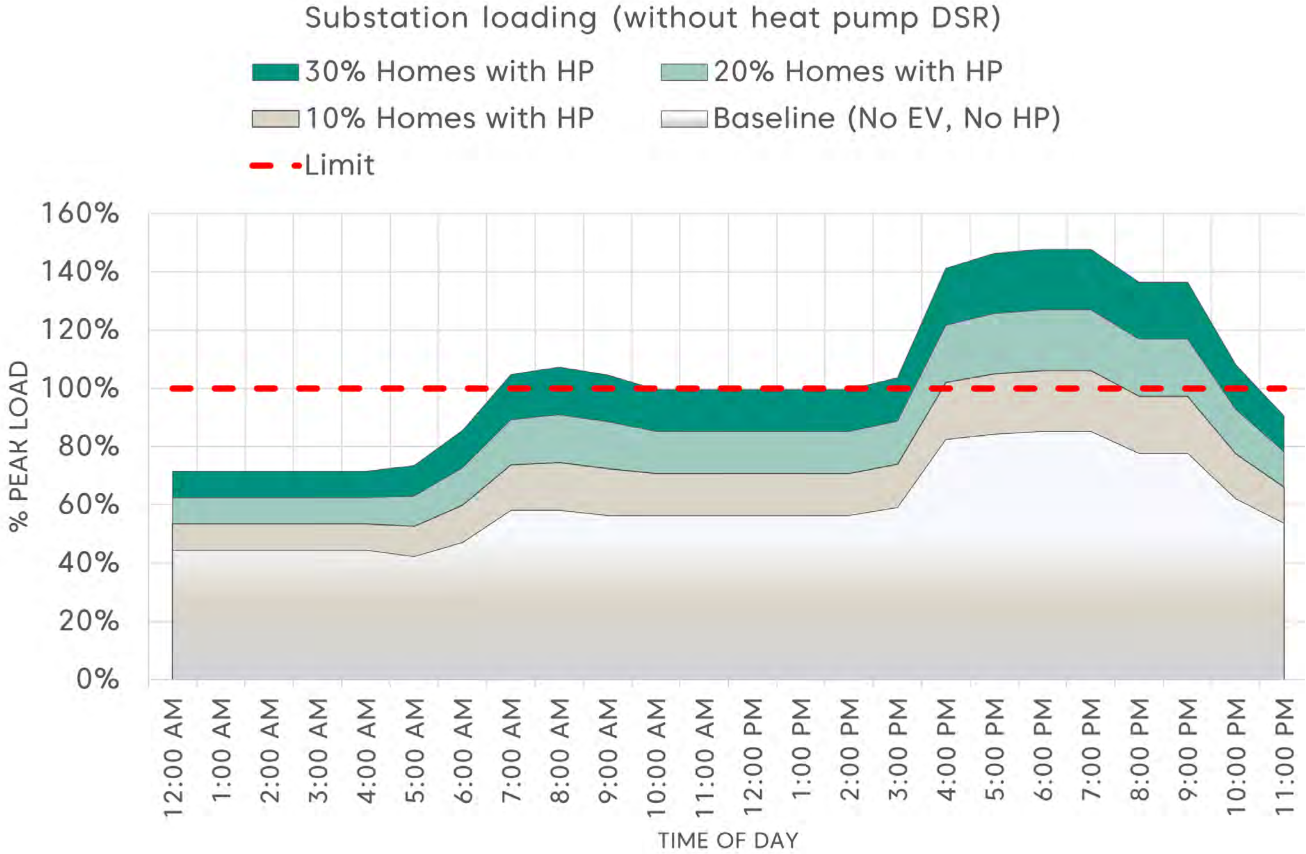

Figure 4 - Our substation transformer modelling results

Peak time load limiting to avoid impact on LV networks

Whilst substation transformers can be replaced with larger ones, there are nearly 500,000 in the UK and each replacement would be a complex, disruptive and expensive task.

In addition to the substations themselves, the feeder cables that connect the substations to homes they serve can also become overloaded.

Replacing low voltage feeder cables with higher rated ones will be very expensive and disruptive especially where roads and pavements need to be dug up.

Something must be done when more and more existing homes have heat pumps added to them.

DNOs will either need to perform extensive infrastructure updates or somehow manage the peak load used by homes with smart technology and storage, or will not allow consumers to have a heat pump fitted which contradicts the UK Government's stated objective.

In the next section, we examine how the peak electrical load of homes fitted with heat pumps can potentially be kept to the same levels as current gas heats homes to avoid LV network grid reinforcement spending.

Exploiting comfort tolerance & pre-heating homes

Exploiting comfort tolerance

When using thermostats, people can accept a small degree of comfort tolerance before they actively notice they feel too hot or too cold. Indeed, traditional thermostats may have a hysteresis built into them of 1°C or more.

If we can exploit this human tolerance to comfort, then it should be possible to turn off the heating and people may not notice it.

There are degrees of comfort error where someone

- cannot perceive being too hot or too cold
- may notice that the room feels cold but accept it without doing anything or
- do notice that they are cold and then override the setting (e.g. cancelling any DSR service)

These levels have been explored in other DSR services (e.g. Google Nest's Rush Hour rewards in the US which controls air conditioning). As the temperature error increased (say to 3°C) consumers were fairly likely to override the DSR event, but at lower temperature differences (e.g. 1.5°C) consumers were prepared to accept it or did not even notice.

Pre-heating homes or storage

It is often suggested that you can pre-heat the home during cheap low-cost electricity overnight so that the home may be warm for the morning when people first get up.

Consumers may be more sensitive to overheating during the night which could disrupt sleep patterns if they are too warm.

To be energy efficient it makes sense not to heat homes when no-one is at home.

With a gas boiler, the home internal temperature may drop to around 16°C in the afternoon (after several hours of being switched off). Prior to the consumers returning at 5:30pm the gas boiler quickly reheats the home back up to 20°C.

> "Overheating the home would be inefficient and would use more energy"

With a heat pump, the lower flow temperatures in the radiators means it makes more sense to keep the building warmer. The heat pump's heat output is lower than a gas boiler and so it will take longer to bring the home temperature back up to 20°C.

It seems logical to keep heat pumps running during the afternoon daylight hours to take advantage of the renewable solar power and avoid homes needing a lot of power from the grid to bring the temperature up quickly as people return home in the early evening.

It is sometimes suggested that overheating the home to 23°C when no-one is at home and letting it cool down to the desired set point of 20°C makes sense, using excess renewable power to overheat the building fabric itself.

Whilst this may seem a good idea, it is important to consider better places to store that energy and not to overheat the home itself (but instead store the heat in a well insulated tank or thermal store). Overheating the home would typically be inefficient and would use more energy.

It may make more sense to store the excess energy into an electrical battery, and use that to power the heat pump and other appliances later.

As we saw in the previous section, heat losses are directly proportional to the temperature difference between inside and outside. Overheating homes will result in the heat being lost at a faster rate - using more energy and potentially costing the consumer more in their bills.

The importance of storage (thermal or electrical battery)

Thermal storage

It makes sense to use excess renewable energy at cheap times in the afternoon to store heat energy in well-insulated thermal storage of some form (either phase-change material or water in a buffer tank or hot water cylinder).

This stored heat can then be extracted during peak times to reduce the electrical load of heat pumps on the grid.

Consider a 7kW heat pump nominally uses 2.3kW of electricity (assuming COP = 3.0).

The heat pump compressor could be switched off entirely, during peak times, just leaving the circulation pump active (60W). The house then keeps warm by extracting heat from the thermal storage.

This would save approx 2.2kW of load on the substation.

Whilst this seems like a relatively small amount of power, if 100 homes on the same substation transformer had reduced the load by an equal amount that adds up to 220kW.

As outlined above, the substation sizing After Diversity Maximum Demand (ADMD) values would be brought back to a gas heated home if these solutions were used.

Our proposal

Heat pump installers and homeowners should be incentivised to fit larger buffer tanks, or other thermal storage systems, which can store several kWh of heat (sufficient for 2-3hrs of typical heat losses).

This would allow heat pumps to pre-charge the thermal storage during off-peak, low carbon periods with power from excess renewables.

The heat pumps can then be switched off during the peak periods (4-7pm) and then the heat energy is extracted from the thermal storage using a low power circulation pump.

There may be some practical challenges to overcome in retrofitting to existing homes.

1. Space needed for large buffer tanks.
2. Weight of water in loft spaces may require structural strengthening of joists.

Alternative solutions

Battery electric storage could be used to offset peak load with additional benefits.

1. 1 kWh of electric storage would allow 3-4 times the heat equivalent thermal storage (based on the heat pump's COP).
2. The electric battery can power other appliances (such as cookers and washing machines) during peak times and can export power to other local homes.
3. Home batteries can often be wall-mounted and take up less space than thermal storage. Alternatively Vehicle-2-Grid / Vehicle-2-Home solutions may provide this capability.

Example #1 - DSR turn-down event on a winter's day

What happens if we try to turn off a heat pump from 4pm-6pm?

Some assumptions used in our model:

- The home was heated up by the heat pump using renewable cheap electricity in the early afternoon (from 2-4pm).
- It is a cold mid-winter day with an external temperature of 0°C (this was chosen as an extreme to show when the grid is under stress).
- The home is now at 20°C (the consumer's desired set point temperature).

Our simulations were performed for 3 different house types, which were 3 bedroom semi-detached:

- Home A (1970's home) which has not been updated with insulation.
- Home B (1970's home) which has been updated to modern draught-proofing and insulation.
- Home C (2010 home) built to building regulation standards.

Table 6 shows the simulation results. We looked to see how quickly different homes would cool down if the heat pump was turned off completely (i.e. no net heat input).

It should be noted that our model assumed a simple box model, without any internal walls, furniture, people or other appliances. As such it may be pessimistic in its results, since the internal walls and furniture would increase the thermal mass, and also help to reduce the heat losses to the outside of the building.

The people and other home appliances, such as cooker, washing machines, kettles etc. would also create some heat input inside the home, however these heat sources are likely to be a fraction of the heat losses in the category A & B homes, but are more relevant in the better insulated category C home.

Table 6 below shows the heat loss in Watts for each home type (when taking in both the loss through air-change ventilation and thermal conduction through the walls, floors, windows, doors and ceilings). A 1970s home that has not been appropriately updated in its insulation and draught-proofing loses a lot of heat (19kW). This serves to illustrate the importance of insulating older homes. In practise this type of home would be unsuitable for a heat pump, but it is included as a reference.

Home B is more typical of a retrofit home and even though it is better insulated, it still loses heat at 10kW in this scenario, taking 40 minutes to cool down by 1°C.

Home type	U-values (W/ m2K)	Kappa (W/mK)	Total Heat loss to external & through ventilation (20°C delta)	Time taken for temperature to drop 1°C	Time taken for temperature to drop 1.5°C
A - 1970's home (not updated)	Ext. walls: 1.6, Ceiling: 1.5, Floor: 1.2, Doors & windows: 4.8	Ext. walls: 190, Ceiling: 9, Floor: 110	19017W (Heat flow losses: 15202W Air ventilation losses: 3815W)	1300 seconds (21 minutes)	2000 seconds (33 minutes)
B - 1970's home (updated insulation)	Ext. walls: 0.5, Ceiling: 0.2, Floor: 0.8, Doors & Windows: 1.8	Ext. walls: 190, Ceiling: 9, Floor: 110	10089W (Heat flow losses: 7228W Air ventilation losses: 2861W)	2450 seconds (40 minutes)	3700 seconds (1 hr 1 min)
C - 2010's building standard	Ext. walls: 0.3, Ceiling: 0.2, Floor: 0.22, Doors & Windows: 2	Ext. walls: 60, Ceiling: 9, Floor: 110	2837W (Heat flow losses: 1883W Air ventilation losses: 954W)	4000 seconds (1 hr 6 mins)	6100 seconds (1 hr 41 mins)

Table 6 - Heat loss timing results

Example #1 - DSR turn down event on a winter's day

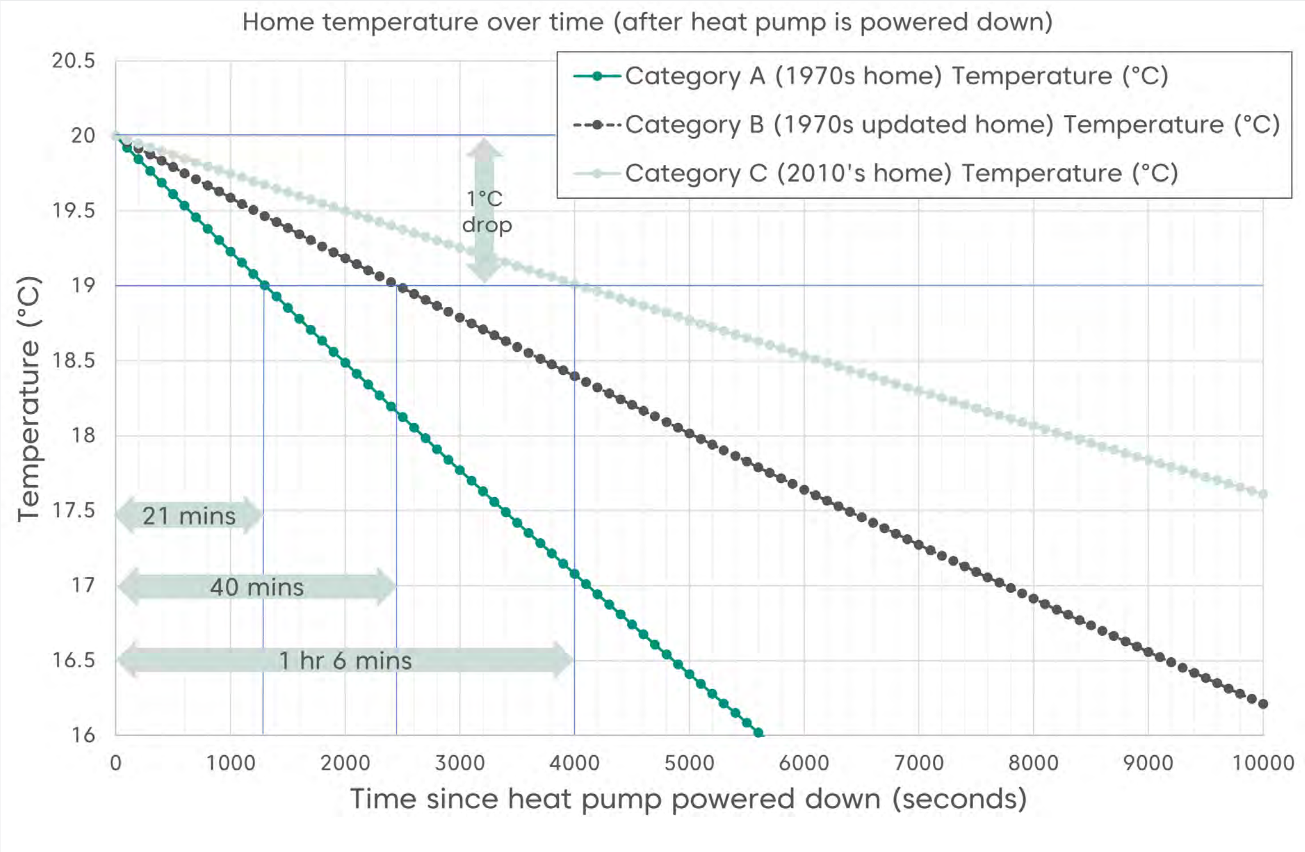

Figure 5 - Heat loss results for different home types

Figure 5 shows raw data points from the scenarios simulated on the previous page (i.e. 0°C external temperature with heating fully off once it has reached the set point temperature of 20°C). It shows the decay curve of each home type as it loses heat over time as a result of the building thermal mass and based on the insulation and air ventilation losses.

The category B home (1970s with updated insulation) has heat losses of over 10kW (for 20°C temperature difference). This implies that in order to maintain the temperature the heat pump needs to produce 10kW of heat output.

However, in order to raise the temperature on cold days it needs a heat pump which produces more than 10kW to allow the home to warm up. As such this home may require a 15kW heat pump in order to do this.

The category C home (2010s built home), however, has a net heat loss of 2.8kW, and takes just over 1hr to cool down by 1°C. This home could be fitted with a smaller 5kW heat pump.

Electrical load savings

Considering home B has a 15kW heat pump, once it has reached the 20°C set point, it would be operating at 10kW (66% heat output) to maintain the temperature. Assuming COP 3.0, this would require approximately 3.3kW of electricity.

In order to maintain the home temperature, the heat pump in home C would need to output 2.8kW of heat (56% heat output), which would require 0.93kW of electricity.

A DSR event on the grid starts at 4pm and requests the heat pump use minimum power (for example 20%). Note that heat pumps typically cannot be switched fully off immediately, but can be commanded to reduce power within a few seconds.

Example #1 - DSR turn down event on a winter's day

In home B, the electrical load drops to:

20% x 15kW (heat) / 3.0 (COP) = 1.0kW

(a saving of 2.3kW)

This could potentially be maintained for at least 40 minutes before the home temperature drops by a degree (a total of 1.5kWh).

In home C, the electrical load drops to:

20% x 5kW (heat) / 3.0 (COP) = 0.33kW

(a saving of 0.6kW)

This could potentially be maintained for at least 1 hour and 6 minutes before the home temperature drops by a degree (a total of 0.66kWh).

We can observe that home B can reduce its electrical power significantly more than home C, but the period over which it can do this is much shorter.

Home B also appears to be able to save more energy, but as we shall see, this energy must eventually be recovered again to bring the home back up to temperature.

What happens at the end of the DSR event?

When the DSR event comes to an end, the home will be cooler than it was before.

It is likely that the outside air temperature may drop further after the sun has gone down, which may reduce the COP, and will also increase the temperature difference (and therefore heat losses).

In order to raise the home temperature back up to the desired 20°C the heat pump will need to increase its output above the previous levels in recovery mode.

For home C, assuming it powers up to 80% this would cause an increase in electric load to 1.3kW (an increase of 0.4kW above the level it was operating before the DSR event).

For home B, since the home has much higher heat losses than home C, it may need to apply 100% heat output to bring the temperature back up within a suitable period. This would require 5kW (an increase of 1.7kW above the level it was operating at before the DSR event).

As we discuss in Paper 1, care must be taken to ensure that DSR events which impact multiple homes on the same substation do not coincide, or else at the end of the event all heat pumps will go into a higher power recovery state simultaneously.

If multiple heat pump heated homes are simultaneously put into heat recover mode, then DSR events may remove the natural diversity factors and actually cause overload situations on the substation transformers if care is not taken to avoid this.

This scenario may also occur if there has been a power cut and when power is restored it may also lead to the same situation. Heat pumps should therefore self-limit their power intake after power is restored. Ultimately, a DNO imposed peak power limitation may be needed after power cuts to bring home temperatures back up gradually, to avoid tripping out the substations repeatedly.

This DSR strategy to reduce electricity load at peak times, by powering down the heat pumps and then powering them back up again later, only has very short-term benefits, with limited amounts of flexibility, likely worse efficiency, and the potential to overload the local networks at the end of the DSR event.

Example #2 - DSR turn up event on a winter's day (thermal storage)

DSR turn up on a winter's day with thermal storage (Home C)

In this scenario:

- It is a cold (0°C), clear sunny day.
- The consumer has solar PV capable of generating 2kW of electrical power.
- The home has a large 200L heating buffer tank as well as a 150L hot water cylinder.
- During the daylight hours the solar panels are generating 2kW of power (for 5 hours from 10am-3pm).
- The house is empty most of the day (the owners are at work), and the electrical base load when the house is empty is 400W (excluding the heat pump).
- The heating does not need to be on during the day when the house is unoccupied.
- The consumers expect the home to be 20°C by the time they arrive home at 5:30pm with a hot water tank heated to 60°C for evening showers.

Calculations

In Figure 6, home C has a 5kW heat pump. As in example 1, the heat losses are around 2.8kW for a 20°C internal to external temperature difference. The home energy management system has determined that it is acceptable to allow the temperature to drop to 18°C when unoccupied.

Due to its better insulation, it takes nearly 2.5 hours to cool down to 18°C (without any heat being sent to the radiators).

The HEMS will ensure that the temperature is brought back to 20°C before 4pm so that after the sun has set the heat pump can be powered off and avoid any excessive import from the grid.

The solar PV would normally export 1.6kW of electricity, so the HEMS switches on the heat pump to consume this excess. This results in a 100% heat output (COP 3.0 = 4.8kW heat).

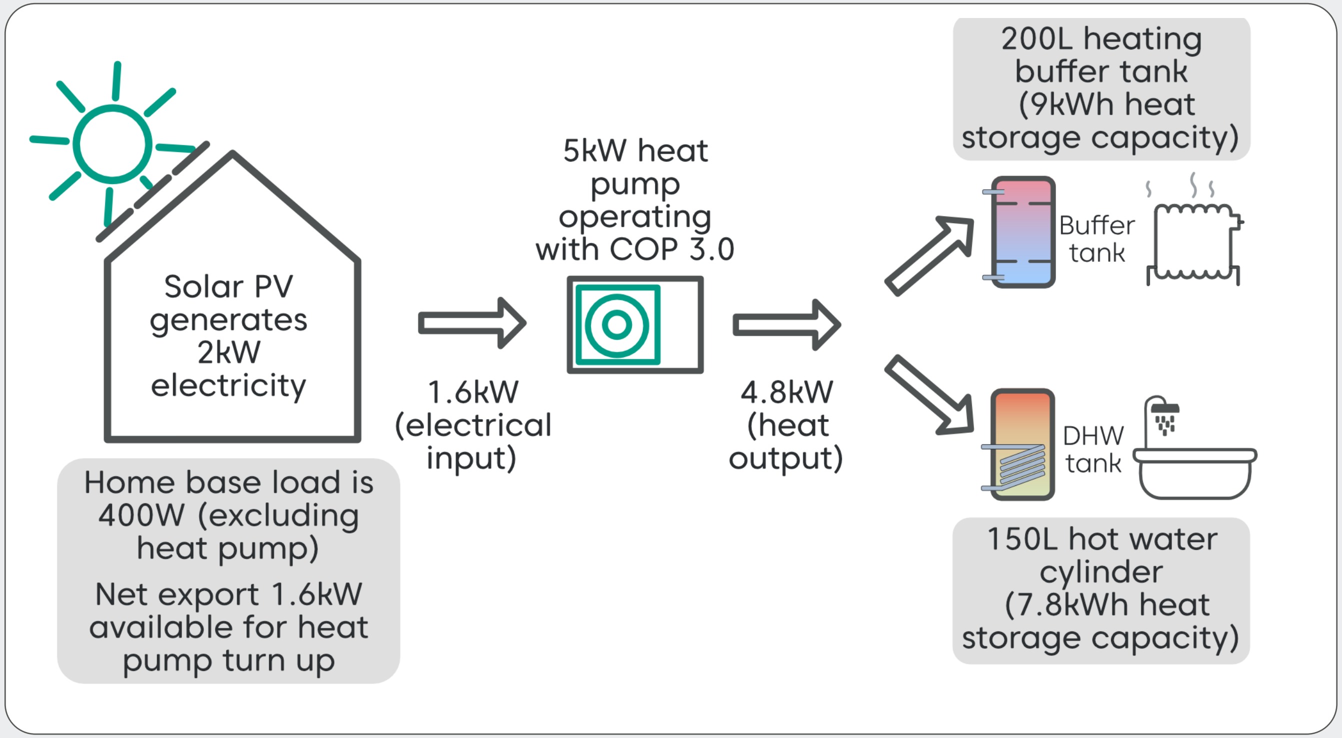

Figure 6 - DSR turn up with solar and heat pump (Home C)

Example #2 - DSR turn up event on a winter's day (thermal storage)

The 150L hot water cylinder can store approximately 7.8kWh of heat at 60°C (see Table 1). The 200L buffer tank can store approximately 9kWh of heat at 55°C.

Assuming the solar PV continues to generate 2kW (electricity) for 5 hours, then the excess 1.6kW x 5hrs = 8kWh of electricity for the heat pump. Assuming that the heat pump is operating with a COP of 3.0, it generates a total of 24kWh of heat energy.

During the first 3.5 hours, the heat pump's 4.8kW of heat output (16.8kWh) is transferred and stored in the buffer tank and hot water cylinders. Both vessels are fully heated by the end of this period.

In the next 2 hours (with solar PV), the heating flow pump needs to be switched back on, to transfer some of the heat back into the building and to start to raise the home temperature back towards 20°C.

At 3pm the solar PV power output starts to drop, and the heat pumps output is correspondingly reduced to ensure there is no net import from the grid. The consumer could accept that the home is over heated slightly, so the excess solar PV may cause the home to reach 21°C by sunset.

By 4pm, the heat pump compressor is switched off to reduce load on the grid, however the heating flow pump is kept on for several hours to keep the radiators fed with warm water until the buffer tank temperature drops. Since the heating buffer tank holds approximately 9kWh of heat, then this should allow the home (losing heat at 2.8kW) to remain at 20°C for over 3 hours (6:30pm).

This has removed the load on the grid from the heat pump, just leaving the relatively low heating flow pump running (60W).

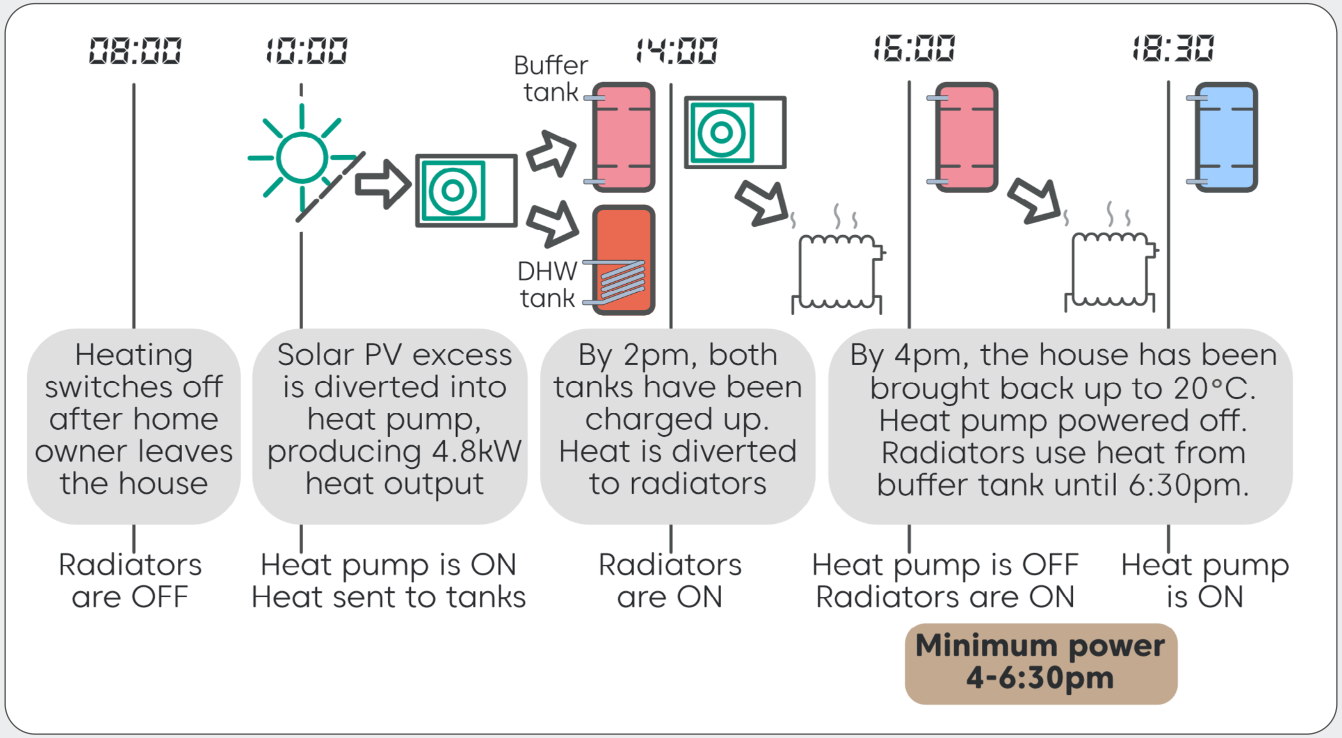

Figure 7 - Timeline for DSR turn up with solar and heat pump (Home C)

This DSR strategy could also be used for homes without their own solar panels, by using energy during the day from the grid. The grid would need to incentivise homeowners via a HEMS to do this automatically.

Example #2 - DSR turn up event on a winter's day (thermal storage)

DSR turn up on a winter's day with thermal storage (Home B)

We assume the same scenario as before but for home B:

- The home has a 15kW heat pump.
- The heat losses are 10kW (for a 20°C temperature difference).
- This home will cool from 20°C to 18°C in 1 hour 23 minutes when the radiators are off.

This home has the same amount of solar PV excess (1.6kW) for 5 hours.

- Home B's solar excess (1.6kW) is converted into 4.8kW of heat output by the heat pump (24kWh of heat overall).
- The solar could heat the heating buffer tank (9kWh) and hot water cylinder (7.8kWh) using a total of 16.8kWh.

The higher heat losses in home B mean that to keep the home temperature at 18°C, the heat pump will need to output more than the heat losses (9.1kW when the temperature has fallen to 18°C), whilst not consuming its buffer store.

This would require importing some extra 3kW of electricity from the grid to make up the shortfall in solar PV during the day which is being used to charge the buffer tank and hot water cylinder.

Once the sun begins to go down (at 3pm), the heat pump will need to draw more power (potentially 100%) from the grid to bring the temperature up towards set point before the local grid starts to enter peak time (4:30pm).

DSR turn down at 4pm

Once in the peak 4-7pm period, the heat pump can reduce its power level to rely more on its heat stored in the buffer tank.

- With a buffer tank storing 9kWh of heat, and heat losses of 10kW, the buffer tank will last just under an hour (assuming the heat pump compressor is off).
- If there was no buffer, then the heat pump would use 3.3kW of electrical power.
- Assuming the buffer tank is drawn down over 3 hours, then the buffer provides 3kW and the heat pump needs to provide 7kW (a total of 10kW). This would require 2.3kW of electricity, A saving of 1kW on the grid.

The impact of having a heat pump retrofitted to the LV transformer cannot be completely offset at peak times due to the higher heat losses in home B. Ultimately the heat lost through the building fabric and ventilation should be reduced as much as possible.

The HEMS can determine the best course of action (e.g. keeping the home under a peak load limit) by dynamically reducing the heat pump output and using the buffer tank to maintain the heat flow into the radiators.

Example #3 - DSR turn up event on a winter's day (battery storage)

As we saw in example 2, home B's heat losses of 10kW would mean that a relatively large 200L buffer tank, storing 9kWh, would allow the heat pump to be switched off for about 54 minutes without a temperature drop.

A typical 200L buffer tank would be approximately 0.55m wide and 1.3m in height. While a 300L tank would be 2m tall, it could store up to 14kWh of 55°C heat, increasing the heat pump off-period to 1hour 24minutes.

Thermal storage using phase change materials, may offer a more compact means of storing heat energy. These can be 3-4 times smaller than an equivalent buffer tank.

In some homes it may not be possible to find the space for any additional buffer tank since existing homes may already have a hot water cylinder, but do not have space for an additional larger sized tank.

Battery storage has the benefit of higher energy density which is further multiplied by the COP efficiency of the heat pump.

Batteries, and in particular the battery inverters, also have a round-trip efficiency factor to contend with. Most battery inverters claim a one-way efficiency of around 95-97% best case, but at higher load levels this can drop to nearer 90%. As such, the charging and discharging round-trip can be as low as 80%. Most of the energy being given up as heat in the power transistors in the inverter.

If the battery and inverter are inside the home then the efficiency losses in the form of heat would act as a radiator, in turn helping to heat the home. Some manufacturers are designing attractive units which can be wall mounted inside the home. However if the battery inverter is placed into a garage, loft or outhouse then this heat is lost into the atmosphere.

A typical inverter in the UK is limited to generate around 3.6kW (due to grid code constraints and fuse ratings), some battery inverter manufacturers do provide 5kW devices. For larger heat pumps (15kW) the peak electrical load can be 5kW, so it may be feasible to couple a larger heat pump with a larger battery inverter. This would potentially enable the heat pump load to be almost offset at peak times.

The battery size is a function of usable capacity. It is common to see batteries available in 2.4kWh, 3.5kWh packs. Some vendors also offer Hybrid PV inverters (meaning the battery and PV inverters are combined into a single unit - which makes sense for homeowners also looking to get solar PV).

Additional packs can be connected to these systems in relative small units (0.4m x 0.4m x 0.1m) each weighing around 24kg.

As an example 4x 2.4kWh (9.6kWh) may only have 80% usable capacity (7.68kWh). The 7.68kWh battery (given a 90% discharge efficiency), would power a heat pump using 3.3kW of electricity (10kW heat output) for about 2 hours.

Batteries can also:

- Provide ability to supply other appliances in the home during peak times.
- Charge overnight at off-peak cheaper electricity tariffs or from solar PV during the day.
- Discharge to the grid if needed.

The main drawback with battery storage is the high initial outlay, and lifetime (15yrs), although the financial payback with solar PV is readily achievable within this time line.

We expect that whilst many homeowners may not opt for battery storage due to their cost, EVs may implicitly offer a similar bi-directional charging capability (vehicle-to-home) in a few years.

Summary

In this paper we have explored the thermal modelling of homes, in particular how the age of the property and the level of insulation and ventilation can lead to very different levels of heat losses.

In home B (1970s home updated with more modern insulation) is loses significantly more heat (10kW) compared to its 2010s counterpart (2.8kW) for the same winter scenario.

This means many of the 21 million homes that the Committee for Climate Change has recommended should have heat pumps retrofitted to, may require larger heat pumps, which in turn consume more electrical power from the grid.

Our modelling has shown that if between 10%-20% of homes which are currently gas or oil heated, are fitted with heat pumps, then they will likely push the existing substation transformers into overload.

Substations are only part of the issue however, feeder cables to homes would also need to be updated to carry more current.

We have examined possible alternatives using DSR technology and HEMS to control heat pumps to help reduce electrical load at peak times.

We examined the concept of pre-heating homes during the off peak periods, or even overheating homes, but noted that this is less efficient (since hotter homes lose heat faster) and will cost consumers more. Instead we proposed to store the extra heat into well insulated buffer tanks.

For newer 2010 homes, an additional buffer vessel could be fitted relatively cheaply (if space can be found in addition to the hot water tank). These homes could use cheaper electricity in the afternoon or from rooftop solar to power the heat pump and pre-charge the buffer tank. These buffer tanks can then keep the house at a stable temperature, without needing the heat pump operational, for around 3 hours.

The older style 1970s homes which have been updated with better insulation, lose heat more quickly, and so the use of larger buffer tanks become less effective, only allowing the heat pump to be kept off for less than an hour. This may help reduce peak demand on the grid, but will not meet the need to completely offset the heat pump's impact in peak periods.

Phase change material thermal storage may offer an alternative more compact solution, but these are a relatively new technology which are still to be proven.

Furthermore, we observed that when a heat pump has been switched off for a period of time and the home has cooled down, then it may enter a high power recovery mode. In this state, it will actually make things worse for the grid. Instead it would be better to leave the heat pumps alone and instead try to control the other appliances in the home.

Finally, we examined the use of home or vehicle-to-grid battery solutions. These appear to offer an attractive solution for the older 1970s homes with added heat pumps, given their relatively higher energy density, and the fact that they can, not only offset the heat pump, but also other appliances in the home and can even export power to the local grid to help the LV network transformers.

#1

When retrofitting heat pumps to older properties, the home needs be brought up to modern insulation standards

This saves energy, reducing carbon footprint and reduces household heating bills.

Better insulation and draught-proofing benefits any home, regardless of how it is heated.

#2

Thermal mass can be a benefit in flexibility

Newer properties tend to have lower thermal mass and house building regulations should be examined to increase thermal mass where possible.

It also helps to reduce summertime overheating in homes which is likely to become an increasing issue seen in the UK as climate changes take effect.

#3

LV transformers may become overloaded if more than 10%-20% of existing homes have heat pumps fitted to them

A heat pump can double the typical ADMD values compared to when it was heated by oil or gas.

Consumers are also likely to ditch their gas hob (to avoid paying a daily standing charge) replacing it with an electric hob.

#4

Thermal or battery storage can be used to reduce impact on local grid at peak times

Vehicle-to-grid (V2G) or home batteries may have advantages over thermal storage, especially if the home can also be fitted with solar PV.

Some form of storage is essential when a heat pump is added. We recommend that governments incentivise installation of storage solutions alongside heat pumps.

#5

Home energy management solutions are needed

A HEMS will be needed to optimise and limit the electrical power load at peak times.

These will need to communicate using standard protocols to various energy devices in homes, and can save cost and reduce carbon emissions automatically.

#6

Homes have different thermal properties which can be time consuming and error prone to calculate

Smart metering coupled with smart thermostats can help calculate real EPC ratings for existing properties.

These digital data assets can be used to target homes which may need better insulation, or can be used to estimate heat pump sizing based on observed historical data for a specific property.

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Glossary

ADMD	After Diversity Max Demand
BESS	Battery Energy Storage System
BUS	Boiler Upgrade Scheme
CAD	Consumer Access Device
CEM	Customer Energy Manager (sometimes also EMS, HEMS)
COP	Coefficient of performance
CPO	Charge Point Operator
CT	Current Transformer (used for metering)
DHW	Domestic Hot Water
DNO	Distribution Network Operators
DSO	Distribution Supply Operator
DSR	Demand Side Response
DSRSP	DSR Service Provider
EMS	Energy Management System (sometimes also CEM, HEMS)
EPC	Energy Performance Certificate
ESA	Energy Smart Appliance
ESO	Energy Supply Operators
EV	Electric Vehicle
HEMS	Home Energy Management System
HHS	Half-hourly settlement
IHD	In-home Display
LV	Low Voltage (distribution network)
SAP	Standard Assessment Procedure
ToU	Time of Use
V2G	Vehicle-to-grid
VPP	Virtual Power Plant

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