CrowdFlex: Alpha

January 2023

D7.2 - Flexible heat roadmap for trial

Strategic Innovation Fund

ESO

Contents

Acronyms

ASHP	Air-source heat pumps
BAU	Business as usual
DHW	Domestic hot water
DSO	Distribution system operator
ESO	Electricity system operator
GSHP	Ground-source heat pumps
RTS	Radio tele-switched
SSEN	Scottish and Southern Electricity Network
TOU	Time of use tariffs

1 Objectives and approach

The purpose of this report is to provide a recommendation on whether there is a role for domestic heat flexibility in achieving the stated aims of the CrowdFlex trials during its Beta phase.

Electrification of domestic heating is a critical pathway for the UK to meet its 2050 and interim net zero-carbon target, as well as Scotland's own 2045 net zero-carbon target. Electric heating is therefore expected to become ubiquitous across the country's homes in the medium- and long-term. It is for this reason that the current report was included in the Alpha scope; to investigate heat flexibility as a potentially useful inclusion within the CrowdFlex trials.

This report first establishes the expected increase in peak electrical demand due to heat electrification roll-out, and to what extent this can be reduced through flexible heating systems and technologies that are expected to be prevalent across the domestic building stock in the coming years.

We also set out the technical potential and commercial value of electric heat to operate flexibility. We do this with a focus on heat pumps, analysing their ability to shift demand at peak times in response to a time-of-use (ToU) tariff, influenced primarily by wholesale prices, but also other time dependent energy price components (e.g. DUoS & TNUoS charges1). Wholesale driven ToU tariffs are readily available commercial offerings and hence are not the focus of CrowdFlex, an innovation project. However, they provide an opportunity to operationally model the load of electric heat throughout the year to understand how electric heat might respond to various price signals and the technical potential of that response. The analysis is analogous and can be applied to other forms of price signals that could be utilised in CrowdFlex.

One example of this that is investigated in this study is the potential for flexible electric heating to limit wind curtailment in Scotland. The ability to avoid renewables curtailment is critical to improving the economics of large-scale renewables supply on the Scottish transmission grid. At certain times of low demand and/or high renewable output (specifically from wind generation), the grid infrastructure is insufficient to export renewable power from Scotland to the rest of the UK. CrowdFlex intends to understand the economic benefit of relying on flexible energy assets, such as domestic heat, versus reinforcing the infrastructure to allow export. Both flexible energy assets and reinforced infrastructure could alleviate the issues associated with wind curtailment at these times of low demand and/or high renewable generation.

A review of completed, ongoing, and planned heat flexibility field trials is also provided. The intention for CrowdFlex: Beta is that it does not simply repeat or replicate the investigations undertaken in other trials. CrowdFlex should seek to address questions not covered by those other trials in order to provide new learnings and therefore value for money.

A recommendation is then made on the potential additionality of heat flexibility in the CrowdFlex Beta trials.

1.1 CrowdFlex trial summary

As the energy system transitions away from fossil fuels to renewables and electricity supply becomes more weather sensitive, we must enable the adjustment of demand to match supply. When supply is high, demand will need to increase to balance the grid by consuming or storing additional energy and avoiding the curtailment of generation assets, which can have economic consequences for asset owners and therefore consumers. When supply is low, demand will need to reduce to ensure the grid is balanced.

Domestic energy demand provides a potentially significant opportunity during this transition (and beyond) to establish a smart energy system by enabling consumers to act as a new source of flexibility. Without this nascent but potentially large resource, supply and demand side challenges might require less economic (low load factor) generation capacity and network investments, likely raising consumer bills significantly.

CrowdFlex is a study to establish domestic flexibility as a reliable energy and grid management resource, alongside business as usual (BAU) solutions such as network reinforcement or new thermal generation capacity. CrowdFlex aims to demonstrate the opportunity by conducting a large-scale trial in parallel with developing a methodology to model domestic flexibility. The trial will test the ability of domestic systems to deliver flexibility services to meet the needs of the ESO and DSOs. This trial will be essential to understand how domestic flexibility can be utilised to align demand to generation, improve coordination across the

[1] Distribution Use of System and Transmission Network Use of System charges respectively.

network, and reduce stress on the system, while also reducing consumer energy bills via new tariffs and incentives.

1.2 The future of heat

Space heating and hot water demands of domestic properties account for 17% of UK carbon emissions[2]. This is driven mostly by natural gas boilers, with 83% of UK dwellings using this technology as their primary heating fuel type[3].

Shifting from natural gas to lower-carbon heating fuel sources is therefore crucial to reducing emissions from homes and achieving the UK government's target of a net zero-carbon economy by 2050. Electric heating has been identified as a critical pathway to meeting this target, as it can benefit from another UK government commitment of a fully decarbonised electricity grid by 2035. It is expected that 79% of generation capacity will be from intermittent sources (wind and solar) for this fully decarbonised grid to be realised[2].

By 2035, 26% of dwellings are expected to have electric heating, with heat pumps consisting of 90% of this group (Figure 1). According to a range of sources, this will add significant further annual electricity demand to the grid by 2035; for example, ESO estimate up to ~21GWh in their Future Energy Scenarios[2]. While this annual increase will have impacts on grid planning and operation, it is the peak demand that will also determine the level of generation and network capacity required by the future grid. This will present a considerable challenge when coupled with the need to electrify transport alongside heating.

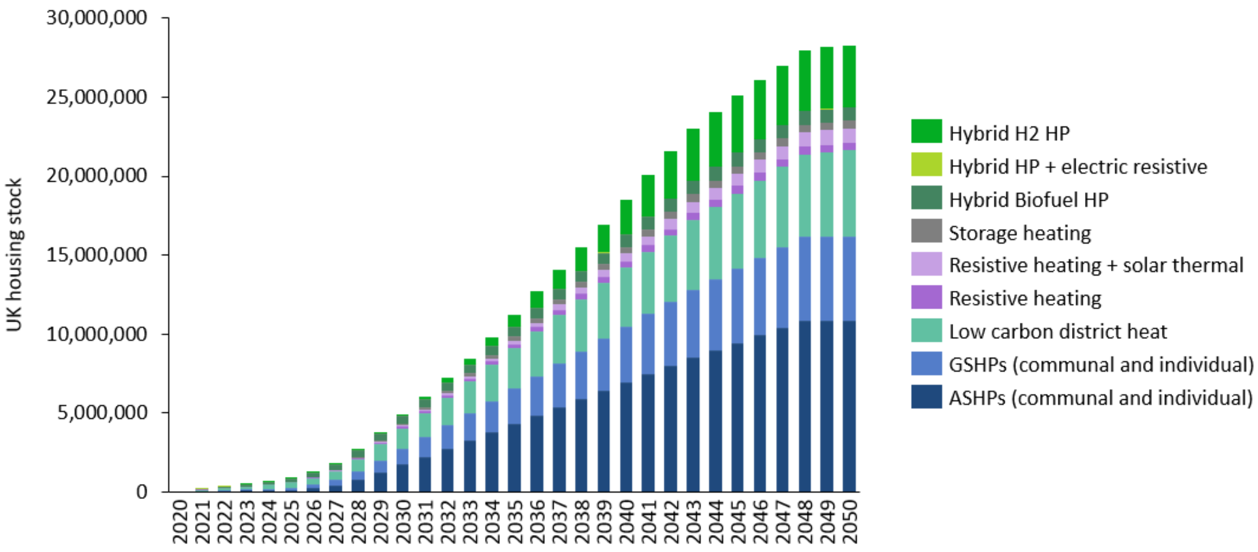

Figure 1: Climate Change Committee (CCC) projections of electric heat technologies across UK dwellings – Balanced Pathway[4]

When aggregated without consideration for flexibility, i.e., when energy demands are "passive" and not smartly controlled, the current total peak heat demand in the UK is roughly 5 times greater than the total peak demand for electricity[5]. The peaks and troughs in heat demand, both within a day and across the seasons, are far greater than the variations in electrical demand and the peaks will likely coincide with peak winter electricity demand. Although these passive heat peaks will be reduced with more efficient low-carbon

[2] UK Parliament: Decarbonising heat in homes Seventh Report of Session 2021-22 https://publications.parliament.uk/pa/cm5802/cmselect/cmbeis/1038/report.html *accessed November 2022*
[3] National Grid: Future Energy Scenarios 2022 Data Workbook https://www.nationalgrideso.com/future-energy/future-energy-scenarios#fullsuite *accessed November 2022*
[4] Element Energy: Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget https://www.theccc.org.uk/publication/development-of-trajectories-for-residential-heat-decarbonisation-to-inform-the-sixth-carbon-budget-element-energy/ *published April 2021*
[5] Ofgem: Future Insight Series – The Decarbonisation of Heat ofgem_future_insights_programme_-_the_decarbonisation_of_heat.pdf *published November 2016*

technology, such as heat pumps, peak electrical demand from heat could reach ~12GW by 2035 and ~30GW by 2050, as shown in Figure 2. This peak demand would be expected to occur in winter, increasing current peak winter electricity demand for Great Britain by 20% by 2035 and 51% by 2050[6].

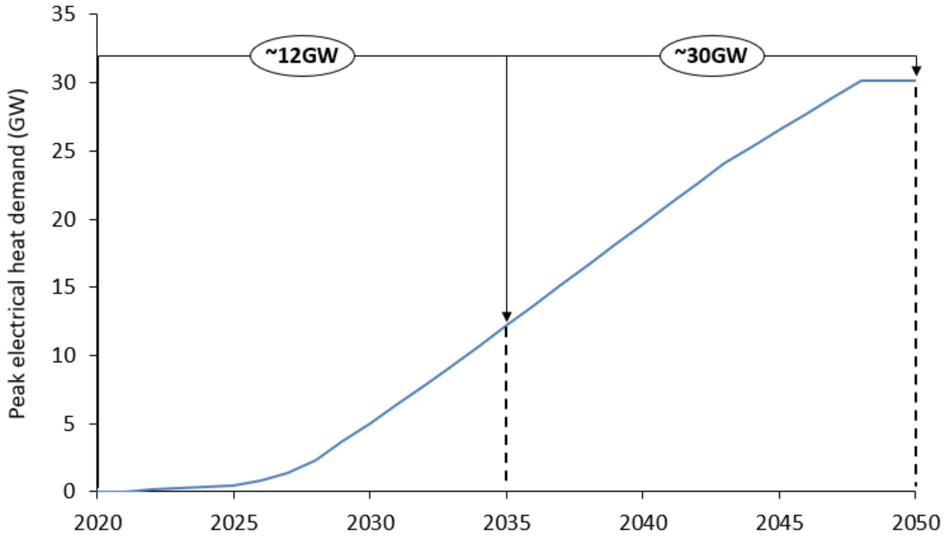

Figure 2: Projected peak electrical heat demand based on CCC projections of electric heat technologies[7]

This increase in peak demand will require a significant uplift in electricity generation capacity, potentially up to more than double current capacity by 2050, as well as supporting network capacity infrastructure. The timing of this peak demand may also, at times, coincide with reduced renewable generation capacity periods, where solar and wind output may be low. This would make the challenge of achieving a net zero-carbon grid by 2035 even harder, as this shortfall in renewables during peak times will have to be met by higher (likely carbon and hydrogen-based) thermal generation unless there is adequate dispatchable storage capacity, which would also require significant investment to build up.

Heat will represent the largest portion of the future domestic peak electrical demand. Domestic heat does, however, offer load shifting potential while maintaining comfort for occupants in their homes. This includes, for

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[6] National Grid: Future Energy Scenarios 2022 Data Workbook https://www.nationalgrideso.com/future-energy/future-energy-scenarios#fullsuite *accessed November 2022*

Based on current peak electricity demand of 58.8GW in 2021 (National Grid, 2022).

[7] Love, J., Smith, A.Z., Watson, S., Oikonomou, E., Summerfield, A., Gleeson, C., Biddulph, P., Chiu, L.F., Wingfield, J., Martin, C. and Stone, A., 2017. The addition of heat pump electricity load profiles to GB electricity demand: Evidence from a heat pump field trial. *Applied Energy*, *204*, pp.332-342.

Dincer, I., 2018. *Comprehensive energy systems*. Elsevier.

EDF: Electric storage heaters explained https://www.edfenergy.com/heating/advice/storage-heaters-explained *accessed December 2022.*

CP1 Heat Networks: Code of Practice for the UK https://www.camden.gov.uk/documents/20142/406533791/Heat+Networks+CP1.pdf/77003976-8160-198c-6abd-51e245731448?t=1645802025375 *published December 2020.*

Based on a diversified peak heat demand of 1.7kW for a heat pump (Love et al., 2017). The peak heat demand for an average resistance heater was found to be 2.4 kW (Dincer, 2018) and for a night storage heater this is 2kW (EDF, 2022). For the resistance heater and night storage heater, a diversity of 0.62 was applied to the space heating demand (CP1, 2020).

example, ‘pre-heating’ the home ahead of peak hours, to reduce or eliminate the need for heat generation during peak hours while keeping the home warm to an acceptable level throughout the heating period. Further flexibility could be provided by the use of dedicated thermal storage, such as an additional hot water storage cylinder to store heat to be used for space heating (as well as water heating) or the emerging ‘heat battery’ technologies that make use of alternative thermal storage media such as phase-change materials. These offer a higher density of thermal storage than hot water, meaning they can provide the same capability while requiring much less space than a conventional cylinder. Technologies such as these could mitigate some of the increased peak demand from heat electrification.

Hence, to understand how domestic flexibility can be utilised to balance supply and demand will require an understanding of the role heat can play. In addition to grid balancing, the development of flexible services to reduce consumer bills will be particularly necessary for heat as this will continue to account for ~65% of household energy bills in an all-electric household with heat pumps (~55% if/when an Electric Vehicle (EV) is included)[8].

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[8] Department for Business, Energy and Industrial Strategy (BEIS) – ECUK 2021: End Use Tables https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2021 *accessed November 2022*
Energy Saving Trust – Getting warmer: a field trial of heat pumps
https://energysavingtrust.org.uk/sites/default/files/EST_Heat_Pump_Trials%20part%202a.pdf *published September 2010*
Element Energy – Electric Vehicle Charging Behaviour Study EV Charging Behaviour Study (element-energy.co.uk) *published March 2019*

From the annual heating and hot water end-use demand for an average household is 13,559kWh and household electricity demand (appliances and lighting) is 3,616kWh (ECUK, 2021). The average annual demand for EVs is 1,760kWh (EE, 2019). An average SCOP of 2.2 for ASHPs was examined in field trials (Energy Saving Trust, 2010). The heating and hot water demand was divided by this SCOP to convert the end use demand to primary electricity demand (6,163kWh), which was compared with the EV and the household electricity demand.

2 Heat flexibility

This section provides an overview of how heat can provide energy demand flexibility in homes, the range of domestic assets relevant to CrowdFlex that deliver this flexibility, and analysis of the flexibility of these assets. This determines the opportunity for specific technologies, systems, and approaches for potential inclusion in the CrowdFlex Beta phase trials.

2.1 Overview

Heat demand in domestic buildings comes in two forms:

1. Hot water (showers, taps, etc.), also known as "domestic hot water" (DHW).
2. Space heating.

Electrified domestic heat can be flexible in both "turn-up" and "turn-down" scenarios:

- Turn-up, which is a supply-driven action:
    - Heat generated outside of peak periods in preparation for higher demands later in the day, thereby flattening demand in these peak periods.
    - Heat generated using surplus power from the grid, allowing for avoidance of renewables curtailment and improving renewable generation assets' economic performance.
    - In the context of electrified heating, which is a critical pathway for decarbonising the UK domestic sector (see section 1), this flexibility can be valuable to the stated aims of CrowdFlex as it provides opportunities to:
        - Consume excess electricity supply from the grid at times of high renewables output and/or low demand elsewhere in the country.
        - Mitigate some of the expected uplift in peak electrical demand stemming from the UK-wide switch from natural gas to electric heating; i.e., the new peaks in electric demand on the grid.
- Turn-down, which is a demand-driven issue:
    - Heat systems turned down or off at peak periods, flattening demand in these peak periods.
    - Again, in the context of electrified heating, this flexibility can be valuable to the stated aims of CrowdFlex as it provides opportunities to:
        - Consume less electricity at times of low renewables output and/or high demand elsewhere in the country.
        - Again, mitigate some of the expected uplift in peak electrical demand stemming from the UK-wide switch from natural gas to electric heating; i.e., limiting the formation of new peaks in electric demand on the grid.

In all scenarios, the aim for flexible heat should always be to maintain the ways in which home occupiers use heat; i.e., the occupier should not have to materially adapt their behaviour or level of comfort to accommodate flexibility. For example, where the internal temperature of a space can be varied to accommodate flexibility functions (as described in section 2.2.4), this should not be varied to such an extent that homes are either too hot or too cold for comfort. Similarly, a home occupier must not be denied the ability to heat their home, or provide instantaneous DHW, in peak times to accommodate a given flexibility function required by the network operator. Furthermore, the occupant should not be required to pay more for their heating in a flexible scenario once accounting for mechanisms such as time-of-use tariffs to incentivise the flexible behaviour. **Only when each of these conditions on comfort, convenience and cost are met can flexibility potential be deemed 'useful'.** The following analysis concerns the potential for 'useful' flexibility potential only.

2.2 Flexible heat assets

Flexible heat assets relevant to CrowdFlex are provided in the following subsections.

2.2.1 Storage heaters

Storage heaters are space heating supply technologies that use electricity to heat up ceramic or clay bricks contained within the units overnight, taking advantage of time-of-use electricity tariffs such as Economy 7 or Economy 10. They then release the heat gradually to keep homes warm the following day by spreading heat around rooms through convection currents.

Storage heaters could provide turn-up and turn-down capabilities. In both scenarios, careful consideration is required for a given consumer's existing electricity tariff (i.e., the economics of generating heat outside of Economy 7 or Economy 10 periods must be factored in).

This technology could be important for CrowdFlex as there are a substantial number of night storage heaters across the Scottish domestic stock, thus providing a potentially large flexible heat source readily available today. It should be noted, however, that storage heaters are not expected to substantially grow in market share over the coming decades due to their low efficiency compared with heat pumps, and in the CCC's Balanced Pathway presented in Figure 1 this technology is expected to represent no more than ~2% of all heating systems across the UK by 2050.

It should be noted that the long wave radio tele-switched (RTS) heaters installed in homes across load managed areas (LMAs) in Scotland, that allow DNOs to automatically control storage heaters to provide flexibility, are being phased out in favour of smart meter-controlled set-ups. It has been noted by Scottish and Southern Electricity Networks (SSEN) that these new control systems are not always as flexible as the incumbent RTS and there is a concern that these consumers could begin to use the storage heaters more passively which could create new peaks. Hence, storage heaters are being considered within the CrowdFlex trials.

2.2.2 Immersion heaters

Immersion heaters are hot water tanks with an electrode for DHW generation and storage. These are typically used with Economy 7 or Economy 10 tariffs to generate DHW overnight, for supply over the day.

Immersion heaters could provide turn-up and turn-down capabilities. In a similar way to storage heaters, careful consideration is required for a given consumer's existing electricity tariff.

Again, this technology could be important for CrowdFlex as typically it exists where night storage heaters, as well as resistive heaters, are used in homes. Its prevalence in Scotland in the coming decades is therefore expected to follow the same profile as storage and resistive heaters, and account for ~6-8% of all heating systems across the country, as shown in Figure 1.

2.2.3 Heat pumps

Heat pump technology uses a refrigerant cycle, powered by electricity, to transfer heat from the environment (air, ground etc.) into homes. Heat pumps can generate both space heating and DHW and are more efficient than night storage heaters and immersion heaters (typically on a 3:1 basis).

DHW can be generated at off-peak times and stored in hot water tanks to avoid electricity consumption in peak periods.

Heat pumps could provide turn-up and turn-down capabilities. Careful consideration is required for the capacity of the heat pump and its hot water tank, which will limit the potential for both turn-up and turn-down.

While currently far less prevalent than storage or resistive heaters in Scotland, heat pumps are expected to dominate domestic heat supply technologies over the coming decades, as shown in Figure 1.

2.2.4 Building thermal mass and heat loss

In combination with any of the above heating technologies, the thermal mass of a building can be used as a source of flexibility in turn-up and turn-down scenarios:

- In a turn-up scenario, the home can be “pre-heated” for space heating purposes before a peak period, which smooths the demand for space heating in the peak period. Any pre-heating must ensure comfort levels are maintained, i.e., internal temperature does not exceed levels that are deemed comfortable for habitation. Similarly, pre-heating must be effective or “useful”; for example, pre-heating a home many hours in advance of a heating period, just to consume excess renewables, may not be useful if the heating energy is lost by the time of the heating period.
- In a turn-down scenario, the home space heating system can be switched off for a given time (typically a few hours), until such a point that the internal temperature is at the lower comfort level, when it will need to be switched back on.

The effectiveness of the home to retain heat depends on its heat loss performance, i.e., the level of insulation and air tightness. Poorly insulated homes can only shift heat energy by a short period because indoor air temperature quickly falls below acceptable comfort thresholds once the heating system is turned off. Homes with a better heat loss performance (lower heat loss parameter) can conserve thermal energy over a longer period and are able to retrieve a greater share of this accumulated thermal energy, giving them a higher potential for useful heat flexibility.

The building’s thermal mass also impacts the potential for useful heat flexibility in a turn-down scenario. The more thermal mass in the building’s structure, the more heat energy can be accumulated during off-peak periods and partly recovered during peak periods[9]. However, the effect of thermal mass on heat flexibility appears to taper off above 80Wh/m^{2}K of effective thermal inertia[10]. For comparison, the approximate storage heat capacity of buildings with brick walls and concrete ceilings is 120Wh/m^{2}K and for concrete constructions it is 200Wh/m^{2}K[11]. Hence, most existing homes would be able to provide some flexibility through their building mass.

2.2.5 Excluded assets

There are other electric heat assets applicable in domestic buildings, but which are not flexible or relevant to CrowdFlex and therefore not considered further:

- Direct (or “resistive”) heater panels are instantaneous heat supply technologies, i.e., they generate heat only when it is required. This technology can offer flexibility; however, they do not have any storage capability, so the duration of useful flexibility would be lower than for heat pumps and storage heaters and they’re penetration is expected to decrease in the UK from ~2% to <1% by 2050[3], so do not represent a significant flexibility potential.
- Electrode /immersion boilers use electricity to generate hot water for use in radiator systems (i.e., for space heating provision) or for DHW purposes. This technology does offer greater flexibility than direct heater panels if coupled with DHW storage. However, they are not expected to be a prevalent heating resource in the UK and so do not represent a significant flexibility potential.

2.3 Analysis

To understand the potential for the above flexible heat assets to deliver benefits within the CrowdFlex requirements, a quantitative analysis has been undertaken to understand how a typical heat pump home can reduce peak electricity demands and help avoid renewable curtailment through heat flexibility.

The analysis is split into two sections. The first analysis determines the level of storage available in a typical home and how much is required to avoid new peaks on the grid. The second analysis has been undertaken to

[9] Reynders, G., Diriken, J. and Saelens, D., 2015, December. A generic quantification method for the active demand response potential of structural storage in buildings. In *14th International Conference of the International Building Performance Simulation Association, Hyderabad, India*.

[10] Le Dréau, J. and Heiselberg, P., 2016. Energy flexibility of residential buildings using short term heat storage in the thermal mass. *Energy*, *111*, pp.991-1002.

[11] Weiss, T., 2020. Energy flexibility and shiftable heating power of building components and technologies. *Smart and Sustainable Built Environment*.

determine how much excess (and otherwise curtailed) wind can be usefully absorbed in flexible heating systems.

This analysis focuses solely on heat pumps with DHW storage tanks as the flexible heat assets in homes. There will be more heat pumps than storage heaters installed in UK dwellings by 2030 and they will represent 90% of electric heat technologies by 2050 (as shown in Figure 1). Hence, it is important to understand the potential of heat pumps to deliver useful flexibility as they will represent a significant portion of future domestic heat flexibility in the UK.

Although storage heaters are not considered in this analysis, they represent the majority of electric heat technologies currently and will still represent a small, but material share of the heating system stock in the long term (~5%). As CrowdFlex is concerned with current and near-term demand-driven and supply-driven issues and with the potential for new demand peaks as storage heaters in LMAs in Scotland move to smart meters (and away from RTS controlled systems), storage heaters remain an important source of domestic heat flexibility and should still be considered for inclusion in CrowdFlex.

2.3.1 Peak demand shifting

Heat demand can be shifted by utilising flexibility provided by storage available from the building's envelope and its thermal mass, as well as DHW storage tanks.

The ability to shift heating demand is constrained by the level of comfort expected and the energy storage capacity of heat storage elements, as well as the need to ensure "useful" heat is delivered to the space (e.g., not heating rooms unnecessarily simply because it allows peak demands to be shifted).

The analysis considers a typical insulated Victorian terrace house, with an allowable temperature deviation of ±1°C. First the "passive" heat pump demand (i.e., without flexibility) is analysed. A "time of use" (ToU) tariff run is then tested; i.e., peak demand is shifted based on the cost-benefit for consumers from incentivising off-peak heat generation. Relative to the baseline, the modelling shifts demand to lower priced electricity hours, subject to meeting the heating constraints outlined above.

The top chart (a) in Figure 3 shows diversified passive heat pump electrical demand, showing high usage in the morning and evening when more people are at home and temperatures are typically lower.

In (b) in Figure 3, where consumers are offered a flexible ToU tariff throughout the day, useful heating is shifted away from the evening peak. The level of flexibility available in the house means that the average hours of heating advance/delay allowed is 2.4 hours for a typical winter's day. This time shift does reduce as the outside temperature decreases (as the building will lose heat more quickly and the lower space heating temperature will be hit more quickly. Figure 3 shows a cold day in winter with allowable turn up/down for 1.3 hours.

Note that the evening peak in electricity demand is typically 3-4 hours wide[12]. Our analysis has demonstrated that, on the coldest day of a typical year for a typical insulated Victorian terrace house, heat pumps with DHW storage can provide only approximately 1 hour of useful flexibility before the internal air temperature goes beyond the allowable temperature deviation of ±1°C. **Although the duration of useful flexibility will vary in homes with more or less insulation and thermal mass and different temperature variation tolerances, the average house will not be able to provide 3-4 hours of flexibility on a peak cold day that is required to be useful to the electricity system.** More storage will be required.

[12] ESO peak generally occurs between 16:00-18:00, while DSO peak occurs between 17:00-19:00.

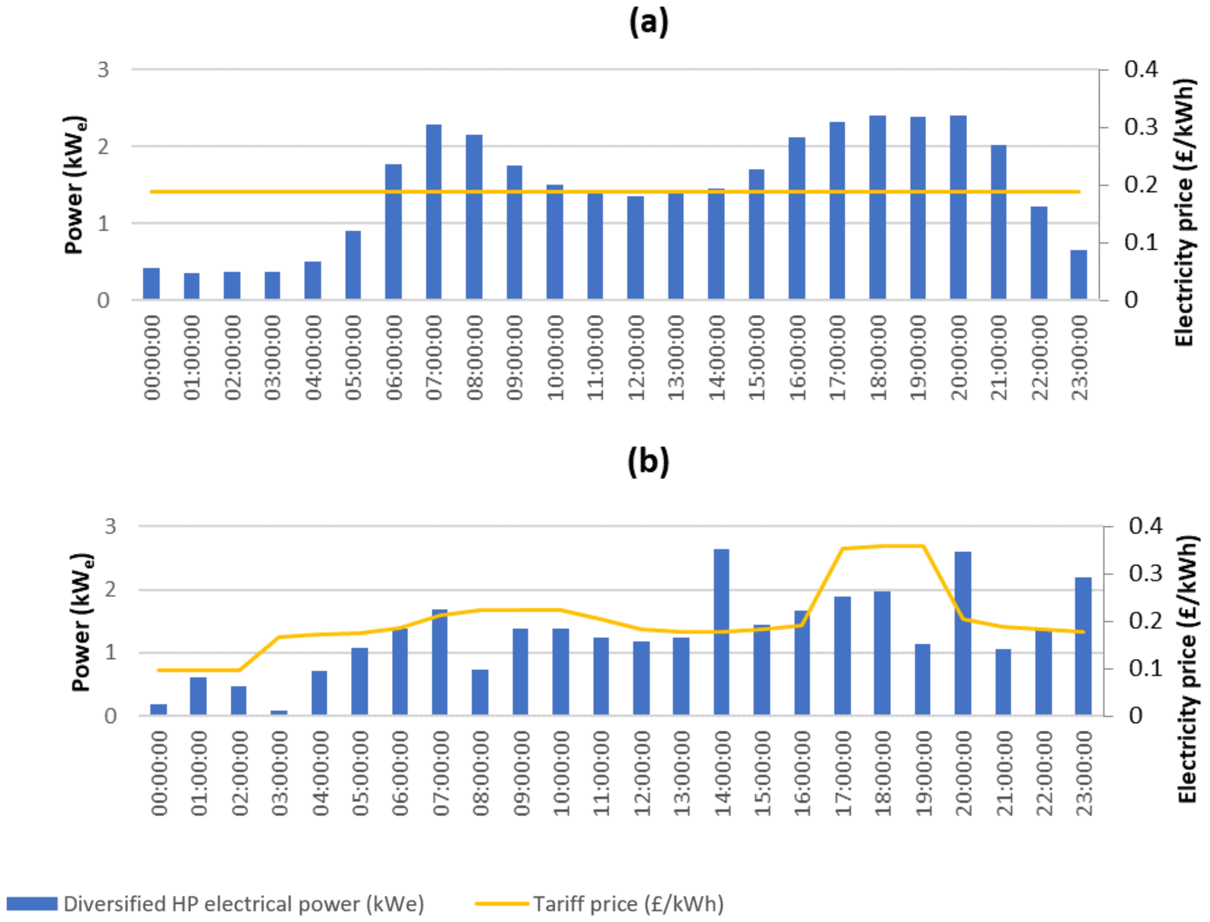


Figure 3: (a) Before – Passive heat pump electrical demand (b) After – ToU heat pump electrical demand using flexibility from building envelope and thermal mass

One solution to increasing the duration of flexibility would be to have additional thermal heat storage, which would store heat in off-peak hours for supply of space heating demand in peak hours. This is impractical in most homes as they do not have adequate space to accommodate additional storage vessels alongside the DHW tanks already required for a domestic heat pump system. In spite of this, further analysis is undertaken to determine the duration of flexibility possible with additional thermal storage, in order to understand the potential for homes that could accommodate more storage capacity.

Analysis (Figure 5) shows the inclusion of a large, additional thermal heat store to supply all space heating demands can increase the duration of flexibility from 1.3 hours to up to 5 hours of peak demand on a peak day, with internal temperature maintained in the peak period from 17:00 to 20:00. This exceeds the typical demand shift duration required by the ESO[13].

To achieve this level of space heating peak demand shifting, additional thermal storage capacity would need to be 26kWh, which is significantly larger than a typical DHW storage tank (6-12kWh), thus potentially requiring 2-4 times additional storage volume in a typical home. To shift the generation of heat for the entire space heating demand outside of peak hours is impractical for a household, and these types of thermal storage tanks are not typically installed with heat pump systems for this reason. Clearly though being able to store heat for space heating supply can provide opportunities for shifting demand out of peak hours.

[13] At present. However as more flexible technologies are deployed and respond to TOU tariffs, the width of the evening peak will become wider.

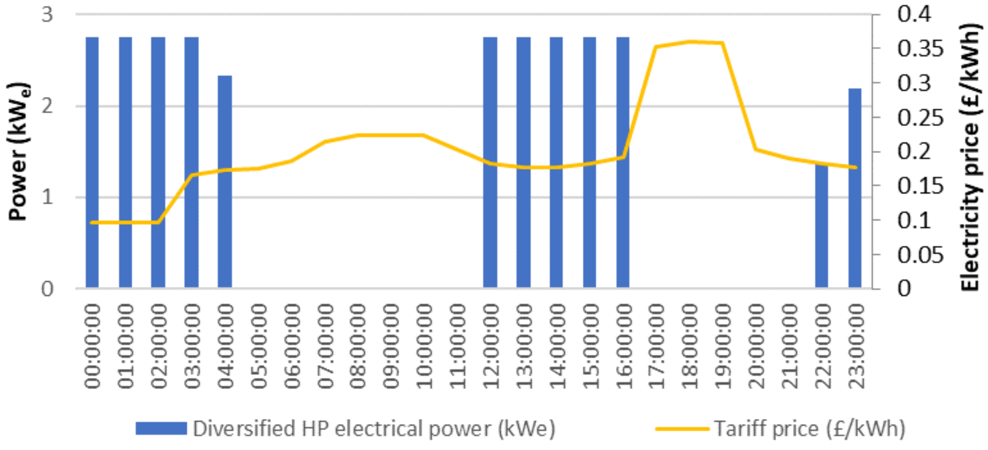
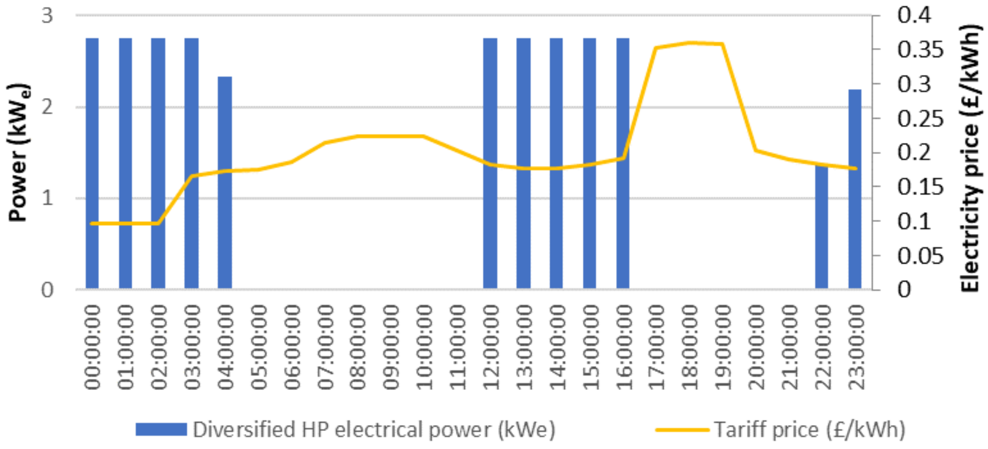


Figure 4: ToU heat pump demand using flexibility from building envelope, thermal mass and thermal storage for space heating provision

There are other factors that can increase the duration of the useful potential of turn-up/turn-down provided by heat pumps during a peak day, which are not covered in this modelling:

- Reducing the thermal loss of the building either by selecting dwellings with higher insulation than the archetype used in this model (e.g., new builds, homes with EPC rating C or higher) or dwellings with lower external surface area (e.g., flats), or both. This increases the building's ability to stay within acceptable comfort thresholds, hence increase the duration of useful potential of turn-up/turn-down.
- Increasing the allowable temperature deviation from the target internal temperature (currently ±1°C) extends the acceptable comfort thresholds to consumers. This increases the duration for which heat pumps can be on/off, thus increasing the duration of useful potential turn-up/turn-down.



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- Increasing the allowable temperature deviation from the target internal temperature (currently ±1°C) extends the acceptable comfort thresholds to consumers. This increases the duration for which heat pumps can be on/off, thus increasing the duration of useful potential turn-up/turn-down.

2.3.2 Wind curtailment reduction

Due to network constraints, wind generation in Scotland cannot always be exported to the rest of the UK, i.e., when there is an over-supply of electricity from high wind generation, the energy movement is too high, and the transmission infrastructure capacity is not sufficient to serve export to England. As a result, at these times of high wind supply/low power demand, wind generation must be curtailed, and (in general) non-renewable generation in England is turned up. In 2020/2021, 2.6TWh of Scottish wind energy was curtailed, costing £445m to the consumer.

An analysis of the wind curtailment data for 2020/2021[14] is shown in Figure 6, which highlights that wind curtailment is most prevalent during autumn to winter months (Oct-Jan), with some limited curtailment still experienced in the summer months (May-July). There appears to be a significant drop in curtailment in January; this could be attributed to lower-than-average wind speeds as this appears an outlier with the other winter months.

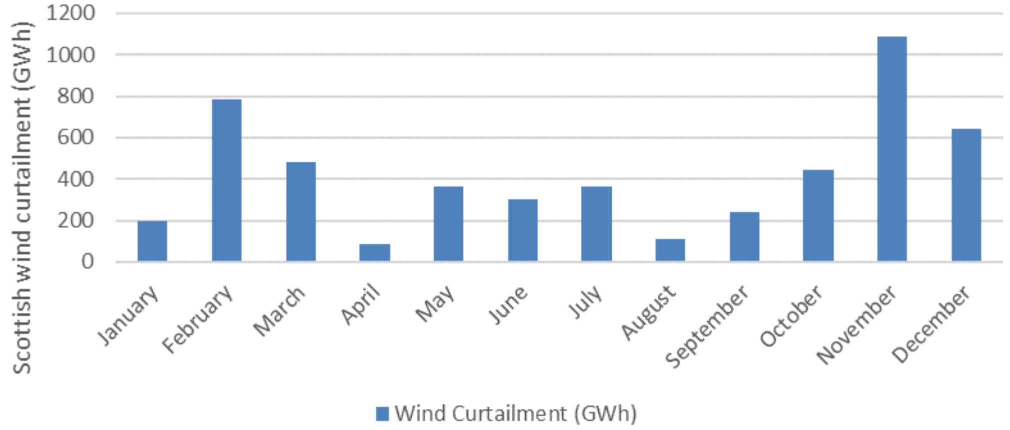

Figure 6: Monthly wind curtailment in Scotland, 2020/2021 (reordered to calendar year from April 2020 to March 2021)

To understand if there is some potential for heat pumps to reduce wind curtailment, the monthly space heating and hot water electrical demand for the Victorian Terrace archetype was mapped against the monthly curtailment values (Figure 7). The annual passive demand profile for the Victorian Terrace archetype was multiplied by the expected number of heat pumps in Scotland by 2030 (approximately 200,000) and then aggregated to show a monthly total.

Figure 7 demonstrates that there is seasonality for both Scottish wind curtailment and heat pump electrical demand, with both being highest during the winter months, suggesting the greatest potential for useful flexibility may be during those periods. However, there is also significant wind curtailment across the whole year, including the summer, and a non-zero amount of heat pump demand across the whole year (primarily for hot water provision in the summer), suggesting that there could be useful flexibility potential year-round. An understanding of the hourly variation of both curtailment and heat pump demand is, however, required to further test the potential for useful flexibility.

[14] National Grid ESO, System Constraints – Constraint Costs and Limits, 2020/21 (extrapolated from system costs)

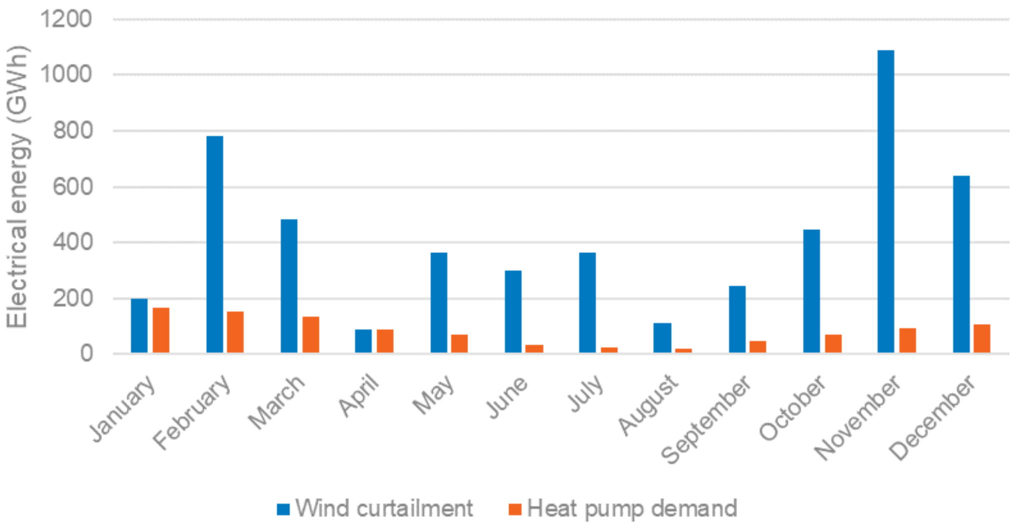

Figure 7: Monthly wind curtailment in Scotland and peak heat pump electrical demand when generating passively (i.e., no flexibility) in 2020/2021 (period running from April 2020 to March 2021, reordered here for ease of interpretation)

Figure 8 presents the average "winter season" profile (defined here as the average profile across the 6 months from November to April), and two example (single) winter day profiles of wind curtailment and passive heat pump electrical demand. The average winter season profile (the first chart in the figure) demonstrates that, on average, wind curtailment occurs across all hours of the day, albeit to a somewhat greater degree during the evening and daytime than overnight.

On any single day, however, given that wind generation is intermittent, the timing of curtailment may vary significantly. This is illustrated in the example (single) winter day profiles (the middle and bottom charts in the figure). For the day of 14 November 2020 (the middle chart), in contrast to the average profile, there is essentially no curtailment in the early hours of the morning, a high and steady level of curtailment through the day, before a slight fall-off to a moderate level of curtailment going into the following night. The peak in curtailment (around 16:30-18:30) is a couple of hours ahead of the broad evening peak in heat demand (around 17:30-20:30) suggesting that, for the particular day in question, there could be some benefit to shifting heat demand earlier in the afternoon to pre-heat homes and reduce wind curtailment. The same is not the case ahead of the morning peak heat demand for the same day, as there is minimal wind curtailment during the hours before the morning heat peak.

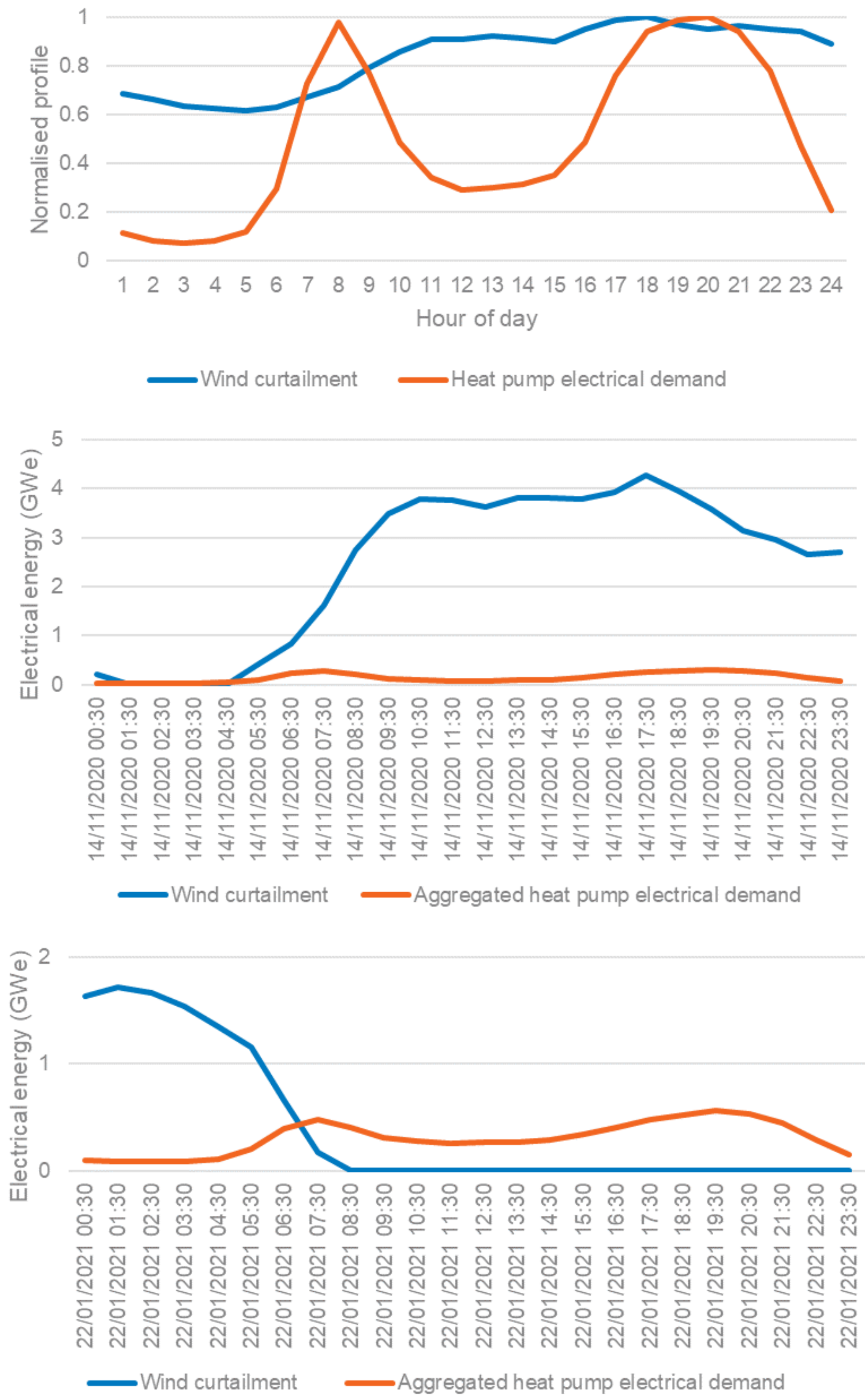

Figure 8: Top: Normalised average winter season (Nov-Apr) profile of wind curtailment and heat pump electrical demand. Middle and Bottom: Example (single) winter day profiles of wind curtailment and heat pump electrical demand

In contrast, and highlighting the variation in wind generation and curtailment between any given days (even in the same season), the bottom chart in Figure 9 shows that on a different example winter day, 22 January 2021, there are high levels of curtailment in the early morning (00:00-07:00), prior to the morning peak in heat pump demand (06:00-09:00). For this example day, there is potential to usefully shift demand for heat by pre-heating homes in the early morning to reduce wind curtailment in that period. The same is not the case ahead of the evening peak in heat demand for that example day, as there is no wind curtailment at that time of the day.

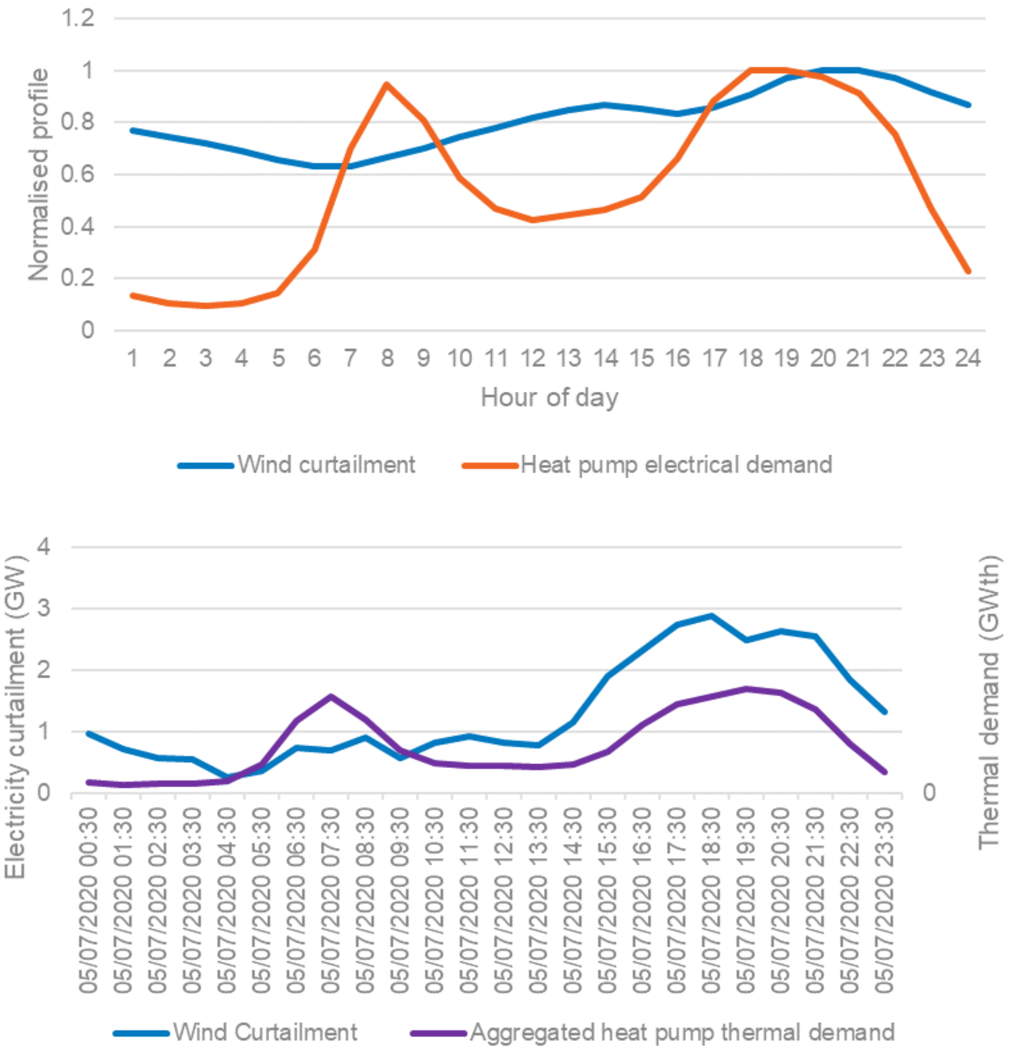

Figure 9: Top: Normalised average summer season (May-Oct) profile of wind curtailment and heat pump electrical demand. Bottom: Example (single) summer day profile of wind curtailment and heat pump electrical demand

Figure 9 shows the average "summer season" profile (defined here as the average profile across the 6 months from May to October) and an example (single) summer day profile of wind curtailment and heat pump electrical demand. Due to the definition of the summer season including months during which space heating remains material (particularly the shoulder season months of May, September and October), the summer season average heat demand profile retains notable morning and evening peaks.

The average summer season profile of wind curtailment (the top chart in the figure) is not substantially different from the average winter season profile, with curtailment occurring across all hours of the day, and (as for winter) to a greater extent in the day and evening than overnight. This suggests that, although the total amount of curtailment and total amount of heat demand is lower in the summer season than winter season, there will still be useful potential for heat flexibility during certain days in the summer season. This is illustrated by the example (single) summer day profile for 5 July 2020 (the bottom chart in the figure), where the curtailment peaks ahead of the evening peak in heat demand (by roughly one hour in this case), offering an opportunity for useful pre-heating to reduce overall curtailment. The average summer season profile which, as for winter, shows substantial curtailment across the whole day, suggests that, across the summer season as a whole, there will be the opportunity for useful pre-heating ahead of both the morning and evening heating peaks.

Figure 7 - Figure 9 suggest that there is potential for useful supply-driven turn-up flexibility through pre-heating in both the winter and summer seasons, ahead of the heating peaks in both the evening and morning, albeit with the greater potential expected ahead of the evening peak and in winter when both curtailment and heating demand are highest. Given the substantial day-to-day variation in the timing of curtailment, we have undertaken an analysis to determine the potential for useful pre-heating across the full example year from April 2020 to March 2021. This analysis was conducted alongside an analysis of the turn-up potential of EV charging to compare the potential of both flexible assets to reduce wind curtailment. The results are shown in Figure 10.

This analysis found that, over the whole year, a typical home with a heat pump can reduce overall curtailment by 448 kWh of electricity, compared with 217 kWh of electricity for an EV – that is, the heat pump can deliver more than double the reduction in wind curtailment versus an EV. For the heat pump, under our deployment assumptions of 200,000 in Scotland by 2030 and 1.2m by 2050, this equates to annual reduction in wind curtailment of 92.5GWh by 2030, and 543GWh by 2050[15]. Based on the cost of curtailment in 2020/2021 of £174/MWh, the reduction in wind curtailment provided by heat pumps would provide an annual saving to consumers of £78 per household. Across all households with heat pumps in Scotland this would amount to £16m by 2030 and £94m by 2050.

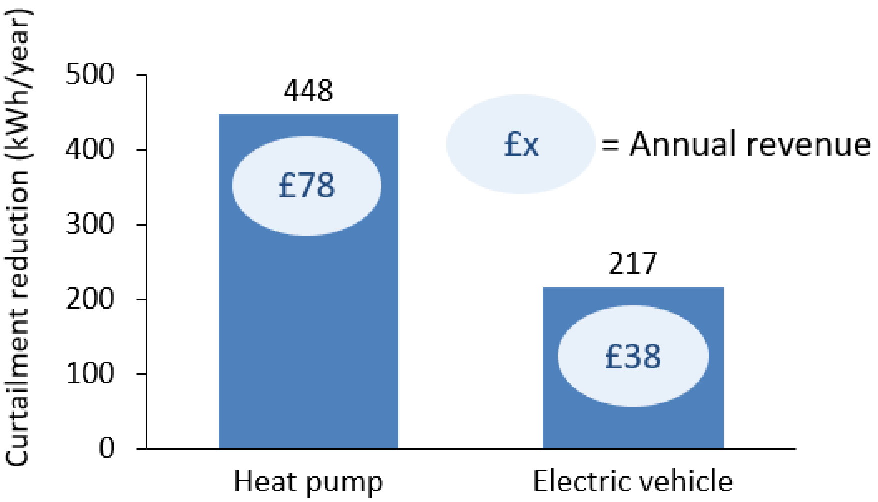

Figure 10: Reduction in wind curtailment and annual revenue for typical home, heat pumps versus EVs

The purpose of this quantitative analysis was to understand how a typical heat pump home can reduce peak electricity demands and help avoid renewable curtailment through heat flexibility, to help establish the potential for flexible heat assets to deliver benefits within the CrowdFlex requirements.

The findings of the first analysis demonstrated that, on a typical winter's day, a typical heat pump home can provide useful flexibility for ~2.4 hours, which would be higher for homes with higher levels of insulation. This means that most heat pump homes should be able to provide useful flexibility on a typical winter's day. However, the primary concern for ESOs and DNOs is shifting heat demand on the coldest day as this will represent the peak demand in a typical year. The analysis demonstrated that on the coldest day of a typical year, a typical heat pump home can provide limited useful demand-driven flexibility (~1 hour) to reduce peak loads. This useful demand-driven flexibility on the coldest day can be improved with homes with higher levels of insulation or thermal mass and different temperature variation tolerances. However, only a small minority of well insulated homes will be able to provide the 3-4 hours of flexibility on a peak cold day that is required to be useful to the electricity system without additional thermal storage.

[15] Element Energy: Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget https://www.theccc.org.uk/publication/development-of-trajectories-for-residential-heat-decarbonisation-to-inform-the-sixth-carbon-budget-element-energy/ *published April 2021*. To a first approximation, this assumes curtailment opportunity scales linearly with HP deployment.
Based on the projections of heat pump households in Scotland: 206,393 by 2030 and 1,211,053 by 2050 -

The second analysis has shown that a typical heat pump home can provide a potentially substantial amount of supply-driven flexibility through the year, which would be of considerable interest to CrowdFlex because this has the potential to reduce wind curtailment in Scotland by up to approximately 90 GWh by 2030. The analysis suggests that there would be value in CrowdFlex investigating the potential for supply-driven flexibility from heating.

However, the potential for this useful flexibility relies on a range of assumptions on factors that are not yet well understood. These include:

- **The impact of different electric heat technologies on the degree and timing of useful flexibility** (for example storage heaters and heat pumps have different profiles under 'passive' operation). Although the analysis above is focused on heat pumps, Section 2.2 highlighted that storage heaters have a high level of in-built storage potential and there are a significant number of units currently in operation across the Scottish domestic stock, thus providing a potentially large flexible heat source. Hence, an important component of understanding the full picture for flexible heating is for CrowdFlex to consider both heat pumps and storage heaters.
- The **impact of building type and level of insulation**, which drives the potential duration of useful flexible response via the heat loss parameter and thermal mass, which determine the rate at which the internal temperature drops in the home after a pre-heating event.
- The **impact of additional thermal heat storage** in enabling further useful flexibility beyond that achievable through pre-heating.
- The **impact of occupant comfort thresholds –** that is, the tolerance for variation from the target internal temperature (in either direction) during and after a pre-heating event.
- The implications of the above factors for the variation of useful flexibility potential over time, both **seasonally and diurnally.**

We are aware of various completed, ongoing, or planned trials that consider heat and flexibility, which may address these factors. Hence, the next section will assess these trials against the above factors to understand the extent of the remaining gaps which CrowdFlex could usefully address.

3 Gap analysis of completed, ongoing and planned flexible heat trials

The purpose of this report is to establish whether there is a role for heat within CrowdFlex, considering the coverage of flexibility from heating in other completed, ongoing, or planned trials. This section examines the scope of those other trials to draw conclusions on whether, following their completion, material gaps remain with respect to the factors identified in Section 2 to demonstrating the potential for heat to provide useful flexibility. Our assessment of the importance of the remaining gaps will form the basis for the arguments in favour of adding heat to the scope of CrowdFlex.

Section 3.1 will outline a set of key criteria, based on the factors identified in Section 2 as being important components to understand the potential for useful flexibility from heat, against which we will assess each of the trials. Section 3.2 will then summarise the scope, key aims and findings (where already completed) of the relevant trials. Section 3.3 will summarise the findings of the gap analysis and set out the areas in which CrowdFlex could provide useful additionality.

3.1 Assessment criteria

To establish the potential for heating systems to provide useful flexibility, where ‘useful flexibility’ ensures occupant comfort is maintained while reducing costs to households, the effect of the following factors needs to be understood:

- The impact of different electric heat technologies on the degree and timing of useful flexibility (for example storage heaters and heat pumps have different profiles under ‘passive’ operation)
- The impact of building type and level of insulation, which drives the potential duration of useful flexible response
- The impact of additional thermal heat storage in enabling further useful flexibility
- The impact of occupant comfort thresholds – that is, the tolerance for variation from the target internal temperature during a ‘pre-heating’ event
- The implications of the above factors for the variation of useful flexibility potential over time, both seasonally and diurnally

These factors have been turned into a set of criteria by which to assess the trials listed in Section 3.1 and establish whether there are any gaps that CrowdFlex could consider.

1.) ***Does the trial include heat pumps?*** ***Table key: Heat pumps***

While not currently widespread, heat pumps are expected to dominate domestic heat supply technologies over the coming decades and outnumber other electric heating systems such as storage heaters by the mid/late 2020s, as shown in Figure 1. This means a full understanding of the potential for heating to provide useful flexibility must include an evidence base on the role of heat pumps.

2.) ***Does the trial include storage heaters?*** ***Table key: Storage heaters***

Section 2.2 highlights that storage heaters have a high level of in-built storage potential. There is a significant number of night storage heaters currently in operation across the Scottish domestic stock, thus providing a potentially large flexible heat source. While storage heaters are expected to form a minority of electric heating technologies in the future, they represent the most material source of flexibility from heat in Scotland over the next few years, and an important component of the full picture for flexible heating.

3.) ***Does the trial generate evidence on the useful potential for electric heating technologies to provide demand-driven turn down flexibility?*** ***Table key: Demand-driven flexibility***

Section 1 highlighted the electrification of heat will cause a demand-driven problem, as this will increase peak winter electricity demand which may at times coincide with reduced renewable generation capacity periods, where solar and wind output may be low, requiring higher carbon thermal generators to meet the shortfall. Heat systems could mitigate some of this expected uplift in peak electrical demand by turning down or off at peak periods. An ideal trial would therefore investigate the useful potential of electric heating technologies to provide useful demand-drive turn down flexibility during peak periods.

4.) ***Do the trials generate evidence on the useful potential for heating technologies to provide supply-driven turn up flexibility? Table key: Supply-driven flexibility***

Section 1 highlighted that the increasing penetration of renewables will cause a supply-driven problem, as during off-peak periods there will be instances of high renewable electricity supply which the grid infrastructure will not be able to export to demand centres, which would increase annual renewables curtailment. This was highlighted as a particular concern for wind curtailment in Scotland, hence, an ideal trial would investigate the useful potential of electric heating technologies to provide supply-driven turn up flexibility during off-peak periods.

5.) ***Does the trial generate evidence on how the useful potential for supply-driven flexibility varies diurnally and seasonally? Table key: Diurnal and seasonal variation (supply-driven)***

This criterion builds on the supply-driven problem highlighted above. The analysis in Section 2.3 demonstrates that wind curtailment in Scotland occurs across different hours of the day and, to varying extents, across all months of the year. Therefore, the diurnal and seasonal variation of useful potential of electric heating technologies to provide supply-driven flexibility should be investigated.

6.) ***How does the useful potential for flexibility vary with different insulation levels and building types? E.g., EPC, detached houses, flats, new builds. Table key: Building type and insulation (heat loss parameters)***

Section 2.2 outlined how a building's ability to retain heat determines the time duration over which heat can be shifted without affecting occupant comfort. The main factors that influence this are the level of insulation, thermal mass, and building dimensions, including number of exterior faces. An ideal trial should include a range of building types and insulation levels to determine the effect on the useful potential to turn up/turn down heat.

7.) ***How does the useful potential for flexibility vary according to the occupant comfort threshold (i.e., the deviation from target internal temperature that the occupant is able to tolerate)? Table key: Occupant comfort threshold***

Section 2.3 highlighted that increasing the allowable temperature deviation from the target internal temperature (modelled in that analysis as ±1°C) increases the duration over which heat demand can usefully be shifted. Hence, a full understanding of the potential for flexibility from heating should investigate the acceptable comfort threshold of occupants.

8.) ***How does the useful potential for flexibility vary with additional thermal storage? Table key: Additional thermal storage***

For most homes, additional thermal storage would be required to provide a useful heat demand shift duration of multiple hours on a peak day. The additional thermal storage could take the form of an additional hot water cylinder or a modern 'heat battery' thermal storage system which can provide the same amount of storage at a fraction of the size. Understanding the additional flexibility that additional thermal storage could provide is an important component of the evidence base.

3.2 Trial summaries

A desktop review was undertaken to understand which flexible heat trials have been completed, are ongoing or are planned in the UK. The list has been limited to those trials focusing on the residential sector, as per the target for CrowdFlex.

3.2.1 Customer Led Network Revolution (CLNR) – (2010-2014)

CLNR tested the potential for heat pumps to provide demand-side flexibility and how this varied with different control methods (direct control vs ToU tariffs) and different levels of thermal storage in the North East and Yorkshire. The trials were conducted on 380 existing homes, with air-source heat pumps retrofitted in the buildings. A wide range of building types were included in the trial, which provided a reasonable representation of the wider UK housing stock. The trial demonstrated individual customers were able to turn down their load for certain periods by up to 2.5kW.

Distinct features:

- This was the first UK trial to explore the technical concept of useful flexibility of heat pumps during peak time in winter
- The trial literature reports that tested how demand-side flexibility varied with different levels of storage. However, it is not stated in the literature what levels of storage were included or what impact this had on the level of flexibility.
- This was the only trial among those studied to explicitly include different building types as part of the trial. However, it is unclear from the literature whether the impact of building types on the level of flexibility was investigated.

3.2.2 Greater Manchester Smart Community Project – (2014-2017)

The Greater Manchester Smart Community Project was a pilot within the social housing sector across Greater Manchester to trial the deployment of 433 ASHPs, 23 with additional hot water buffer (storage) tanks, and 117 hybrid-ASHPs and test the effectiveness of Demand Response (DR) in 400 of those properties. The trial investigated the power capacity and response times for the automatic turn-up and turn-down of heat pump systems over an 18-month period. There were 47 turn-up events conducted between two one-hour periods (13:00-14:00 and 15:00-16:00) and 231 turn-down events during the morning and evening across weekdays and weekends. The reporting from the trial does not include an assessment of the variation of supply-driven flexibility across different months and seasons of the year.

The trial also modelled the effect of an agile tariff (hourly tariff) on encouraging peak shift in demand. The trial demonstrated that it is possible to achieve on average ~0.4kW of demand turn down per household for 60 minutes (against an average load of ~0.5kW) and that ~0.2kW of demand turn up response per household was achievable for between 30-60 minutes (against an average load of ~0.3kW).

Distinct features:

- This the only trial to consider the duration of flexibility in demand-driven and supply-side flexibility events.
- This is the only trial to examine the useful potential of heat pumps to provide supply-side flexibility.
- The trial has mentioned it installed additional buffer tanks with 23 of the heat pumps to increase demand response capacity. However, it is not stated what size the installed buffer tanks were. The impact the buffer tanks had on the level of flexibility does not appear to have been reported.

3.2.3 Project LEO

Project LEO is an upcoming trial working with 3 owner-occupied households in Oxfordshire to test whether domestic air-source heat pumps can deliver flexibility services to the network. The trial aims to see how the use of remote digital technology can generate financial benefit for households as well as the local energy system by regulating electricity demand in the area. The trial is set to be run during winter 2022.

Distinct features:

- It is currently unclear from the available information whether this trial will focus on demand-driven turn down or supply-driven turn up.
- The trial has only 3 participants, so will not allow an assessment of the variation in useful flexibility potential across a range of different building types and consumer types.

3.2.4 Centrica and Glen Dimplex

This is an upcoming trial that will examine the role storage heaters could have in balancing the grid as part of an advanced virtual power plant (VPP) platform. The trial will install smart storage heaters in 375 local authority and housing association properties. The storage heaters will be automatically controlled and operate to match the supply of renewable energy. The trial will be run for two years and will add 2.5MW of capacity to the existing 16MW on the VPP platform. The platform will participate in the Balancing Mechanism to trade flexible and stored energy to grid operators.

Distinct features:

- This the largest UK trial to test the useful potential of turn up/ turn down of smart storage heaters.
- This trial is being run for longer than one winter period which will help establish the long-term useful potential of turn up/turn down of smart storage heaters and, potentially, the impact of a wider range of weather and energy system conditions.

3.2.5 EQUINOX

This is an upcoming trial that will examine how the useful potential for heat pumps to provide demand-driven flexibility during winter peak periods varies with three novel commercial methods. The trial is aiming to recruit 1,000 participants and will run for three winter periods. The trial focuses on the winter peak period and will not explore supply-driven flexibility at other times of the year.

The three novel commercial methods are:

- Method 1 – 'Save in advance'
  - In this method, the energy supplier, and in turn, the end-customer, receive an upfront flexibility payment in return for offering a fixed, minimum obligation of flexibility.
- Method 2 – 'Save as you go'
  - In this method, the energy supplier, and in turn the end-customer, are not committed to a fixed, minimum obligation but instead have more control over the flexibility they offer based on (near) real-time signals delivered in an automated way.
- Method 3 – 'Save in advance & boost as you go'
  - The method will combine aspects of both upfront flexibility payments (M1) and dynamic price signals (M2).

The trial will also aim to demonstrate how varying risk/reward frameworks between DNOs, suppliers and customers can influence the amount, cost, and reliability of flexibility from portfolios for varying customer segments including the fuel poor and vulnerable.

Distinct features:

- This is the only trial that is focusing on the effect of novel consumer mechanisms on the useful potential for heat pumps to provide turn up/ turn-down flexibility.
- This is the largest recruitment of participants to test the useful potential for heat pumps to provide turn up/turn down flexibility.

3.2.6 Flexible Heat

Flexible Heat is an Ofgem Innovation project that has just completed the discovery phase. The aim of the project is to demonstrate the value of flexibility unlocked through domestic Thermal Energy Storage (TES). During its discovery phase, Flexible Heat undertook desk-based modelling that assessed the level of additional thermal storage required, for a typical home with an ASHP and hot water cylinder (HWC), to deliver the desired reduction in electrical demand during peak periods and then linked this to the storage capacity of different TES technologies. The analysis included various TES technologies: smart controls and thermal inertia, phase change materials (PCM), primary thermal storage (PTS), and electric batteries.

The project used the results of the modelling to develop a cost-benefit analysis (CBA) of the various TES technologies under consideration. The CBA included the balance of the capital and operational cost of the technologies with the potential revenues to the consumer generated through their use e.g., avoided curtailment, avoided reinforcement and flexibility payments by ESO and DSO. The project then performed a sensitivity analysis to explore how the CBA might be influenced by a range of value and cost variations.

The CBA determined that the baseline technology (ASHP + HWC) could be significantly mitigated using smart controls and the thermal inertia of the building. However, there were instances where thermal comfort might be compromised using this approach, thus not providing useful flexibility. The CBA highlighted PTS as the most cost-effective of the TES technologies but recommended all TES technologies to be evaluated further in the alpha phase. In the beta phase, Flexible Heat proposes a trial that will assess the efficacy of TES technologies to deliver peak demand reduction and evaluate commercial models that may deliver the desired modifications in demand profiles.

Distinct features:

- This is the only trial that is focusing on the effect of several different TES technologies on the useful potential for heat pumps to provide turn up/ turn-down flexibility.
- In the CBA, there are cost savings derived from the useful flexibility provided by the TES technologies, such as avoided curtailment and avoided reinforcements. However, it is not stated in the currently available information what the parameters for useful flexibility were in this project (e.g., duration of useful flexibility required, occupant comfort thresholds) or the time period these parameters were calculated over (e.g., peak day, winter season, whole year).
- This project has only recently completed its discovery phase, with no timeline set for its subsequent alpha and beta phases so it is not clear when a future trial is expected to occur.

3.2.7 Flexible Tower Block

Flexible Tower Block was a recent trial that aimed to explore the capability of smart storage heaters and hot water systems to provide demand-driven flexibility in Cartcraigs tower in the southside of Glasgow. The trial at Cartcraiags was scheduled for winter 2021/22; however, delays meant that this did not take place until the summer months. This meant that the trial could not examine useful flexibility from the storage heaters but instead monitored demand movement from hot water storage via a connected response control device.

In addition to the trial, the project identified commercial arrangements as the biggest barrier to practical deployment of flexibility of storage heaters and therefore performed desktop tariff modelling to determine the best options for customers and networks to make use of storage heaters within tower blocks. This modelling identified stretch E7/E10 tariffs as the best novel flexible smart tariff for storage heaters that could bring benefit to customer and networks.

Distinct features:

- This trial identified stretched E7/E10 type tariffs would be the most appropriate to help enable the useful potential for smart storage heaters to provide turn up/turn-down flexibility. However, it was not stated how these tariffs differ from traditional E7/E10 tariffs.
- The project states that it has generated learnings that show there is a large amount of flexibility available within storage heaters. However, the trial only monitored flexibility from hot water storage and the subsequent results from this are not publicly available, so it is unclear how the project demonstrated the large amounts of flexibility available within storage heaters.
- The trial does not state the number of participants within the trial, the timing of events (either which hours within the day or which months), or the useful flexibility observed during the events, so it is not possible to determine the learnings from it.

3.2.8 Project Re-HEAT

Project Re-HEAT is an upcoming trial where heat pumps and heat batteries will be installed in 150 homes in Scotland, with 50 homes located in the Highlands. The project will look to use smart controls to control the heat pump systems to demonstrate solutions to reduce demand on the electricity network.

Distinct features:

- The available information suggests the trial will focus on demand-driven turn down, but it is not clear whether it will also consider supply-driven turn up. It is also not clear whether the effect of building insulation, building type, and occupant comfort thresholds on the duration of useful flexibility will be considered.
- It is not clear from the current available information how long the trial will run for (i.e., will it consider the impact of a wider range of weather and energy system conditions) and the size of the heat batteries, installed as this will affect the duration of useful flexibility.

3.3 RAG assessment and summary of evidence gaps

Our assessment of the completed, ongoing and planned trials is shown in Table 3.2 below.

Key:

Y	Investigated / plan to investigate within the trial
P	Partially investigated / plan to partially investigate within the trial
N	Not investigated / do not plan to investigate within the trial
U	No information available

	CLNR	Greater Manchester	Project Leo	Centrica	EQUINOX	Flexible Heat	Flexible Tower Block	Project Re-HEAT
1. Heat pumps	Y	Y	Y	N	Y	Y	N	Y
2. Storage heaters	N	N	N	Y	N	N	P	N
3. Demand-driven flexibility	Y	Y	Y	Y	Y	Y	Y	Y
4. Supply-driven flexibility	N	Y	U	Y	N	U	U	U
5. Diurnal and seasonal variation (supply-driven)	N	P	U	Y	N	U	U	U
6. Building type and insulation (heat loss parameters)	P	P	N	U	Y*	P	U	U
7. Occupant comfort thresholds	N	N	U	U	Y*	N	U	U
8. Additional thermal storage	N	N	N	N	N	Y	N	Y

* These criteria are green for EQUINOX based on a discussion with EQUINOX on the 6th January 2023; however, the exact details of the information gathered is unknown at this stage.

Figure 11: Completed and upcoming flexible heat trials

3.3.1 Summary of evidence gaps

The assessment indicates that the trials studied have collectively considered some, but far from all, of the topics that we propose are important to develop a full understanding of the potential for heating to provide useful flexibility. While both demand-driven and supply-driven flexibility from both heat pumps and storage heaters have been considered (or will be considered) in these trials, there are important gaps relating to the coverage of different technologies, diurnal and seasonal variation, building characteristics and occupant behaviour.

First, none of the trials fully addresses how the useful potential for heat pumps to provide supply-driven turn up flexibility varies diurnally and seasonally. The analysis in Section 2 suggests that there is potential for useful supply-driven turn-up flexibility through pre-heating in both the winter and summer seasons, ahead of the heating peaks in both the evening (most frequently) and morning (less frequently). It is therefore important to gather evidence, through a real-world trial, on the seasonal and diurnal variation of useful supply-driven flexibility to address wind curtailment. The Greater Manchester trial performed supply-driven response events; however, these were limited to two one-hour events in the middle of the day ahead of the evening heating peak rather than covering other times of the day. The reporting from the trial has not included an assessment of the variation of supply-driven flexibility across different months and seasons of the year. Therefore, while the trial provides useful evidence on supply-driven flexibility, it does not fully address the question of how the useful potential for supply-driven flexibility varies seasonally and diurnally.

Second, none of the trials addresses how supply-driven flexibility changes according to building type and insulation level, or according to the variation in tolerance for deviations from the target internal temperature among different occupants. This is required to ensure the findings on heat flexibility can be linked to building heat loss and occupant heating requirements which is crucial to accurately determining the potential for supply-driven flexibility across the full building stock in Scotland and the UK. EQUINOX are gathering information on occupant comfort and building insulation; however, this trial is focused on their effect on demand-driven flexibility and not on supply-driven flexibility.

Third, none of the trials address how supply-driven flexibility changes with additional thermal storage. The presence of additional thermal storage can increase the duration of supply-driven flexibility by storing heat in off-peak hours for supply of space heating demand in peak hours. From the analysis in Section 2.3, additional thermal storage has the potential to increase the supply-side flexibility of heat pumps by up to five times on a cold peak day. Hence, it is important to understand the impact of different additional thermal storage sizes on supply-driven flexibility. The CLNR and Greater Manchester trials stated that they included thermal storage but did not state the level of storage included and did not report on the impact it had on the level of flexibility observed. Project Re-HEAT will include additional thermal storage but like CLNR and Greater Manchester, the level of storage that will be included is not clear. Flexible Heat is focused on the useful flexibility provided by additional thermal storage; however, this has only modelled the potential useful flexibility and it is not clear what their parameters for useful flexibility were.

3.3.2 Implications of including heat for CrowdFlex trial design

The evidence gaps identified in the section above represent the topics which could, in principle, be addressed by CrowdFlex to provide valuable additions to the evidence base on useful flexibility from heating. For CrowdFlex to properly address these topics brings a number of implications for the trial design, which are set out below:

- To capture the variation in useful flexibility across the different technology, building and occupant types (see below), the trial would need to include a significant number of homes with heat pumps or storage heaters. The trial should include **at least several hundred homes with electric heating technologies** to provide useful statistics and build on the existing evidence base. The precise target number of electrically heated homes would need to be defined through consideration of the sampling requirements relating to the range of other objectives of CrowdFlex, and the additional costs associated with recruitment and monitoring (see below) that this would entail. It should be noted that for electric heat technologies there will be variances in the manufacturer, quality of installations and installed metering, which may add to complexities and costs in running the CrowdFlex trials. However, these problems are not limited to electric heat and will likely be seen for other low carbon technologies.
- The trial participants with electric heating would need to occupy homes with a **range of EPC ratings** to capture variation in heat loss parameter. **For the homes with heat pumps, we propose these homes**

have a minimum EPC rating of C in order that they can be expected to provide a useful level of flexibility. This requirement is less stringent for homes with storage heaters given the associated additional in-built thermal storage capacity. We therefore propose a **mix of EPC A-C for participants with heat pumps, and a mix of EPC A-E for homes with storage heaters**. The EPC rating for each participant must be known so this information can be linked to the data from the flexibility events.

- The trial participants with electric heating would need to **occupy a range of building types**. The building type must be known for each participant so that the building type can be linked to the data observed from the flexibility events.
- The trial should **monitor the internal temperature of homes during flexibility events** and analyse the results **to understand the influence of consumer comfort threshold** on supply-side flexibility. An alternative approach to live monitoring is for occupants to log whether they experienced a change in their comfort levels, which is being employed by EQUINOX. This has the added benefit of reducing costs and is less complex than live monitoring, however, this will be less reliable than live monitoring. The benefits of either approach will have to be weighed against their relative costs and complexity.
- The trial should **spread flexibility events across different times of the day (ahead of both morning and evening peaks in heat demand) and across the year (including summer and winter seasons)** to test the diurnal and seasonal potential for supply-driven turn up flexibility.
- Where possible, the trial should **seek to include homes with additional thermal storage for space heating (not only for domestic hot water)**. Given the anticipated challenges in identifying and recruiting homes with additional thermal storage for space heating, as this is not typically included alongside heat pump or storage heating installations, we propose an ambition of at least 5% of the participating electric heating homes having additional storage.

In the final section below, we draw together the findings above to draw conclusions on the potential value of including heat in CrowdFlex.

4 Summary and recommendations

This report has assessed the value case for the inclusion of heat in CrowdFlex, considering the modelled potential value of flexibility from heating, and the coverage of flexibility from heating in other completed, ongoing, or planned trials. The conclusions of this work are summarised below.

We find that heat has significant potential to deliver useful flexibility, including a reduction in curtailment of wind generation of close to 100 GWh by 2030.

The report has analysed the technical potential for heat to provide useful demand-driven flexibility, where heat that can be shifted during peak times and supply-driven flexibility, where heat can be shifted to times of high-renewable supply, both whilst maintaining occupant comfort and reducing household energy costs. It has been demonstrated that heat has the potential to provide a limited amount of useful demand-driven flexibility on a peak day, but a potentially substantial amount of supply-driven flexibility through the year. Based on an analysis of hourly profiles of wind curtailment and heating demand, we find the greatest potential for useful flexibility in winter and ahead of the evening heating peak, when both curtailment and heat demand are highest. However, we also identify a significant, if reduced, potential across the whole year and ahead of the morning as well as evening heating peak.

For an example year between April 2020 and March 2021, our modelling finds that application of supply-driven flexibility using a heat pump in a typical home, through pre-heating alone, could deliver on the order of 448 kWh of reduction in wind curtailment, saving consumers approximately £78 per household. This compares with 217 kWh of wind curtailment for the same year for an electric vehicle (EV), suggesting that heating could provide roughly twice as much useful flexibility as EVs for a typical household. Under our deployment assumptions of 200,000 heat pumps in Scotland by 2030 and 1.2m by 2050, this equates to a potential annual reduction in wind curtailment of 92.5 GWh by 2030, and 543 GWh by 2050. **The high potential for heating to deliver curtailment reduction should be of considerable interest to CrowdFlex.**

We identify key gaps in the evidence base on flexible heat in other trials

The potential for useful flexibility relies on a range of assumptions and factors which are not yet well understood. These include:

- The impact of different electric heat technologies on the degree of useful flexibility and the typical timing (for example storage heaters and heat pumps have different profiles under 'passive' operation).
- The impact of building type and level of insulation, which drives the potential duration of useful flexible response.
- The impact of additional thermal heat storage in enabling further useful flexibility.
- The impact of occupant comfort thresholds – that is, the tolerance for variation from the target internal temperature during a 'pre-heating' event.

This report has assessed the scope of other completed, ongoing and planned trials, including coverage of heating system flexibility to draw conclusions on whether, following their completion, material gaps remained with respect to the above questions. Three important gaps have been identified based on the information available in the literature for those other trials:

- **None of the trials fully addresses how the useful potential for heat pumps to provide supply-driven turn up flexibility varies diurnally and seasonally.** Our modelling suggests that there is potential for useful supply-driven turn-up flexibility through pre-heating in both winter and summer seasons, ahead of the heating peaks in both the evening (most frequently) and morning (less frequently). It is therefore important to gather evidence, through a real-world trial, on the seasonal and diurnal variation of useful supply-driven flexibility to address wind curtailment.
- **None of the trials addresses how supply-driven flexibility changes according to building type and insulation level, or according to the variation in tolerance for deviations from the target internal temperature among different occupants.** This is required to accurately determine the potential for supply-driven flexibility across the full building stock in Scotland and the UK.

- **None of the trials addresses how supply-driven flexibility changes with additional thermal storage.** The presence of additional thermal storage can increase the duration of supply-driven flexibility by storing heat in off-peak hours for supply of space heating demand in peak hours. Our modelling suggests that additional thermal storage has the potential to increase the supply-side flexibility of heat pumps by up to five times on a cold peak day. Hence, it is important to understand the impact of different additional thermal storage sizes on supply-driven flexibility.

The technical potential assessment and gap analysis of other heating flexibility trials described above make clear that CrowdFlex could provide valuable additions to the evidence base on useful flexibility from heating.

For CrowdFlex to usefully address the evidence gaps, this would have implications for the trial design which could add material cost and complexity

For CrowdFlex to properly address these topics brings several implications for the trial design. These are set out and justified in more detail in the main report above, and summarised below:

- The trial should include **at least several hundred homes with electric heating technologies.**
- The trial should include a **mix of EPC A-C for participants with heat pumps, and a mix of EPC A-E for homes with storage heaters**, and the EPC rating for each participant must be known.
- The trial participants with electric heating would need to **occupy a range of building types**, and the building type must be known for each participant.
- The trial should **monitor the internal temperature of homes during flexibility events to understand the influence of consumer comfort threshold** on supply-side flexibility.
- The trial should **spread flexibility events across different times of the day (ahead of both morning and evening peaks in heat demand) and across the year (including summer and winter seasons)**.
- The trial should **seek to include homes with additional thermal storage for space heating (not only for domestic hot water)**, and we propose an ambition of at least 5% of the participating electric heating homes having additional storage.

While we have set out the potential benefits of including heat in CrowdFlex, and the implications for the trial design, we do not yet have the information required to quantify (cost) the potential disbenefits of including heat resulting from this. The costs/disbenefits of including heat in CrowdFlex are expected to include:

- the **increased level of effort required for recruitment and information gathering** (on building type and EPC rating for example);
- the **additional costs of internal temperature monitoring** requirements to understand impact of occupant comfort thresholds;
- requirement to test flexibility ahead of both morning and evening heating peaks and across the year, leading to the potential for **conflicts with the intended timing of flexibility events relating to other target technologies** (EVs or other appliances).

Our provisional recommendation is that there is value in including heat in CrowdFlex, subject to the quantification of the additional costs and disbenefits

We propose that the gaps in the evidence on flexible heat are sufficiently large to provide a strong value proposition to including heat in CrowdFlex as set out above.

However, the recommendation is provisional as we recognise that the benefits need to be weighed against the costs/disbenefits of including heat which we have listed above, as well as any others that the consortium identifies.

To better quantify the costs/disbenefits to allow a definitive decision on the inclusion of heat in CrowdFlex, we recommend the following next steps:

- Review Octopus' existing customer data to understand how many customers have heat pumps and storage heaters to better understand the additional challenges and costs of recruiting participants with electric heating, and to establish whether additional consortium members would be required to support this.

- Review the available data held by Octopus on customers' building type and EPC rating to establish whether or not an additional survey to gather this data would be required during the recruitment process to ensure sufficient coverage of different types and EPC ratings to deliver the required insights.
- Develop an estimate of the cost impact of monitoring internal air temperature during the trials (including the cost of the equipment, installation, data validation and analysis). An alternative approach to live monitoring is for occupants to log whether they experienced a change in their comfort levels, which is being employed by EQUINOX. This has the added benefit of reducing costs and is less complex than live monitoring, however, this will be less reliable than live monitoring. The benefits of either approach will have to be weighed against their relative costs and complexity.
- Assess the cost impact of including electric heating from the perspective of sampling, including whether this would reduce the sample size of other target groups for CrowdFlex (such as electric vehicle owners or others) and/or whether this would require an overall increase in the number of participants for the desired insights to remain statistically sufficient and significant.

The cost assessment relating to the above points should then be set against the potential value of including heat, to inform a final decision among the consortium.