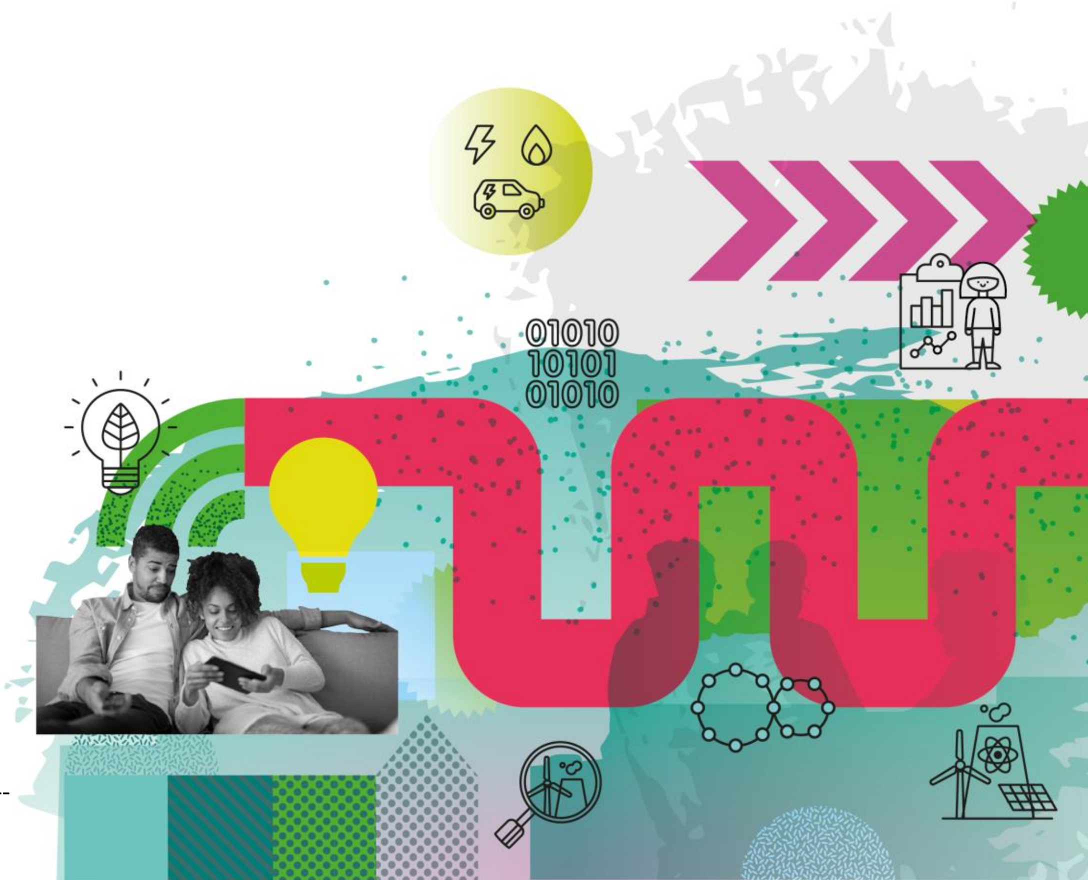
D8 Decarbonising Heat: Understanding how to increase the appeal and performance of heat pumps

Winter trial 2018/19

20th December 2019

Department for Business, Energy & Industrial Strategy



This document is marked as confidential

Document control

ESC programme name	Smart Systems and Heat Phase 2+
ESC project number	ESC00229
Version*	3.0
Status	Approved
Restrictions*	Open
Release date	20/12/2019
External release ID	N/A

* Refer to the Information Classification Policy

Review and approval

	Name	Position
Author	Tom Furlong	User Research Analyst
Author	Julien Caudron	Data Scientist
Author (Technical Report)	Warwick Brown	Analyst- ICT
Reviewer	Jody Osborn	Trial Team Manager
Reviewer	Matt Lipson	Business Leader
Reviewer	Simon Pearson	Business Leader
Approver	Denis Richard	Head of Major Programmes
Approver	Richard Halsey	Director of Innovation

Revision history

Date	Version	Comments
30/09/2019	1.0	Release
29/11/2019	2.0	Updated following BEIS feedback
20/12/2019	3.0	Minor text amendment. Restriction status changed to Open

Document protection

Arising IP

Description	Owner	Category
Decarbonising Heat: Understanding how to increase the appeal and performance of heat pumps (this report)	ESC	Confidential

Background IP

Description	Owner	Category*
Glossary text	ESC	Public
Temperature Clusters	ESC	Confidential
Heat Pump Website - Questions	ESC	Public

*Public / Confidential (Confidentiality agreement required) / Secure (Cannot be shared)

Trademarks, licenses and disclaimers

Description	Owner	Category*
N/A		

Contents

1. Executive summary

This project was part of the Smart Systems and Heat Programme. It used the Energy Systems Catapult's (ESC) Living Lab to trial a Hybrid Heating System – comprising controls, heat pump and gas boiler – to understand how households used it to get warm. A heat pump was integrated into a Home Energy Services Gateway (HESG) and tested in the Salford Energy House. Then a control strategy was chosen, and five households recruited to have the system installed in their homes.

It was hard to find homeowners with gas boilers who wanted a heat pump, even though it was being offered for *free*. They worried about energy bills, maintenance costs and, due to a lack of familiarity with the technology, what ownership of a heat pump entailed. Participants from the Living Lab were much more likely to accept heat pumps than members of the general public. Their previous positive experiences trying out new technologies may have increased their confidence that this new, unfamiliar heating system would work in their home.

Some potential volunteers lived in homes that proved unsuitable for our Hybrid Heating System. Four of the five homes that were suitable still needed additional work during installation. This included removing a hedge, running pipes up walls, replacing radiators with larger ones, laying concrete plinths to support heat pumps and installing cabinets for safety and aesthetical reasons.

All participants were able to use their Hybrid Heating Systems to reach the temperatures they wanted. They reported levels of comfort that were as good as, or better than they had reported with their gas boilers, though the improvement was not significant. The way they used their heating influenced how much the heat pump or gas boiler were used to warm their home. The system used the heat pump more if they scheduled long heating periods and rarely changed the temperature.

Two households frequently adjusted their temperatures. They were asked if they were open to heating their home for longer periods to use their heat pump more often. They were receptive to the idea but worried it might increase their heating bills. They were more willing to schedule longer heating periods if they were reassured that they would not be exposed to any increase in costs.

All participants were reluctant to make expensive investments to improve the energy efficiency of their homes just to enhance the performance of their heat pump. They were more interested in less costly upgrades and tangible benefits, such as lower bills or greater comfort.

To decarbonise domestic heat much higher numbers of consumers will need to replace their gas boilers with low carbon alternatives. Four participants were open to removing their gas boilers and relying only on a heat pump to warm their home if they could buy their heat as a service. This might bundle the costs of their heating system, installation, servicing and heat into one fixed weekly cost. They also said they would be more confident heating their home for longer periods to suit a heat pump if they could have cost certainty through a fixed price. Including the costs of any maintenance might also reduce their concern about installing unfamiliar heating technologies.

However, it is hard for businesses to sell heat as a service with low carbon systems like heat pumps. They will need to know how to use data to make sure they can deliver the experiences customers want and estimate the cost of delivery. Some data sources, like energy performance certificates and smart meters, may be open to access. Yet others, like heating schedules and control algorithms, are often closed. Improved interoperability could accelerate the emergence of new business models that can improve consumers' confidence in low carbon heating systems.

2. Introduction

2.1. Heat Pump trial 18/19

This report describes findings from a trial conducted over the winter of 2018-19 to understand if homeowners could use a Hybrid Heating System to get comfortably warm at home. It is part of the Smart Systems and Heat Programme and used the Energy Systems Catapult's (ESC) Living Lab of connected homes. The ESC integrated a Home Energy Services Gateway (HESG) with an Air Source Heat Pump (ASHP) and the homeowners' existing gas boiler to create a low carbon Hybrid Heating System. We then recruited five members of the public who were willing to trial the system and installed it in their homes.

The research goals of the trial were to:

- Identify if trialists could control the system to deliver their required heating outcome;
- Explore how the performance of the Hybrid Heating System compared with a gas boiler;
- Understand how results in real homes compare with Salford test-house in terms of ability to achieve required comfort levels;
- Explore insights into requirements for more sophisticated control solutions for Hybrid Heating Systems to perform as well as or better than gas boilers;
- Explore insights into the potential for Hybrid Heating Systems to support future heat as a service value propositions.

This project did not seek to explore the efficiency or running costs of the hybrid heating system.

2.2. Who are the Energy Systems Catapult?

The Energy Systems Catapult (ESC) was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth. The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research. We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, in order to decarbonise the energy system at the lowest cost.

2.3. What is the Living Lab?

Energy Systems Catapult has created a Living Lab of over 100 real-world homes spread across the UK, with each property upgraded to smart home levels that will be common by the middle of the 2020s. Each home is connected to our cloud-based digital platform, the Home Energy Services Gateway (HESG), which uses extensive in-home IoT sensors/actuators, advanced data science and machine learning algorithms, providing residents with room-by-room temperature control from their mobile phone.

HESG is an open, technology agnostic platform that draws on over four million data points per home per day and offers interoperability between energy service providers and device manufacturers, enabling them to test new products, services and business models directly with consumers.

3. Hybrid Heat Pump performance and integration testing

3.1. Summary of Salford Energy House research

Prior to offering and installing heat pumps within the Catapults Living Lab, testing was undertaken in the controlled environment of the Salford Energy House in Spring 2017. This sought to test and confirm the ability to integrate the ESC Home Energy Services Gateway digital platform to control a Hybrid Heating System comprised of a heat pump and gas boiler.

3.2. Learnings from the Salford House experiment

A hybrid heating system was chosen as it could meet homeowners' needs for heat without the disruption of insulating their home and removing their gas boiler as would have been required for a heat pump only solution.

Testing at the Salford Energy House confirmed it would be possible to control the heat pump using the Home Energy Services Gateway (HESG) and to test this within the ESC Living Lab. The testing did confirm that a heat pump is slower to warm than a boiler and that where the heating system is poorly designed the heat pump may not be able to produce acceptable heating outcomes in the context of time taken to deliver requested temperatures. The use of a bivalent or Hybrid Heating System combining the existing gas boiler and a heat pump provided flexibility to look at different strategies while minimising the risk that a participant may be left with unacceptable heating.

A conservative algorithm was chosen to minimise disruption to the participant

Based on insights from the SSH programme the control strategy chosen aimed to minimise the time consumers had to wait to get to the temperature they wanted. This involved using the gas boiler for achieving the target temperature and Heat Pump to maintain the temperature requested, both combining to form a Hybrid Heating System.

The testing conducted within the Salford Test house was primarily aimed at testing HESG integration and developing a control scheme. It was not intended to test the ultimate potential of the system, and therefore did not include the provision of other potential upgrades such as improved insulation or larger radiators, which could be deployed in a real-world environment. To minimise potential disruption to the occupier it was decided instead to opt for a more conservative algorithm.

The algorithm implemented meant the heat pump was tasked with maintaining temperatures and the following heating events delivered by the gas boiler:

- Pre-heating: the time to achieve the requested individual room temperature for the time scheduled;
- Topping up: enabling the temperature to remain in the requested target temperature band when the temperature fell below the minimum threshold;
- Manual override: a request from the user to increase the heating target from that scheduled immediately.

This strategy appeared to work well, being able to satisfy the occupier's heating requests as successfully as a gas boiler only system and so was implemented as the approach for the 18/19 Heat Pump trial.

The appendix contains a technical summary offering greater detail around the integration of the Home Energy Systems Gateway (HESG) with a heat pump (Appendix F). It includes a full description of the control algorithm. It also explains that the software included a specific parameter that could be adjusted to allow the heat pump to fulfil "topping up" temperature requests if desired. This was used during the trial to explore if the heat pump could deliver more of the heating requests (see section 12.2).

4. Recruiting owner occupiers with gas to install a heat pump

4.1. Identifying suitable candidates

Two different methods were used to recruit candidates to install the five Hybrid Heating Systems:

1. Facebook and Google adverts targeted the general public;
2. Living Lab participants who were interested in low carbon heating systems were approached. (See Appendix D for details)

Ultimately all the homes selected were recruited from Living Lab candidates. Only 9 of the 23,000 members of the general public who saw the advert completed the screening process. However, none of them passed the eligibility criteria to join the Living Lab (the criteria are detailed in the Appendix D). On the other hand, of the 21 Living Lab trialists approached, 5 agreed to having a heat pump retrofitted in their home.

Two of the five homes that had heat pumps installed were ESC employees. This was to enable us to pilot the process and confirm the software upgrades didn't cause issues before being deployed to other trialists. Research was conducted with the partners of both employees to improve the legitimacy of the feedback.

<u>Google and Facebook advertising campaign</u>

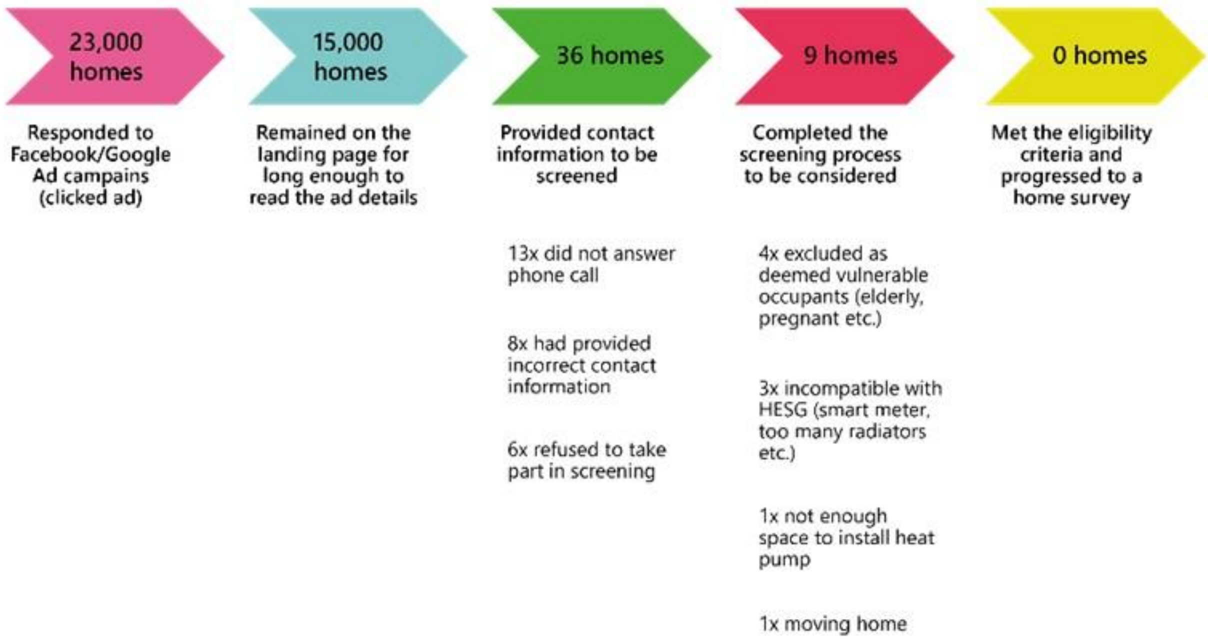


Figure 1: Representation of recruitment for those responding to Facebook and Google adverts

Living Lab recruitment

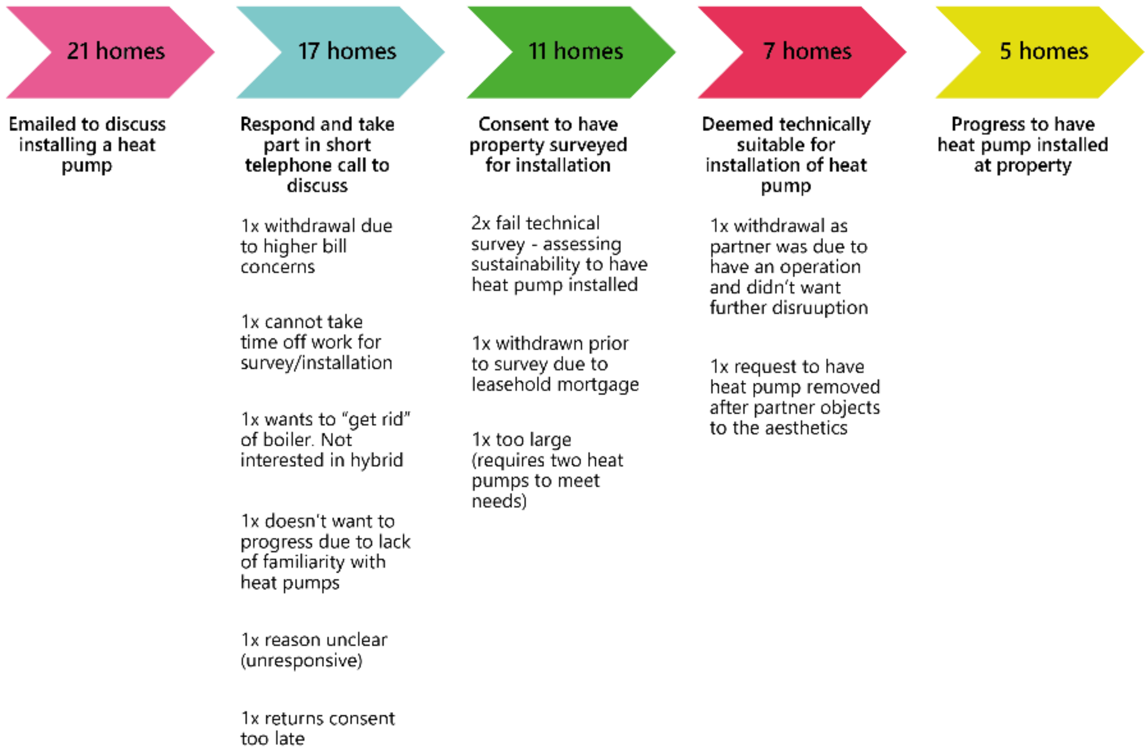


Figure 2: Representation of recruitment efforts focused on Living Lab participants.

4.1. Heat Pump Awareness

Most people hadn't heard of Heat Pumps

Prior to approaching participants, a survey was issued to all 100 Living Lab homes to find out how many were aware of heat pumps, with 80 participants responding to offer feedback. It was demonstrated that more than half of the respondents had never heard of a heat pump and subsequently never considered replacing their gas boiler with one. The Freedom project found that only 12% of respondents reported good or excellent awareness of Hybrid Heating Systems [1].

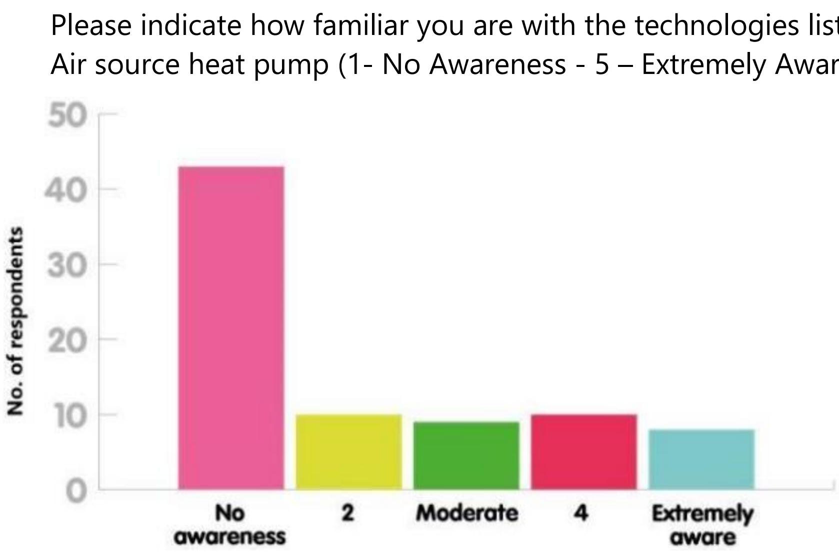


Figure 3: Representation of heat pump awareness amongst Living Lab homes

Mrs Watt[1] "You expect to have a boiler to heat the house, and that's all anybody knows. They (most people) don't even realise there's the option of any other form of heating. When the boiler's old you don't think 'is there any other alternative' you think 'the boilers old, I'll replace it with another boiler'"

4.2. Installation lessons and observations

People aren't prepared for installing a heat pump or aware of the practicalities involved

Before installing the equipment, participants were sent a variety of materials to prepare them for the installation (Appendix D), as well as taking part in a short informative telephone call. The materials dispatched included:

- Photographs of the equipment and the corresponding dimensions;
- A photograph of their property with an image of where the heat pump would be located, and the proposed pipe work super-imposed on it;
- A link to the manufacturers website where they could find detailed information of the model of heat pump being used (Mitsubishi Ecodan ultra quiet air source heat pump).

Despite this, all five properties indicated some surprise at the size of the heat pump and the scale of work required to install the equipment. A sixth home asked for the equipment to be removed after it was installed. They were particularly surprised at the scale of work required, in particular the required pipework. It later transpired that the homeowner had not shared the materials they had been sent with other members of their household.

It was concluded that issues of this nature could be circumvented in the future by implementing better processes prior to installation such as those detailed below:

- Dispatch an item that replicates the true dimensions of the heat pump before it is installed (for example a large cardboard box). This would allow householders to position the item in the proposed location and would mean they are better prepared for the changes they should expect.
- Provide more detailed images of the pipework required, showing not only its proposed route but also its diameter.
- Require all residents sign the consent form to indicate they have reviewed the proposed works, rather than just one.

4.2.1. Heat Pump removal

One home requested to have their heat pump removed after the installation had been completed. This home had initially been identified as a borderline pass following the home survey as it was considered a complicated installation. Specifically, the pipework would result in lost space in the utility room, and the wooden decking in the garden would have to be partially cut away to allow a stable concrete base to be installed. This was to support the weight of the heat pump and avoid the higher noise emissions that can occur when using a wooden base. Following a conversation to discuss the survey outcome, the homeowner indicated they were still keen to progress. Diagrams of the proposed work and a consent form offering greater detail on the work required were dispatched and promptly signed and returned.

1. Pseudonyms have been assigned to all participants discussed within this report to protect their anonymity

It would later transpire however that the homeowner had not discussed the proposed works with their partner in any detail, and additionally had not shared any documentation about the heat pump or the proposed installation. Consequentially their partner was poorly prepared for the scale of the work and the size of the equipment which resulted in a request to have the heat pump removed the day following the completion of the work. When exploring the reasons behind their partners' decision, the following key issues were identified:

- Disliked the appearance of the equipment and associated pipework;
- Anxious the noise could cause friction with their neighbours who were sensitive to noise;
- Frustrated we could not provide any assurance of how their energy bills would change;
- Believed heat pumps were a new technology and did not want to be a test subject;
- Concerned the heat pump would not be able to deliver the warmth they required;
- Unconcerned about reducing carbon emissions.

Notably, the household never actually heard the noise of the heat pump or discovered whether if it was capable of delivering the warmth they desired, as it was never actually turned on in their home.

Partner's comment, "I wanted to say no straight away, I didn't want it from the start"

A discussion was held with the partner to understand what they would need to consider switching to low carbon alternative to a gas boiler in future. This revealed the following requirements:

- Be unable to see the heat pump or any pipework from inside their home;
- Would have to be confident the system could deliver the temperatures they desired;
- Noise emissions would have to be minimal;
- Guaranteed reduction in their energy bills.

Partner's comment, "Of course it's only worthwhile if I save money!"

One way to solve most of these problems might have been to conceal a smaller heat pump at the side of their property. However, this solution was not explored with the household in this case.

5. Summary of findings

5.1. Hybrid Heating System performance

The algorithm worked as designed and the Hybrid Heating System was able to deliver the same heat outcome for each home as had been accomplished when using a gas boiler

The Hybrid Heating System delivered the temperatures requested as well as the gas boilers had. There was only 1-2% difference in the proportion of target temperatures met, with each system doing slightly better than the other in some cases.

5.2. Comfort outcome

Participants were as comfortable with the Hybrid Heating System as with their gas boiler

Participants reported no change in their level of comfort after having the heat pump installed. Some self-reported higher comfort scores after their heat pump was installed. However, following discussion none felt that their comfort had really changed. In addition, participants were unable to distinguish whether the heating was being provided by the boiler or the heat pump.

Mrs Johnson "I can't tell if it's the heat pump or the boiler running when I'm in the house, I have to go outside and look to see if the fan is moving"

5.3. Heating behaviours

Household heating behaviours had a significant impact on the proportion of heating delivered by the heat pump (for the specific design of algorithm deployed in this trial).

Heat pumps delivered between 6% and 63% of the heating in different homes. They delivered less of the heating in households that frequently increased the target temperature either because they had scheduled short periods of heating or set temperatures cooler than they found to be comfortable. This was because the control algorithm used the gas boiler to increase the target temperature.

Participants did not change their behaviours when heating with a heat pump

Only one household changed the way they were controlling their heating after the heat pump was installed. However, this household included an ESC member of staff who knew how heat pumps worked and how the control algorithm had been designed. None of the other households said that they had changed how they controlled their heating after the heat pump was installed. They knew little about heat pumps and so may have expected them to perform the same way as their gas boilers.

Participants were receptive to changing how they schedule their heating but needed reassurance that their bills wouldn't increase

Households who frequently adjusted their target temperatures or scheduled their heating intermittently were asked if they were open to heating their home for longer periods to increase the amount of time their heat pump was used. They were receptive to the idea, but worried that it would increase the cost of their heating. They were more willing to schedule longer periods of heating if they were given reassurances that they would be reimbursed if their provider issued increased energy bills, although this was not calculated by the ESC.

5.4. Heat Pump receptiveness

Participants indicated they were put off accepting a free heat pump because they were worried about the cost of their energy and the cost to maintain the equipment

A survey of Living Lab participants found upfront payment and running costs were the biggest reasons that put them off low carbon systems. This is consistent with other research that found a strong relationship between lower energy costs and satisfaction with the heating system [2].

Discussing the offer of a *free* heat pump with participants revealed more nuance. Some were still put off by uncertainty around whether their running costs would increase. Others worried that they would not be able to use the heat pump to get comfortable, complained about the appearance, or disliked the idea it would make a noise. They said hearing that their friends or family had enjoyed positive experiences would likely reduce their concerns.

Consumers hold very different preferences when it comes to heating [3] Those who accepted the offer of a free heat pump never cited financial aspects as a top concern, with regards what they prioritise from their heating. This suggests that people who are less worried about cost might be more open to heat pumps.

5.5. Heat as a Service as an enabler for Low Carbon Heating

Four of the five participants with a hybrid system were open to removing their gas boiler and relying entirely on a heat pump if they could buy their heat as a service

Participants discussed the concept of buying their heat as a service where they would pay a fixed weekly amount for their energy, maintenance and their heating system. All but one said they would feel confident removing their gas boiler and relying only on their heat pump if they could buy their heat in this way. They explained that fixing the costs of their heating would give them the confidence to leave their heating on for the longer periods of time a heat pump would need to warm their home. Additionally, having inclusive servicing and maintenance would offer confidence in embracing an unfamiliar technology. This concept was also more popular than the existing way of buying heating when it was tested it with the rest of Living Lab participants.

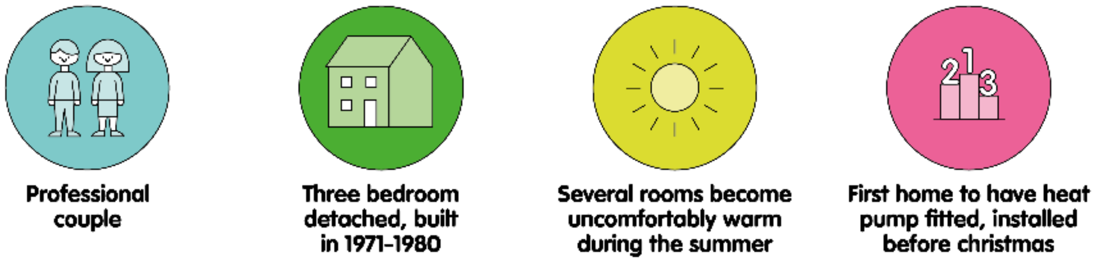
5.6. Openness to insulating the home

People were more open to insulating their home to improve comfort and lower bills than to make their home more suitable for a heat pump

Participants were asked if they were open to using their data to get advice about renovations to improve their comfort, lower energy bills and make their home more suitable for a heat pump. They all said they would be far more likely to make changes supported by data because they thought they were more likely to have the desired effect. They all preferred less costly improvements, shorter payback periods and renovations that improved comfort or cut bills over those that improved the performance of the heat pump.

6. Case study: Mrs Watt

6.1. Who are they?



- This participant was previously identified as 'Steady and Savvy' when clustering heating behaviours (rarely adjusts the heating schedule and almost never uses the override function). (More information about the different temperature clusters that were identified during the 2017/18 winter trial is provided in Appendix E [4])
- This household uses relatively little heating compared with the other households in our sample, with one of the least active heating systems, with both the boiler and heat pump inactive for around 87% of the time.

6.2. Home survey and installation

This home appeared to be a reasonable candidate for an air source heat pump because it was located on an end plot, and there were a couple of places the heat pump could be placed. The gas boiler is contained within the airing cupboard with a hot water cylinder in the loft.

There were, however, a few challenges to overcome. A bush had to be removed and a concrete plinth installed to provide a stable base for the heat pump in a location that minimised intrusive pipework. Flow and return pipes were run up the outside wall and into the loft to minimise disruption. The low loss header was put into the loft to retain the space in the airing cupboard. The owner also replaced one radiator with a larger size to improve heating levels in one room.

6.3. Heating behaviour vs hybrid heating system performance

Mrs Watt has a predictable routine, and prefers temperatures to be 18, 19 or 20 degrees, depending on the room. She prefers to schedule most of her heating and as such the manual override function is rarely used. When the weather gets colder her preference is simply to "wrap up warmer" which means that even in the colder months her heating schedule is consistent.

Following the heat pump's installation Mrs Watt demonstrated the lowest reliance on the manual override facility of all homes in the trial, with this function accounting for less than 1.5% of all effort generated by the gas boiler. Mrs Watt indicated, however, that she now only schedules 20 degrees, rather than the previous range of temperatures. This was to allow the heat pump to better deliver her heating and was based on advice from her partner (an ESC employee). This household displayed the second highest reliance on heat generated by the heat pump (information regarding the data analysis techniques used can be found in Appendix E).

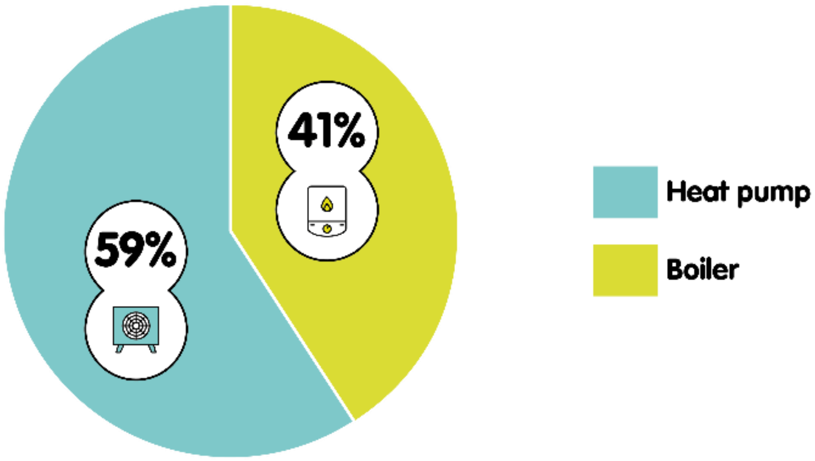


Figure 4: Proportion of heat delivered by boiler against that delivered by heat pump for Mrs Watt when comparing periods of similar weather [5]

6.4. How successful was the system in delivering their heating?

Before the hybrid heating system was installed, HESG was able to deliver Mrs Watt's heating requests 99% of the time when paired with a gas boiler. Following the installation of the heat pump, the performance was seen to be equal, also accomplishing a success rate of 99%. This percentage represents the time weighted average of the data presented in the charts below (the lounge has more influence on the average than the library because it is heated for more hours).

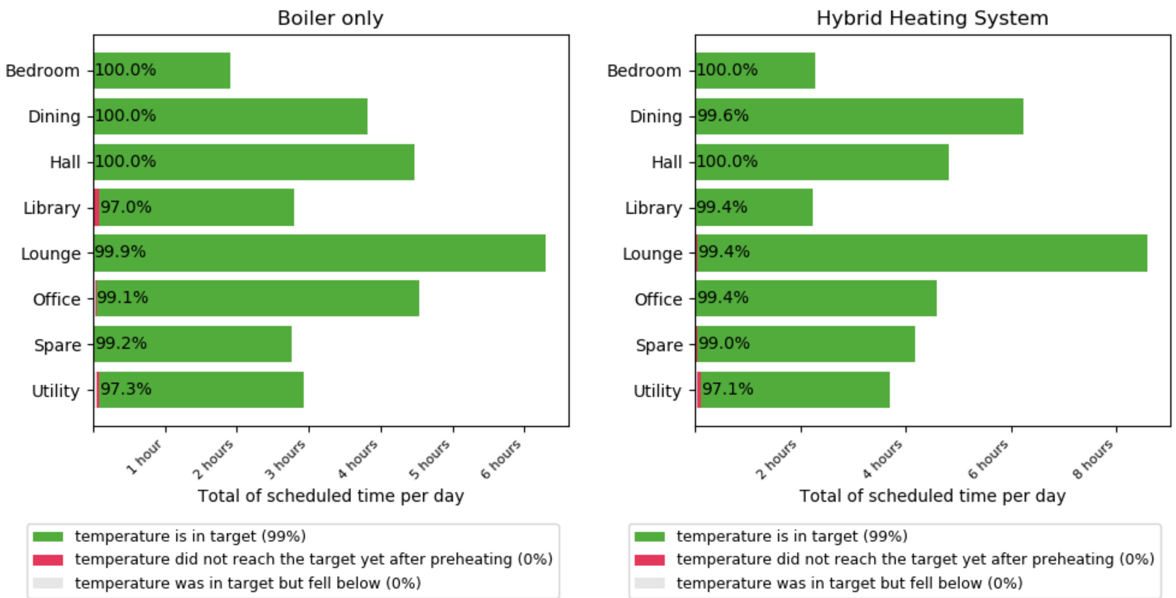


Figure 5: Percentage of time heating temperature requests are accomplished, missed and fell below target during a heating period for Mrs Watt, gas boiler performance against hybrid heating system. The number in brackets shows the percentage of time the target was not met overall (green), was not reached at the start of a heating period (red) or fell below the target during a heating period (grey).

6.5. Changes observed in experience and behaviour

To explore whether households exhibited any change in behaviour or heating experience following the installation of the hybrid heating system, several consistent metrics were used across all homes. These values were captured when the homeowners were heating with a boiler only, and again when using the hybrid heating system. These metrics included;

- Comfort level: A self-reported comfort score given on a 5-point scale, 5 indicating full satisfaction
- Overrides: A request from the user to increase the heating target from that scheduled immediately
- Warm Hours: An hour of time when a user requests any room to be warmed to a target temperature

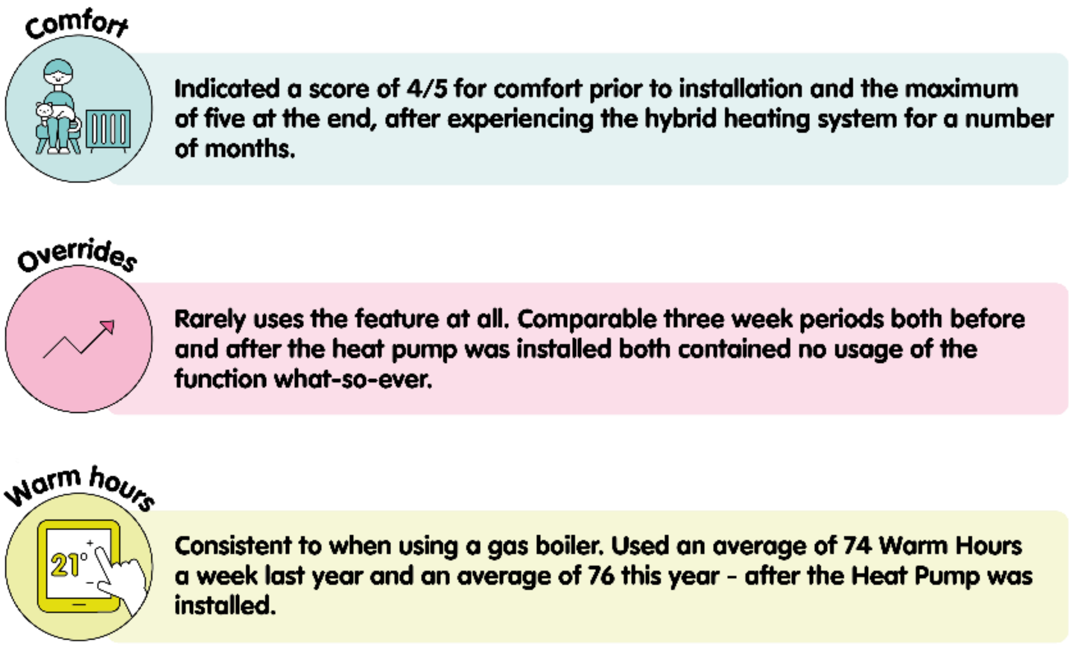


Figure 6: Representation of behaviours observed and reported for Mrs Watt – gas boiler compared with heat pump experience

7. Case study: Mrs Green

7.1. Who are they?

Family of three, two parents and their older child (18+)

Three bedroom, semi-detached house built in 1960s

Unpredictable routine. Shift work (weekends and overnight), and work from home

Recently built a large extension to home, potentially influencing experiences/behaviours

- Previously identified as an 'On-Demand Sizzler 'when clustering heating behaviours (favours higher temperatures, and often uses heat spontaneously rather than scheduling it in advance).
- Frequently amends heating schedules due to unpredictable routines and to be less wasteful.

7.2. Home survey and installation

This home had a good space for the heat pump in the back garden and suitable levels of insulation. However, they had recently extended the property and installed a new kitchen, this meant that there was limited available (safe) space to install some of the equipment required. Therefore, some of the heat pump components were installed in an external cabinet in the back garden, beneath the kitchen window. A nearby drain was used for defrost discharge and a long external cable run to the consumer unit at the front.

7.3. Heating behaviour vs hybrid heating system performance

After the hybrid heating system was installed, Mrs Green continued to heat her home as she previously had, setting only a basic heating schedule and relying heavily on the override facility to make impromptu changes. As a result, the heat delivered to this home was initially delivered almost entirely via the gas boiler rather than by the heat pump (with only 6% of heating delivered by the heat pump, the lowest across all homes).

More than 21% of the effort delivered by the boiler resulted from the tendency to use the override feature, rather than schedule heating in advance. This figure was more than three times the amount observed for any other user (with all other homes falling between 1.5% and 7%).

In addition to relying heavily on the manual override facility the participant scheduled heating in shorter blocks, as they perceived these to be less costly and more environmentally friendly. This meant the home was often cool and took a long time to warm up to the temperatures requested.

The control algorithm used the gas boiler to pre-heat the home and meet the overrides requested. The heat pump was only used to maintain these temperatures for the short periods of time they were scheduled.

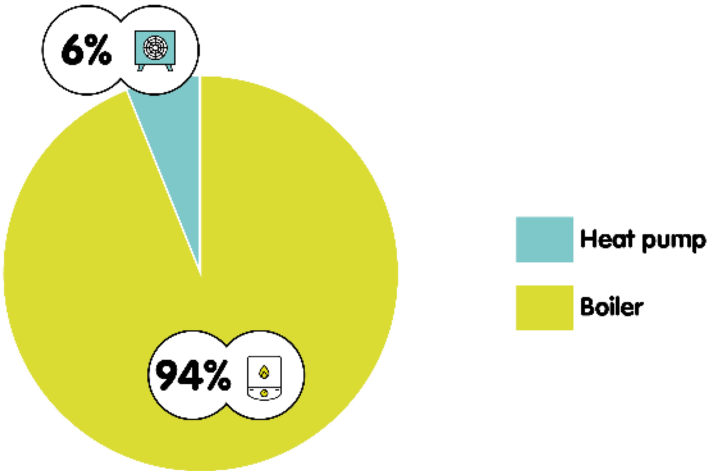


Figure 7: Proportion of heat delivered by boiler against that delivered by heat pump for Mrs Green when comparing periods of similar weather [5]

7.4. How successful was the system in delivering their heating?

When comparing periods of similar weather [5], the hybrid heating system demonstrated a success rate similar to that observed when only using a gas boiler. Requested temperatures were accomplished 91% of the time when delivered by a gas boiler and 92% of the time when using the hybrid heating system.

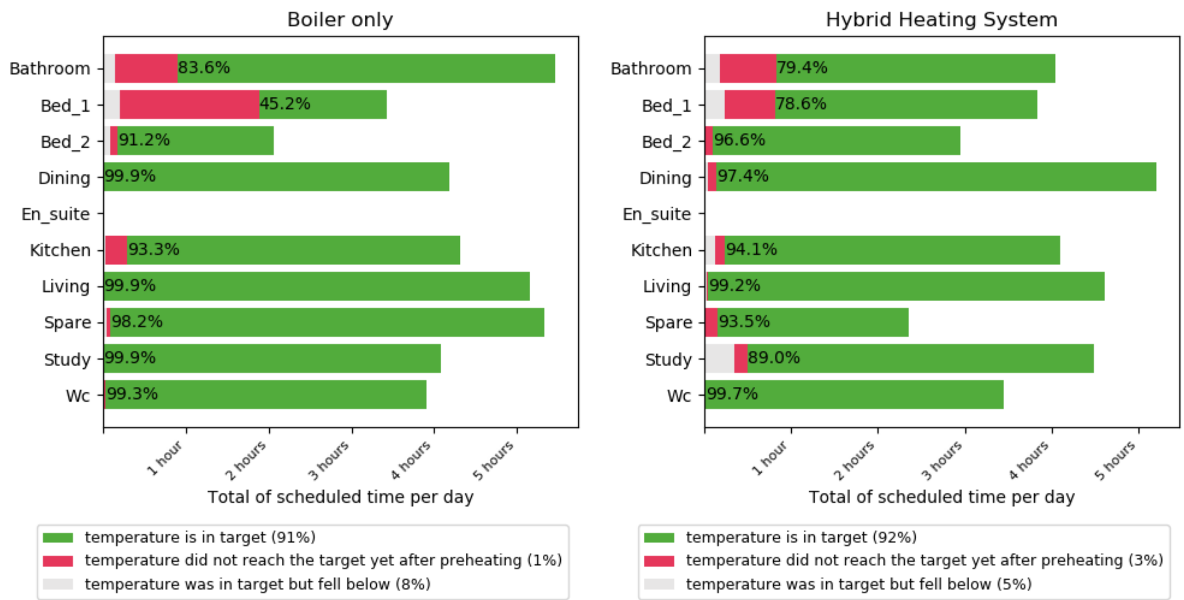


Figure 8: Percentage of time heating temperature requests are accomplished, missed and fell below target during a heating period for Mrs Green, gas boiler performance against hybrid heating system. The number in brackets shows the percentage of time the target was not met overall (green), was not reached at the start of a heating period (red) or fell below the target during a heating period (grey).

7.5. Changes observed in experience and behaviour

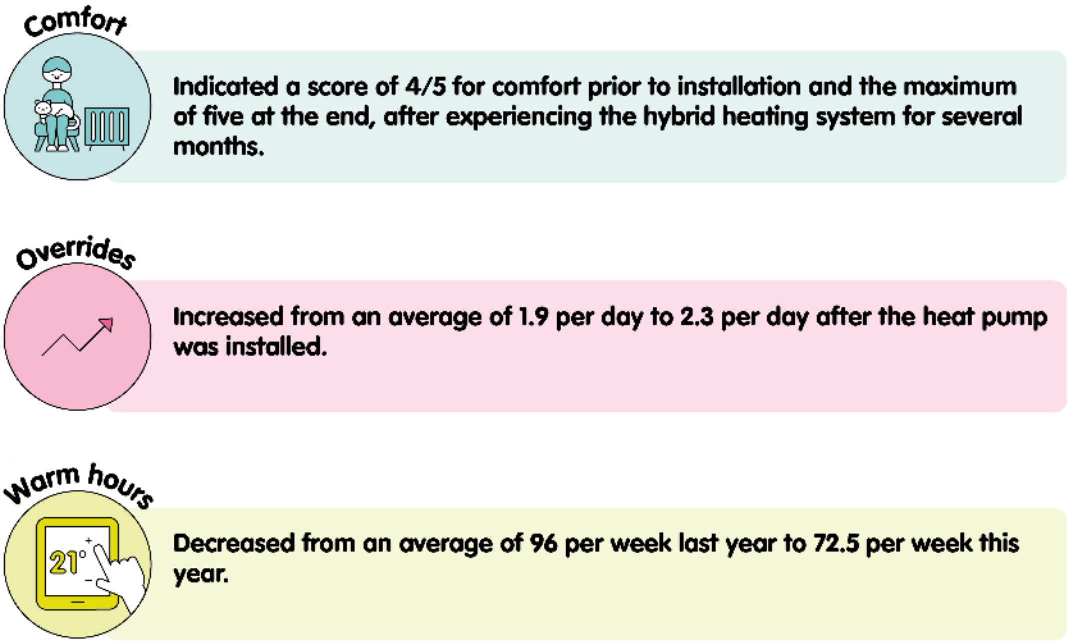


Figure 9: Representation of behaviours observed and reported for Mrs Green – gas boiler compared with heat pump experience

Mrs Green reported making no changes to how she was heating her home. However, the data revealed that she was overriding more often, perhaps because she had scheduled fewer hours.

8. Case study: Mr Dean

8.1. Who are they?

Family of four, two parents and two young children

Four bedroom detached property built in 1985

Has a modern, energy efficient home

Routine predictable enough to schedule almost all heating

- Previously identified as 'Steady and Savvy' when clustering their heating behaviour (favouring cooler temperatures of around 19-20 degrees, and only heating a few rooms at once).
- Has their heating scheduled to be on for 24 hours a day, and rarely overrides or makes adjustments.
- One of the more energy efficient homes in the trial with temperatures seen to decrease slowly after the heating has been turned off.

8.2. Home survey and installation

There were no obstacles to installation identified in this property. It had suitable levels of insulation and the boiler was located in the garage with uninhabited space available for the low loss header. This meant the heat pump could be located on the rear wall of the garage on the opposite side to the existing gas boiler. There was an enclosed, secure space with a drain nearby, the noise should cause no disturbance and the household were satisfied with the location proposed.

8.3. Heating behaviour vs hybrid heating system performance

After the hybrid heating system was installed, Mr Dean did not deviate from his carefully considered 24-hour a day heating schedule which he had refined over the previous winter.

Whilst the heating was typically scheduled in some shape or form 24 hours a day, the heating system was only active 27% of the time. This was because the home was efficient, only a few rooms were heated at once and temperatures were never set above 20 degrees.

The heat pump delivered a higher proportion of the heating in this home than for all the others, with the gas boiler contributing only 37% of all heating delivered.

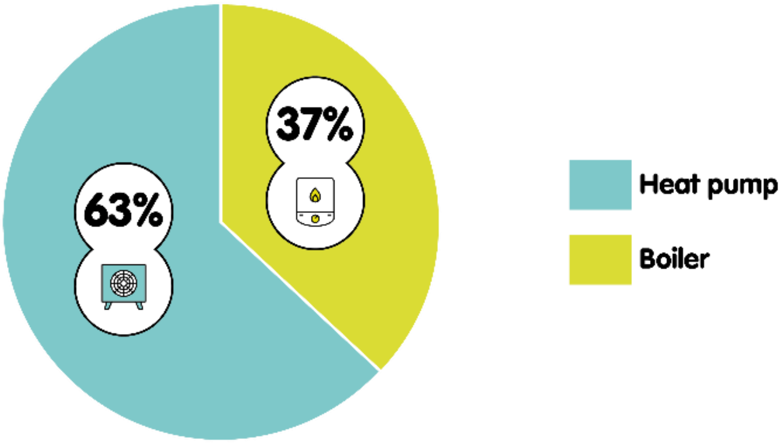


Figure 10: Proportion of heat delivered by boiler against that delivered by heat pump for Mr Dean when comparing periods of similar weather [5]

8.4. How successful was the system in delivering their heating?

In Mr Dean's home it was again demonstrated that the heating system performed in a way that was fairly consistent with the gas boiler in delivering the target temperature. A success rate of 99% had been observed when delivered by the boiler only, with the hybrid heating system accomplishing 98% success.

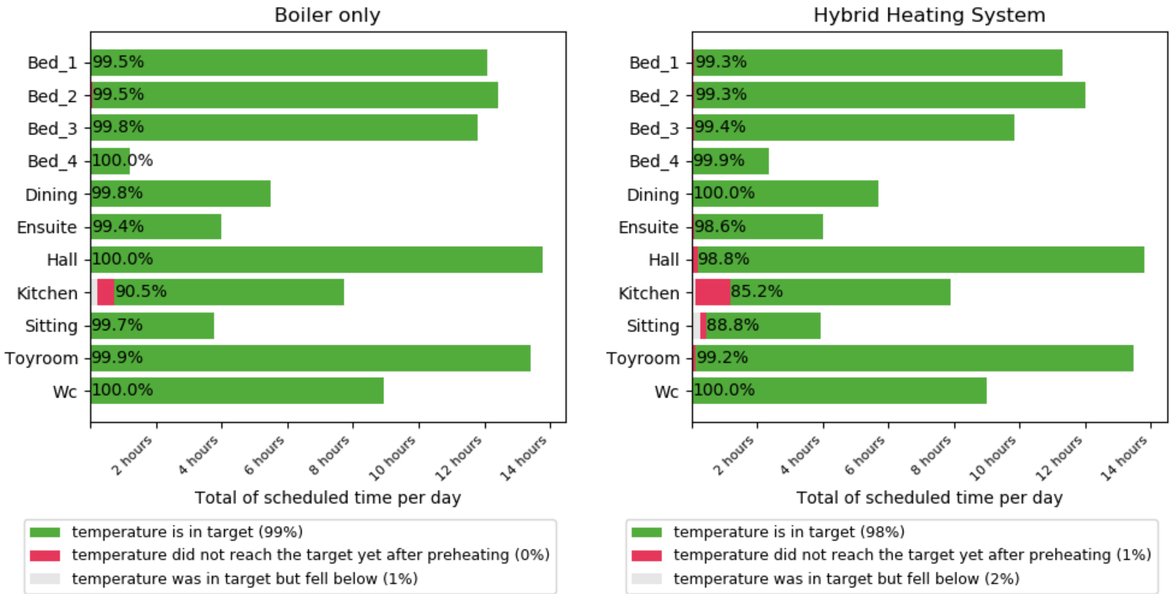


Figure 11: Percentage of time heating temperature requests are accomplished, missed and fell below target during a heating period for Mr Dean, gas boiler performance against hybrid heating system. The number in brackets shows the percentage of time the target was not met overall (green), was not reached at the start of a heating period (red) or fell below the target during a heating period (grey).

Mr Dean: "There's been no difference to the comfort since the heat pump has gone in. I haven't found anything different."

8.5. Changes observed in experience and behaviour

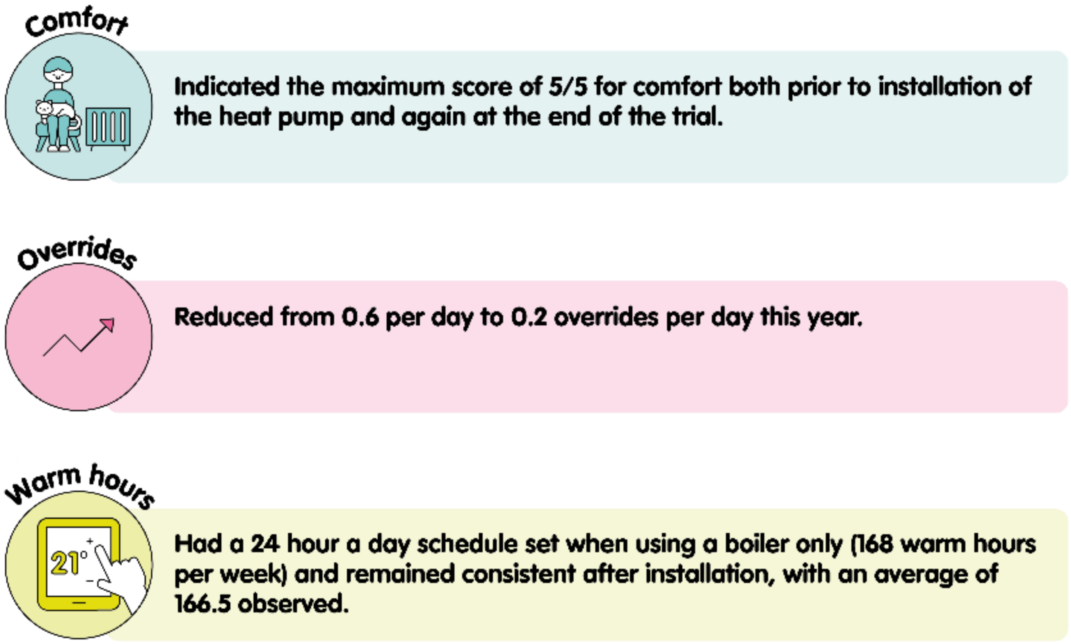


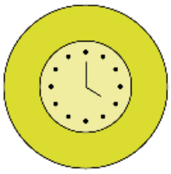
Figure 12: Representation of behaviours observed and reported for Mr Dean – gas boiler compared with heat pump experience

9. Case study: Mrs Johnson

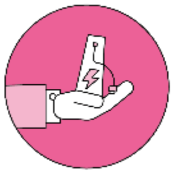
9.1. Who are they?

Family of five, two parents and three children

Five bedroom semi-detached house built 1950-1980s



Predictable working pattern



Is environmentally conscious and already has an electric vehicle

- Previously identified as 'Steady and Savvy' when clustering their heating behaviour.
- Used among the fewest warm hours across all homes in last year's trial.
- Tends to heat to cooler temperatures, but often boosts the temperature within a heating period if she is feeling cold.

9.2. Home survey and installation

This property had a suitable level of insulation and the heat pump could be installed in the garden, beneath the kitchen window near a drain that could be used for defrost discharge. The boiler was in a secure and easily accessible loft space.

However, a concrete plinth had to be installed to provide a stable base for the heat pump as there were slate chippings in the garden. Partial surface mounted cabling was also required from the floor to the ceiling in the landing and the bathroom radiator had to be replaced with a larger one.

9.3. Heating behaviour vs hybrid heating system performance

Mrs Johnson used her heat sparingly after her heat pump was installed. Her heating system was one of the least active of all the homes with a Hybrid Heating System. Despite using relatively little heating, Mrs Johnson put the heating on for her children who spend most of their time upstairs in their bedrooms. As such their bedrooms were always heated in the mornings before school and when they got home from school until they went to bed.

However, it proved to be hard to heat the upstairs bedrooms to the target temperatures. This may have been because some of the rooms upstairs, in particular bedroom 3, was positioned above an uninsulated garage. As the heating system struggled to meet the set point temperatures, the control algorithm often used the gas boiler to boost the heating – thereby reducing the time the heat pump was used to maintain the temperatures. As such this home experienced the second lowest proportion of heat delivered by the heat pump.

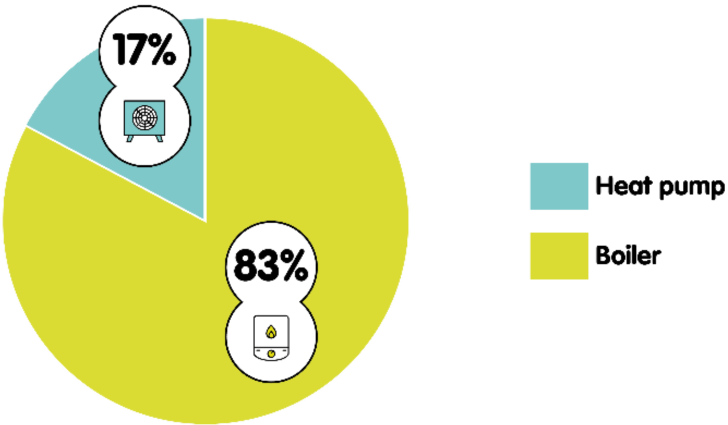


Figure 13: Proportion of heat delivered by boiler against that delivered by heat pump for Mrs Johnson when comparing periods of similar weather [5]

9.4. How successful was the system in delivering their heating?

In exploring the success rate for the heating system to accomplish the temperatures requested, Mrs Johnson's home was fairly consistent, with a slight fall from 98% when delivered by a gas boiler to 96% when delivered by the Hybrid Heating System. As outlined above, the bedrooms appeared to be the troublesome area. It may be that this small fall in performance was caused by the bedrooms taking slightly longer to warm up than other rooms (see Appendix C for a discussion of this point).

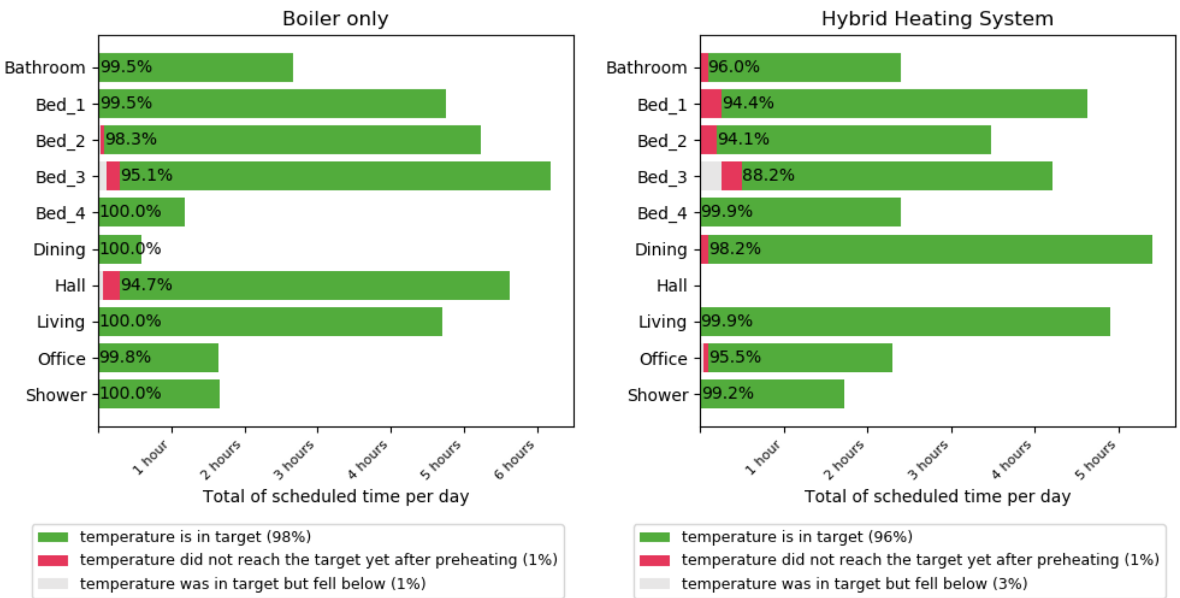


Figure 14: Percentage of time heating temperature requests are accomplished, missed and fell below target during a heating period for Mrs Johnson, gas boiler performance against hybrid heating system. The number in brackets shows the percentage of time the target was not met overall (green), was not reached at the start of a heating period (red) or fell below the target during a heating period (grey).

9.5. Changes observed in experience and behaviour

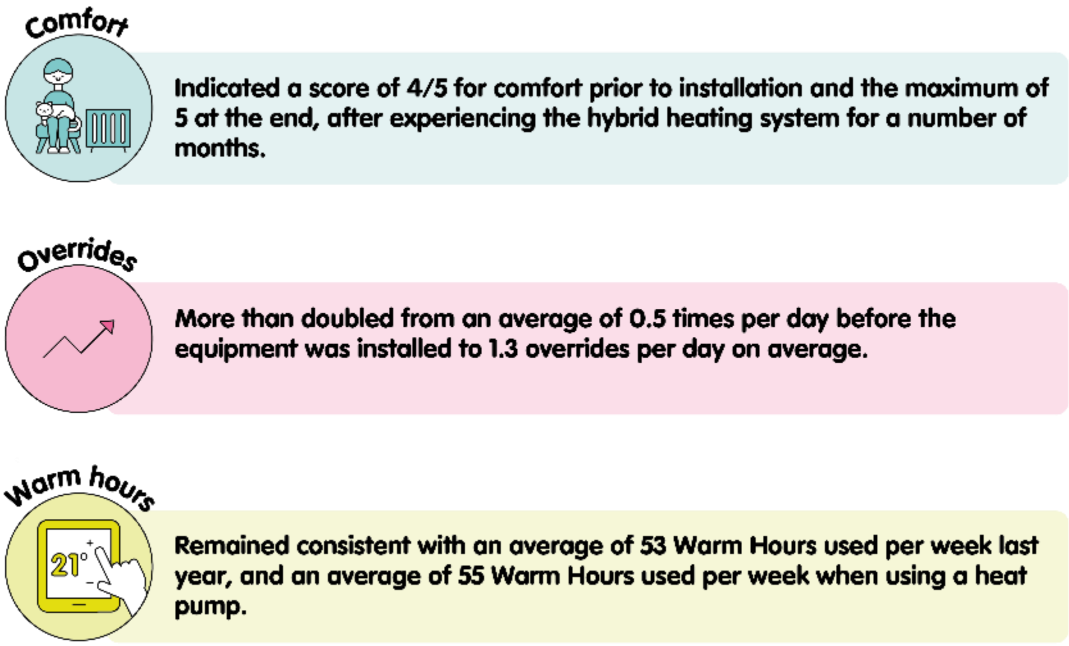
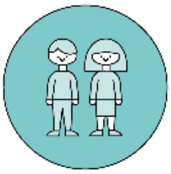


Figure 15: Representation of behaviours observed and reported for Mrs Johnson before and after the hybrid heating system was installed

Mrs Johnson was not aware of changing how she used her heating. However, she did say that she was not the only member of her household who controlled the heating and that others may have changed it without her realising.

10. Case study: Miss Coltrane

10.1. Who are they?



Professional couple

Three bedroom mid-terrace built around 1990

Thermally sensitive, always prioritise comfort over cost

New to the trial and have never experienced the controls with a boiler

- New to the trial, so previous heating behaviours are unknown
- Only override the schedule in the living room and bedroom where comfort is of paramount importance
- Scheduled their heating to prevent the noise waking them up early in the morning

10.2. Home survey and installation

There was a sheltered space for the heat pump beneath the kitchen window in the back garden with a nearby drain available for defrost discharge. It had to be placed just to the left of the centre of this wall to meet requirements for minimising noise disturbance. The boiler was located in a large, uninhabited attic space, which allowed major system components to be installed efficiently and with minimal disturbance.

However, one kitchen radiator needed replacing with a larger one and bedroom wardrobes had to be moved to attach electric cables to the bedroom wall. Specialist high-level equipment was required to route pipework from the heat pump to the boiler in the attic. The property may also have had less insulation than normally recommended for an 8.5kw heat pump to warm the home up in cooler weather. This was not considered a concern here because the existing gas boiler was also being used.

10.3. Heating behaviour vs hybrid heating system performance

Having only ever experienced using the controls with the hybrid heating system it is not possible to compare Miss Coltrane's heating behaviours before and after the equipment was installed.

Miss Coltrane said she often overrode her schedule to increase the temperature when the heat pump was first installed, but after a while scheduled higher temperatures instead. She is thermally sensitive and enjoys a range of temperatures from 16 to 21 degrees, but sometimes higher. Heating to cooler temperatures and a rare use of the manual override feature meant that the heat pump was able to deliver more than half of the requested heat at this property.

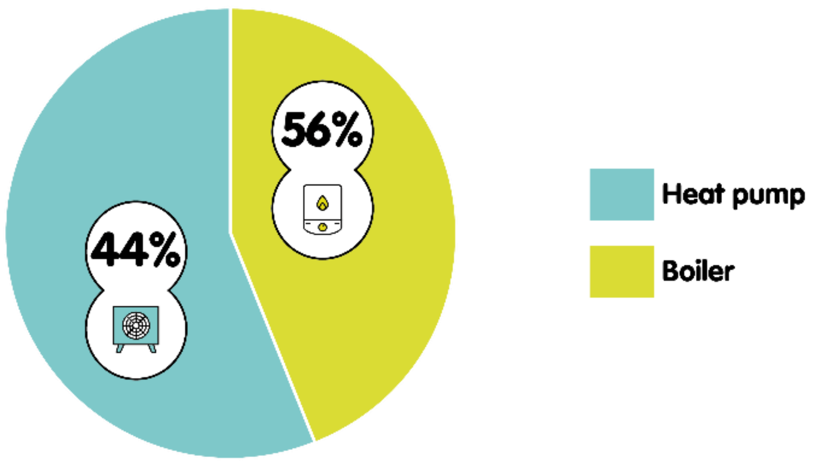


Figure 16: Proportion of heat delivered by boiler against that delivered by heat pump for Miss Coltrane when comparing periods of similar weather [5]

10.4. How successful was the system in delivering their heating?

Miss Coltrane was able to accomplish her chosen temperature request 97% of the time using the hybrid heating system.

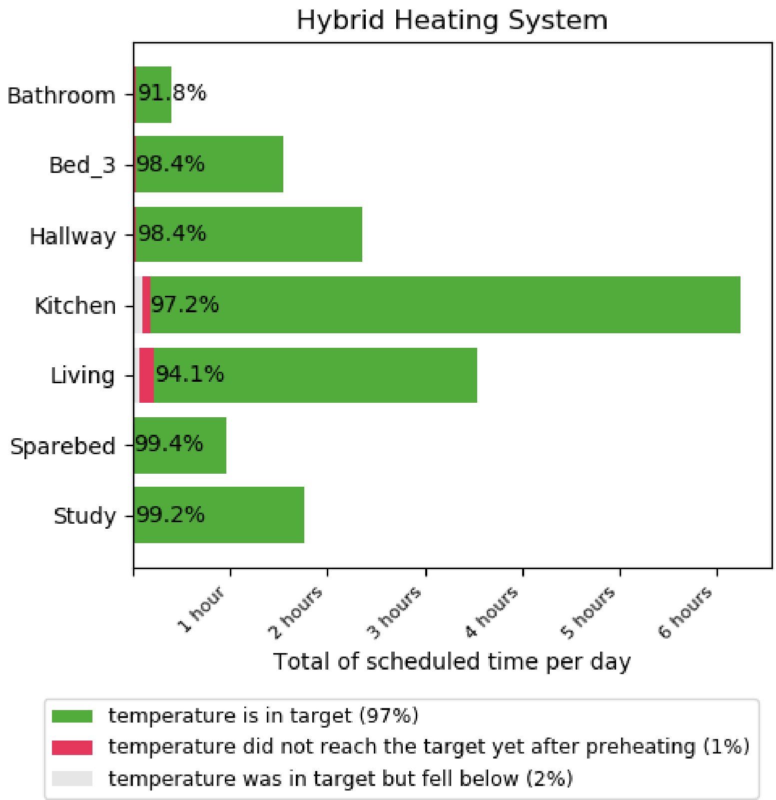


Figure 17: Percentage of time heating temperature requests are accomplished, missed and fell below target during a heating period for Miss Coltrane, gas boiler performance against hybrid heating system. The number in brackets shows the percentage of time the target was not met overall (green), was not reached at the start of a heating period (red) or fell below the target during a heating period (grey).

10.5. Changes observed in experience and behaviour

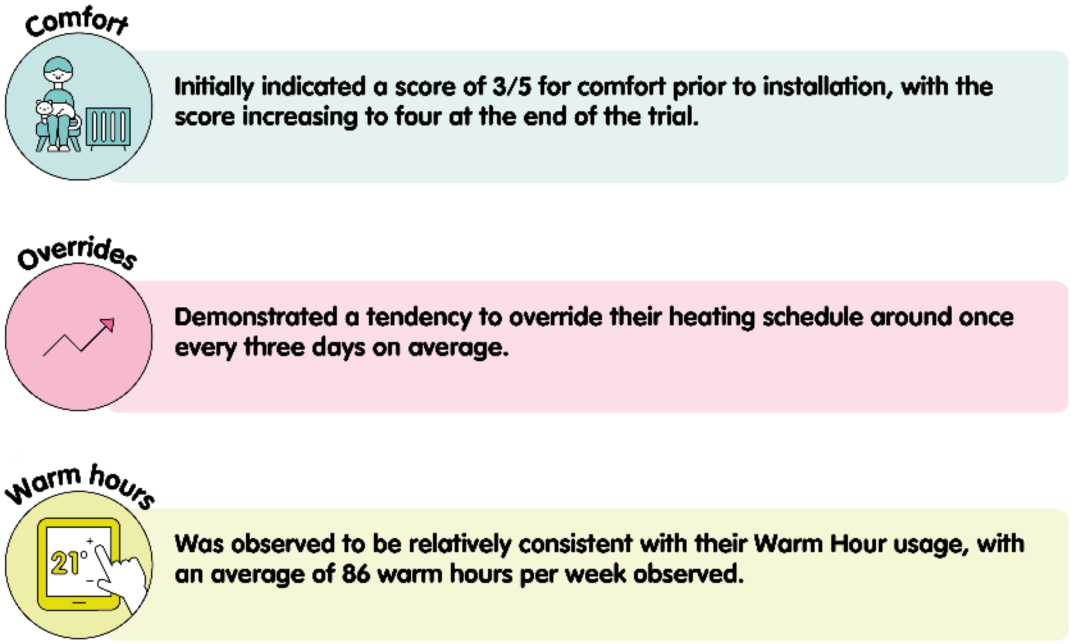


Figure 18: Representation of behaviours observed and reported for Miss Coltrane – gas boiler compared with heat pump experience

11. Improving the experience of heat pumps

The case studies show that hybrid heat pump systems can perform as well as gas boilers. This section discusses how improved integration could set consumers' expectations more clearly and improve the algorithms that decide when to use the gas boiler or heat pump. Although other studies have shown that the experience of using a heat pump can improve over time [2], good early experiences could be key to building consumers' confidence in switching away from gas boilers.

11.1. Changing heating schedules

Participants wanted to use their heat pump to reduce their carbon emissions, but they did not know how to and were worried about the costs of scheduling their heating differently

We approached the two households where the heat pump delivered a relatively low proportion of the heating, Mrs Green and Mrs Johnson, to discuss the home's performance data. When we told them that the boiler was still being used to deliver most of their heating, both indicated that they were keen to make alterations. They said that they felt they had made sacrifices to lower their carbon emissions and were disappointed with the results.

We made several recommendations, drawing on data about how they used their heating, to help them adjust their schedule so that the heat pump would provide more of the heating:

- Schedule heat for when you routinely use the manual override feature (giving specific examples);
- Schedule low temperatures before high temperatures in less efficient rooms;
- Schedule longer periods of heating, rather than short intermittent blocks.

Neither participant had realised that scheduling their heating in this way would use the heat pump more. They were concerned that if they scheduled more hours it would increase the cost of their heating. We offered to pay for any increase in the cost of their energy if the changes suggested increased their bills. This emboldened them to try out the recommendations. Only Mrs Green made contact after enacting the changes to ask whether the heat pump was now delivering more of her heat than before.

Mrs Green: "I've set a new schedule and banned the override button."

Clearly these kinds of suggestions could be made automatically by the control interface in future and it would be simple to reassure consumers about the cost if they bought their heat as a service. This is discussed further in Section 13.

The NEDO project found a strong correlation between overall satisfaction of using heat pumps and understanding how they work [2]. This also suggests consumers may enjoy heat pumps more if they know how to use them to get the experience they want.

11.2. Changing the control algorithm

The Salford House experiment showed that the heat pump would take longer to warm homes. Therefore, the algorithm used the gas boiler to pre-heat to the temperature set point and top rooms up if they cooled down during a heating block (see Section 4.2). For the two households discussed, the software was adjusted to allow the heat pump to be called upon instead of the gas boiler to top rooms up when the temperature fell during a heating block. The Salford House test results suggested that this would only take slightly longer than the time taken by a gas boiler. Clearly this is just one of many ways that the control algorithm could be changed to use the heat pump more.

11.3. Impact of better integration

The schedule and software changes were made in close succession to ensure data was gathered before the winter ended. It is therefore difficult to decipher the impact of the actions individually. Observations in the days that followed showed that the heat pump was used for more time without the households' reporting reduced comfort. In Mrs Green's home, the proportion of heat delivered by the heat pump rose from 6% to 51% and the proportion of temperature requests achieved rose from 92% to 98%.

However, these changes were made at the end of April as the weather was getting warmer, which may also have contributed to the effect. The heating system was active 14.5% less often, probably because of the milder weather conditions. Indeed, Mrs Johnson switched her heating off altogether in preparation for the summer shortly after changes were implemented, so the extent to which the suggestions had the desired effect is unknown.

Overrides

After implementing changes Mrs Green's average number of overrides dropped from 2.3 per day to 0.3.

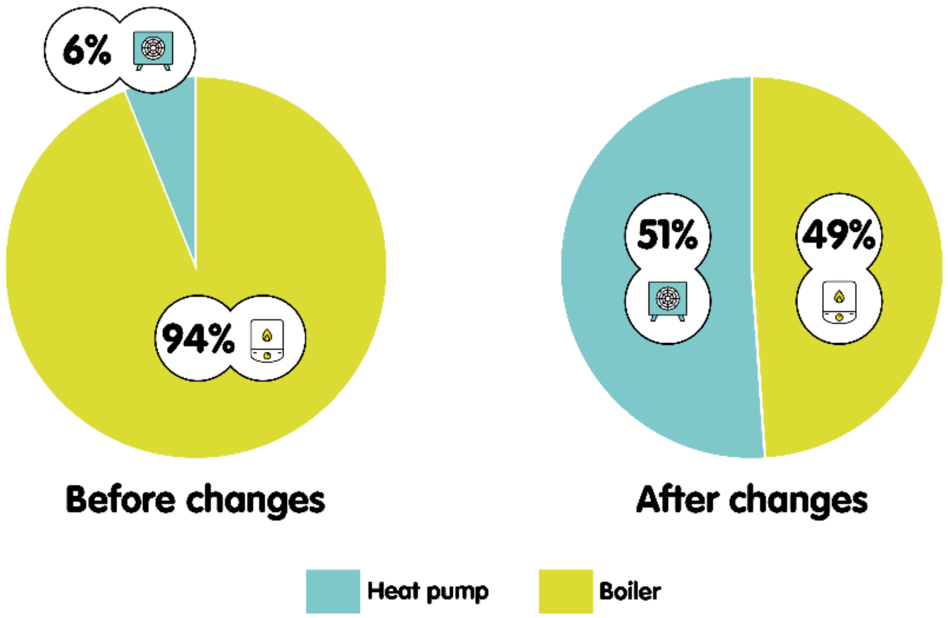


Figure 19: Proportion of heat delivered by boiler against that delivered by heat pump for Mrs Green before and after the changes were made (when comparing periods of similar weather [5])

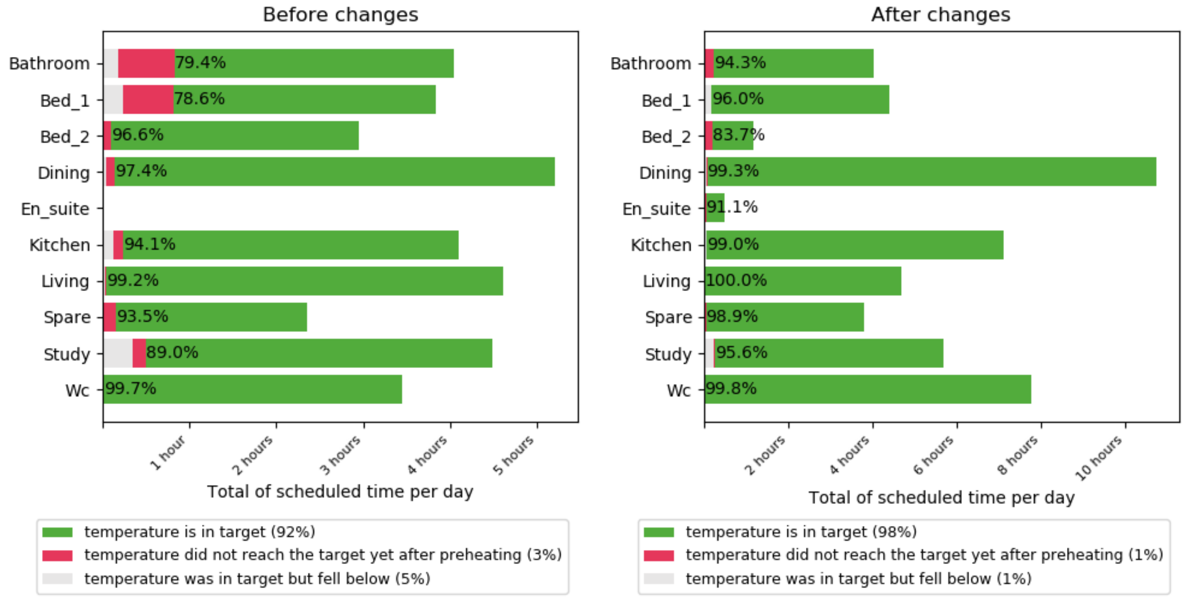


Figure 20: Percentage of time heating temperature requests accomplished for Mrs Green, before and after changes to schedule and control algorithm were made

12. Could hybrid heat pumps be part of a heat service offer?

Even if better integration improves heat pump performance, consumers will need to believe they can get the heating they want for a price they are prepared to pay, before they buy a system and experience the benefits [4]. Recent findings show that consumers like the idea of buying a heat pump with a heat service because this would reassure them that they could get the heating outcomes they wanted for a fixed price [6] [7].

Prospective heat service providers will need to be confident that they can deliver the outcomes a specific customer wants and that they can estimate the cost of delivering these outcomes using a heat pump. This section discusses whether providers can use data to identify a home and a customer who is ready for a heat pump and some of the potential risks they will face in estimating the cost of delivering their services with a Hybrid Heat Pump System.

12.1. Identifying homes that are 'heat pump ready'

Those better suited to a heat pump may be identifiable prior to installation

It is well known that heat pumps are more suited to well insulated homes and that this data is available from Energy Performance Certificates. What is less often discussed is that heat pumps will also be better suited to delivering schedules with long heating periods at relatively consistent (low) temperatures. Occupants' heating preferences could obviously be identified from the schedules used to control their heating before a heat pump was installed. What may be less obvious is that they could also be identified from how their existing boiler is being used.

Figure 21 shows how the boiler and Hybrid Heating System were used to heat Mr Dean's home. The boiler was used to maintain temperatures for about half the time before the heat pump was installed. After the heat pump was installed, the heat pump maintained the temperature instead. Mr Dean's home used the heat pump more than any other home with a Hybrid Heating System.

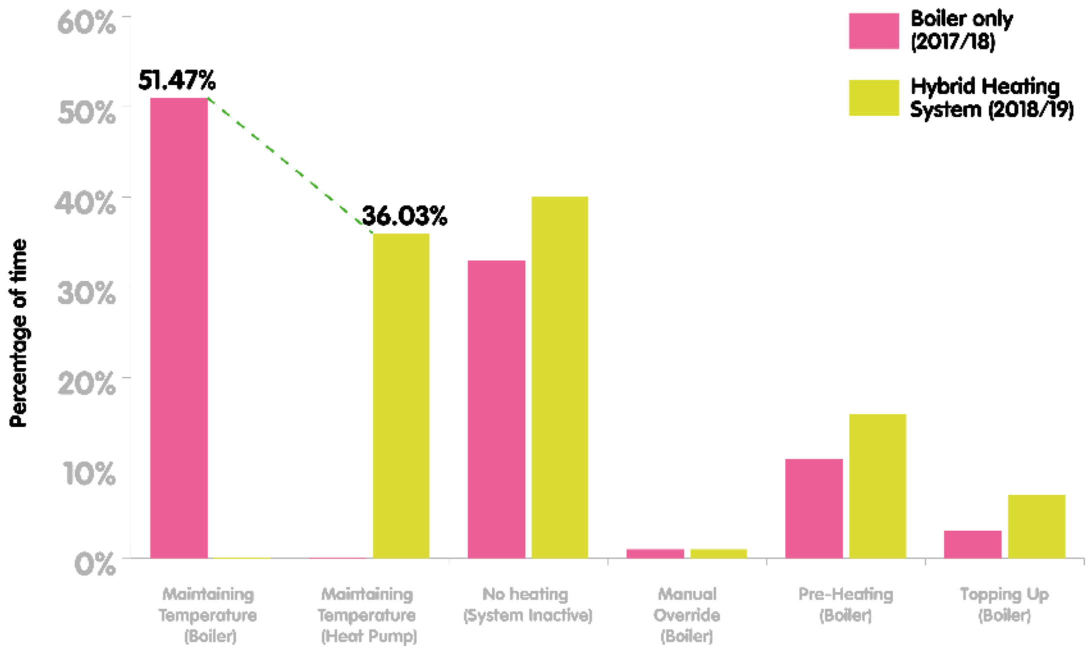


Figure 21: Proportion of boiler dedicated to maintaining temperature prior to heat pump installation against how much heating delivered by heat pump (maintaining) following installation for Mr Dean (all data – not adjusted for periods of similar weather)

The same information is plotted for Mrs Green, below, because her heat pump was used least of all the homes with a Hybrid Heating System. The boiler was used to maintain temperatures for only 11% of the time before the heat pump was installed. After the heat pump was installed, the heat pump maintained the temperature instead, but this only delivered a small proportion of the total heating.

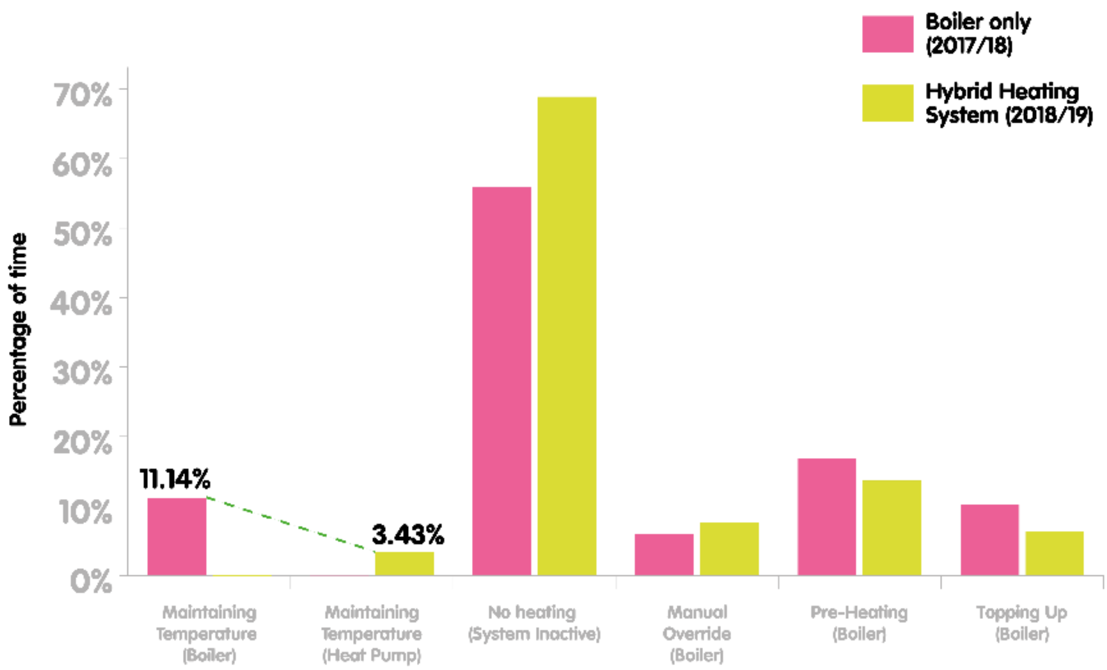


Figure 22: Proportion of boiler dedicated to maintaining temperature prior to heat pump installation against how much heating delivered by heat pump (maintaining) following installation for Mrs Green. (all data – not adjusted for periods of similar weather)

This shows that prospective service providers might be able to use gas boiler performance data to predict how well they will be able to meet consumers' needs using a heat pump.

12.2. Effect of behaviour on energy consumption

In addition to the agreed scope before the start of the project, a preliminary investigation was conducted on energy consumption. Findings come with the caveat that these observations are only based on a small number of homes. Larger sample sizes and deeper analytics will significantly improve this understanding in future.

Figure 23 shows that some homes varied a lot in how much gas and electricity they used for non-heating purposes. It was easier to detect the impact of installing a heat pump in homes that used less energy for things other than heating or used a more consistent level of energy.

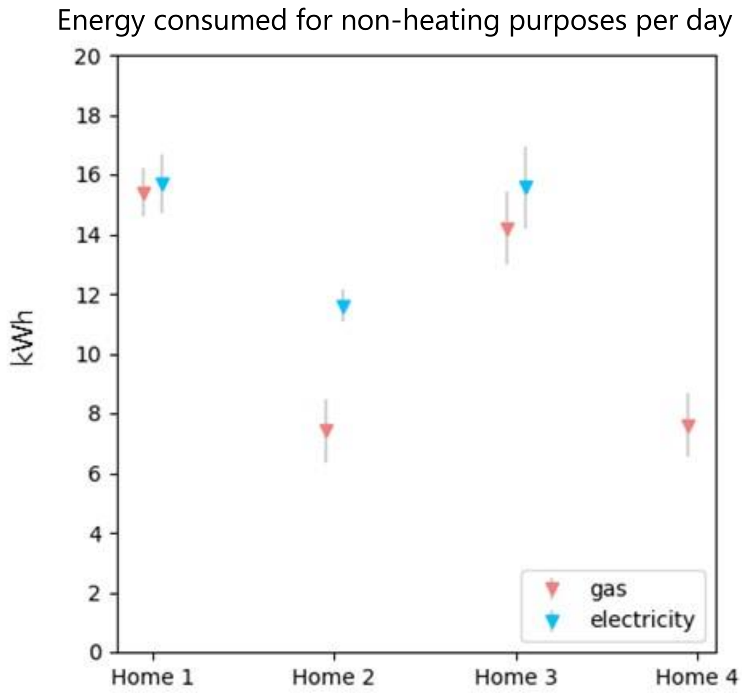


Figure 23: Variability in energy consumption for non-heating purposes for homes individually and compared with other homes. 2 homes gave unreliable electricity readings and 1 home gave unreliable gas readings and so are excluded. For more information on issues with data quality please refer appendix E.

Figure 24 compares the gas and electricity consumed in one home for a period of time when the external temperature at the nearest weather station was similar [5] (after confirming that the same number of rooms were heated, and similar temperatures requested). It shows that gas consumption decreased, and electricity consumption increased after the heat pump was installed. This is consistent with more electricity being used to heat the home. The total energy consumption also reduced. This may be because the heat pump required fewer kilowatts of energy input per kilowatt of heat produced.

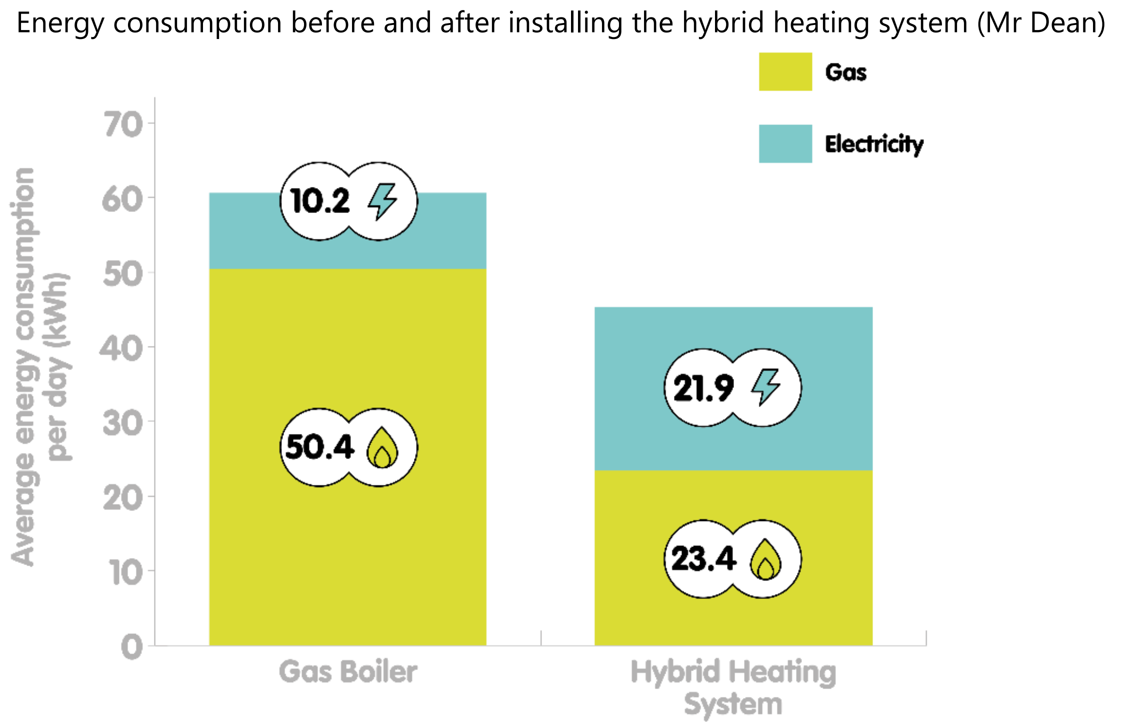


Figure 24: Graph represents gas and electricity consumption when using a boiler only against usage observed when using a hybrid heating system. Usage is captured over periods of similar weather conditions.

Finally, Figure 25 plots the amount of energy used to run the heat pump or gas boiler for 1 hour. This shows that there was significant variation across homes.

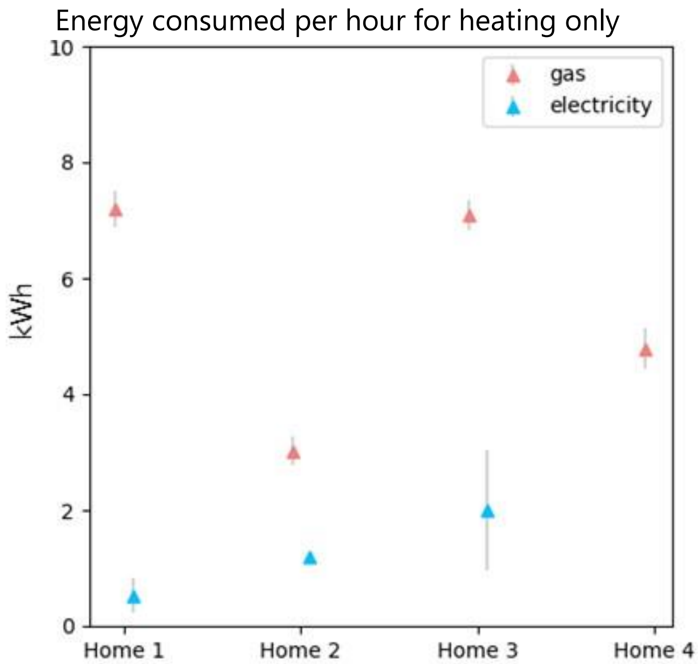


Figure 25: Variability in energy consumption to deliver one hour of heating for homes individually and compared with other homes. 2 homes gave unreliable electricity readings and 1 home gave unreliable gas readings and so are excluded.

Observations from this analysis should be considered cautiously, especially when comparing the extracted values. As outlined above, there is an overall degree of uncertainty involved particularly given that consumption could be impacted by a number of factors including the weather, room insulation and occupier behaviour, and by the way in which they schedule their heating (where even a small change can have a notable effect). This preliminary investigation demonstrates that we are ready to proceed to more advanced analyses with heat pump installations and a larger, more diverse sample of households.

12.3. The challenges of estimating the costs of a heat service

The cost of delivering a heat service with a new heating system will depend not only on the costs of the system – including the capital costs and maintenance costs – but also on the cost of the gas and electricity used. Clearly, the amount of fuel used will depend on the heating schedule and overrides made, the building physics, the system efficiency and the weather. Any prospective provider will want to use the costs they expect to face to influence the price they charge their customer for delivering the service. Additionally, they may want to implement controls to limit the level of risk they expose themselves to by way of a 'fair usage policy' or similar.

However, if the new heating system is a hybrid, the problem is slightly more complex. The service provider will also need to know something about the algorithm that is used to control the two heating systems. That is because the control algorithm determines when the gas boiler or the heat pump are used, and therefore gas or electricity is consumed (see section 4.2).

In this trial the Catapult provided participants with an experience that integrated various aspects including the heating system, fuel, control system, control algorithm, user interface and customer services. In future the same experience could be delivered by different commercial entities working together. Individual service providers could invest in integrating the entire supply chain themselves to deliver their offer. Interoperable standards might lower the costs of this effort both to the sector and the consumer, overall. They could also be used with an aggregator for greater savings by operating in other markets to anticipate and reduce peak demand, as was demonstrated in the NEDO project [2].

13. Conclusions

This project integrated a heat pump, gas boiler and controls to create a Hybrid Heating System; recruited five homeowners; installed heat pumps; and showed households could get comfortable. Indeed, participants reported levels of comfort that were as good as, or better than they had reported when living only with gas boilers, though the improvement was not significant.

This was partially because the algorithm that controlled when to heat with the gas boiler or heat pump was initially designed to minimise the risk of disrupting consumers. It used the gas boiler to warm rooms up to temperature and top heating up if rooms got too cold. Even with this cautious approach, the heat pump delivered more than half the heating in three of the five homes. These households were scheduling their heating in a way that suited their heat pumps.

Changing the heating schedule and control algorithm increased the proportion of heat delivered by the heat pump in a fourth home. It may be that this approach could also have increased heat pump use in the other homes, but the weather warmed before it was tried. There is probably potential to integrate the controls with the control strategy more effectively. The challenge will be finding an algorithm that uses the heat pump and gives people the heat experiences they want.

Previous experience influenced how open consumers with gas boilers were to heat pumps. It was easier to persuade households from the Living Lab to accept a *free* heat pump, than members of the general public. Their experience trialling smarter controls and new heat services may have made them more confident that they would be able to get the heat they wanted from heat pumps.

Whilst promising, these findings should be treated with caution. The sample was small and included members of staff, though research was conducted with other people in these households. The fourth participant described above also needed reassurance that their heating bills would not rise before they were willing to adjust their heating schedule to suit the heat pump.

There are of course other challenges to solve before consumers will take up heat pumps at scale. They will need to feel confident they will get the heating they want for a price they are willing to pay before they decide to buy one. They may also need to put up with disruption when they install their heat pump. Our participants had pipes run up walls, radiators replaced and concrete laid.

It may be that new business models could help solve these problems. For instance, if businesses sold heat as a service, they could offer consumers the heating they want for a known cost. They could learn what upgrades homes needed when delivering their service with a gas boiler, then recommend tailored renovations that prepared homes for a heat pump over time. They could reassure consumers their bills would not rise if they changed their schedule to suit their heat pump.

However, businesses would need to know they could deliver the heat their customer wanted and estimate what this would cost *before* selling them their energy as a service. This means they would need to find out who was well suited to heat pumps. If they used hybrid solutions, they would also need to know enough about the control algorithm to predict the cost of the two fuels used.

More open, interoperable market arrangements have enabled hardware manufacturers and service providers in other sectors to change the technologies consumers use every day. The energy market could learn from these successes to discover how to give consumers confidence that they will be able to get the comfort they want from heat pumps.

14. References

[1] Freedom Project, “Final Report,” 2018.

[2] “NEDO Greater Manchester Smart Communities Project,” 2017.

[3] Energy Technologies Institute, “Smart Systems & Heat Phase 1: Consumer Segmentations,” 2018.

[4] Energy Systems Catapult, “D21 SSH Phase 2 Home Energy Services Gateway: System Test Reports and Trial Conclusions,” Birmingham, 2018.

[5] Met Office, “metoffice.gov.uk,” [Online]. Available: https://www.metoffice.gov.uk/services/data/datapoint. [Accessed 2019].

[6] Energy Systems Catapult, “SSH Phase 2: Consumer perceptions of low carbon heating systems in hypothetical future energy market scenarios,” Birmingham, Forthcoming.

[7] Energy Systems Catapult, “Learning from continued use of smart heating controls and understanding attitudes towards Heat services,” Birmingham, Forthcoming.

[8] Energy Technologies Institute, “Consumer Challenges for Low Carbon Heat,” 2015.

15. Appendix A: Glossary

Air Source Heat Pump: A kind of renewable energy technology which take the warmth from the air outside (even when it's quite cold) and use it to heat the home.

Few: Less than or equal to 10% of the sample (or part of the sample being discussed at that point).

Heat Plan: A bespoke energy tariff that provides customers with an assured heating outcome, providing a chosen number of "warm hour" units at a fixed weekly cost.

Heat Service: A Heat Plan is one example of a Heat Service. Another example might include the cost to purchase and install the heating system as well as servicing and maintenance charges.

Home Energy Services Gateway: A gateway that allows people to access a market including home energy services offered by many service providers.

Internet of Things: The interconnection via the Internet of computing devices embedded in everyday objects, enabling them to send and receive data.

Living Lab: More than 100 real-world homes distributed across the UK. Each property has been upgraded to smart home levels that will be common by the middle of the 2020s. Refer to section 3.2 for full description.

Manual Override: An immediate request from the user to change the heating target from that scheduled.

Many: Greater than two thirds of the sample (or part of the sample being discussed at that point). point).

Most: Greater than 50% of the sample (or part of the sample being discussed at that point).

Pre-Heating: The time to achieve the temperature requested for an individual room for the time scheduled.

Target temperature: The temperature requested for a specific room in the schedule (or as an override). The system attempted to keep the temperature within 1 degree of this. For example, a target temperature of 20 degrees results in a range of 19 to 21 degrees.

Topping up: Enabling the temperature to stay within the requested target temperature band when the temperature falls below the minimum threshold.

Warm Hour: An hour of time when a user requests any room with HESG sensors to be warmed or kept warm to a target temperature at or above 10 degrees (9-11 degrees range). A Warm Hour did not include the time to warm up the room to that target temperature. If the target temperature was requested in two or more spaces in any one Warm Hour, this was still one Warm Hour.

15.1. Acronyms

ASHP	Air Source Heat Pump
ESC	Energy Systems Catapult
HESG	Home Energy Services Gateway
HHS	Hybrid Heating System
IoT	Internet of Things
LBP	Learned Building Physics
SSH2	Smart Systems & Heat: Phase 2 programme
TRV	Thermostatic Radiator Valve
WRV	Wireless Radiator Valve

16. Appendix B: Research Objectives

The table below describes where the report covers the five areas of research described in the grant offer letter.

Grant offer letter	Report Section
A) Can trialists control the system to provide the required heating outcomes.	• Learnings from Salford Energy House Experiment (3.2) • Summary of findings (5.1, 5.2) • Case studies (6-10)
B) How does the performance of the integrated HESG/HHS system compare with the performance of the HESG with gas boilers in delivering the required heating outcomes?	• Learnings from Salford Energy House Experiment (3.2) • Summary of insights (5.1, 5.2, 5.3) • Case studies (6-10) • Improving the experience of heat pumps (11)
C) How does testing the integration in real homes compare with Salford test-house integration results – what additional insights are revealed	• Learnings from Salford Energy House Experiment (3.2) • Technical report (18)
D) What insight is given into the requirements for more deeply integrated HESG/HHS systems to achieve levels of performance that equal or exceed those provided by gas boilers?	• Summary of insights (5.3) • Improving the experience of heat pumps (11)
E) What insight is given into the potential for HHS to support future heat as a service value propositions (preliminary outline on key requirements)	• Summary of insights (5.4, 5.5, 5.6) • Improving the experience of heat pumps (11) • Could hybrid heat pumps be part of a heat service offer? (12)

Table 1 shows the research objectives for the trial

17. Appendix C: Impact of slow warm up times on algorithm performance

The HESG algorithm adjusts the heating system (boiler or heat pump) and radiators based on the predicted time to warm a room to the target temperature. Various problems can cause the system to miss the target temperature. For instance, room temperature could be raised by a person entering the room or fall because a window is opened. Alternatively, the algorithm could start later than needed, or incorrectly decide to turn the heating off for a short period, for instance if the weather is a little colder than expected. Figure 26 shows that these same causes will have bigger impacts in rooms that take longer to warm up.

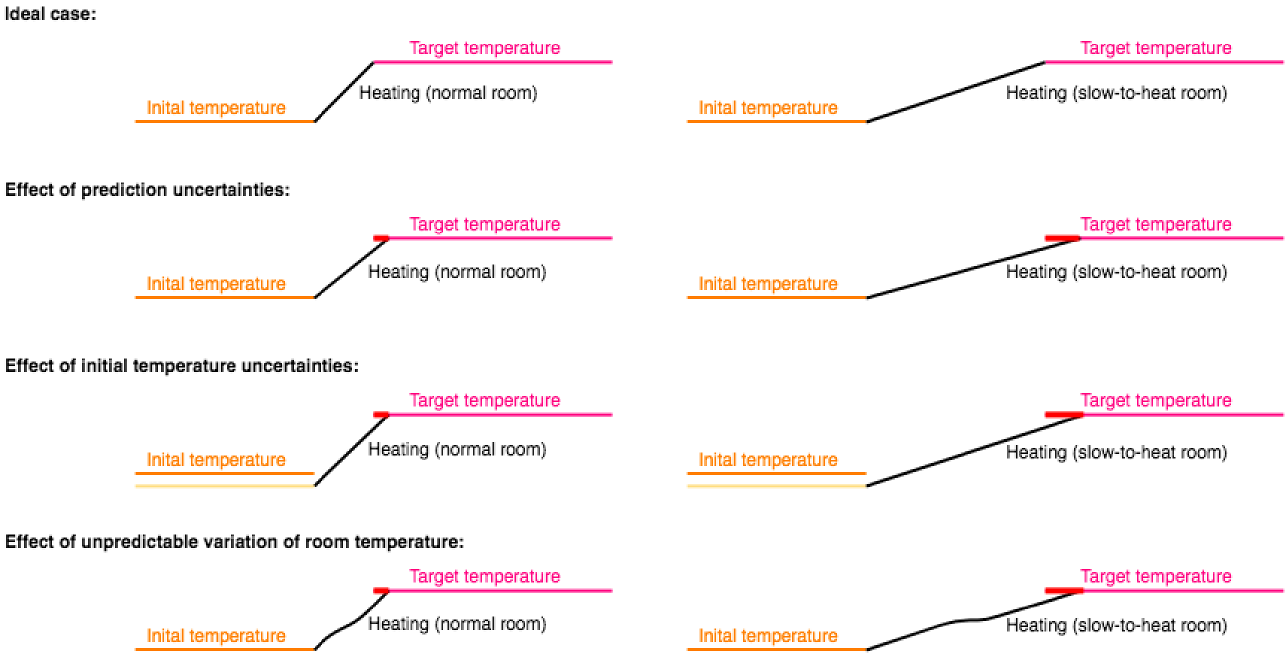


Figure 26: Impacts of a small effects affecting the prediction curve on the time during which the target temperature is not reached. In the left, the effect is applied on a quickly increasing temperature, on the right, the same effect is applied on a slowly increasing temperature.

The bedrooms in Mrs Johnson's house warmed up relatively slowly. It is unlikely that installing the heat pump caused the pattern of errors because the gas boiler was still being used to warm rooms up and top them up when temperatures fell below the target. It may be that instead, there was just a higher incidence of other problems, like the ones illustrated in Figure 14

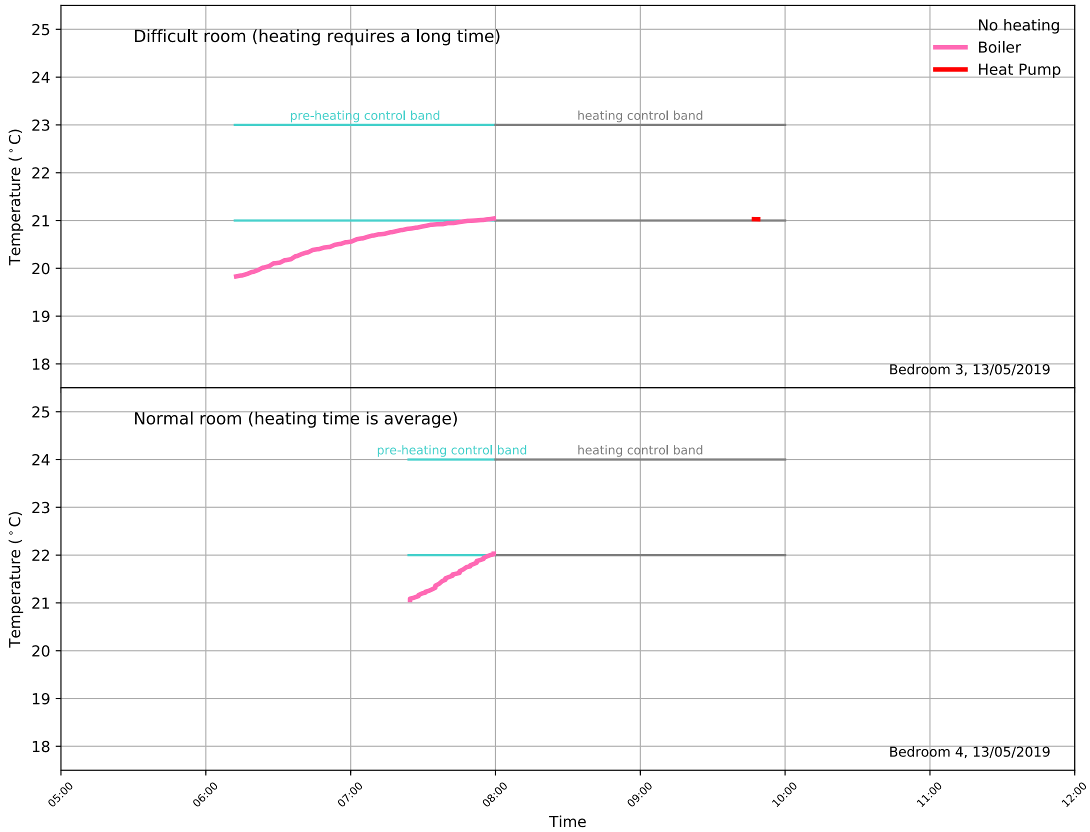


Figure 27: Temperatures in the room Bedroom 3 and Bedroom 4 in a real house. Bedroom 3 is difficult to heat; Bedroom 4 is less difficult to heat.

It is therefore believed that the inefficiencies observed in those rooms are subject to large uncertainties and that, when doing a comparison before and after the Heat Pump installation, a relatively big absolute difference in the percentage number can be the result of a fluctuation inside the uncertainty band. In other words, an increase of +5% of the inefficiency can be the result of random effects that had occurred by chance in one case and not the other and is therefore not significant.

Quantifying these uncertainties is challenging, it would require a careful systematic uncertainty study of each effect for each room individually, and this is out of the scope of this report.

It is still believed that the conclusions on the general house trend provided in this report are still significant despite not accounting for these uncertainties, because these general trends are driven by many rooms, the majority of them being not difficult to heat and therefore not suffering of large uncertainties.

18. Appendix D: Recruitment

A survey dispatched to all returning Living Lab homes at the start of the winter trial 2018/19 contained questions designed to identify homes receptive to installing a heat pump at their property. The responses to the questions detailed below, as well as some indicative feedback given by participants at various research points in the previous trial.

18.1. Questions used to identify Heat Pump candidates from within the living lab

How likely are you to consider a low carbon alternative to gas central heating when it's time to replace your boiler? (Extremely Unlikely 1-10 Extremely likely)

Please select the option below that is most applicable to you when considering low carbon alternatives to gas central heating.

- I'm open to considering a low carbon alternative, even if it means making sacrifices in other areas.
- I'm open to considering a low carbon alternative, as long as I don't have to make sacrifices in other areas.
- I'm confident using my gas boiler and I'd be concerned swapping to a technology I'm unfamiliar with
- I wouldn't consider a low carbon alternative to gas central heating

Please select the option below that is most applicable to you when considering low carbon alternatives to gas central heating.

- I'm open to considering a low carbon alternative, even if it means making sacrifices in other areas
- I'm open to considering a low carbon alternative, as long as I don't have to make sacrifices in other areas
- I'm confident using my gas boiler and I'd be concerned swapping to a technology I'm unfamiliar with
- I wouldn't consider a low carbon alternative to gas central heating

Please select the option below that is most applicable to you when considering low carbon alternatives to gas central heating.

- As long as my home is warm and comfortable, I don't care how it's heated
- The cost to run and maintain the equipment is my biggest concern
- How it looks and where I would have to install it is most important
- Being reliable and easy to use is what matters to most

18.2.Heat Pump Website

Below is a screen shot for the heat pump website used for a market transformations project conducted by the ESC. Participants were asked to provide feedback indicating whether a heat service made the prospect of moving to a hybrid heat pump more appealing (approx. 15 questions). After answering the questions (and if they had not been screened out by any of the eligibility criteria) they were asked to provide their contact details and would subsequently been asked to take part in a telephone screener to be considered for inclusion within the heat pump research. Recruitment figures can be located in section 4.1.

Figure 28: Screenshot from the heat pump recruitment website

18.3. Eligibility criteria

Below details a sample of the eligibility criteria to be surveyed for a heat pump rather than the full list of participant and property requirements.

<u>Heat Pump Website</u>

- Size of house (no. of rooms)
- Age of house
- Insulation levels / efficiency
- Current gas costs (yearly)
- Boiler age
- Boiler fuel (Gas central heating)
- Boiler type
- Postcode

The Heat Pump website was for external recruitment efforts only. After completing the questions detailed, and if eligible, participants would then be informed of the trial and to expect a telephone call to participate in the telephone screening questions. Existing living lab homes have already been through the telephone screener but answered some additional questions (e.g. available outdoor space)

<u>Telephone screener sample</u>

- Homeowner bill payer
- Have Gas central heating
- Age band (no occupant below 1 or over 75 years old)
- House type (No flats above ground floor)
- House age
- Space outdoors for heat pump
- Gas meter type
- Boiler age
- Medical issues/Vulnerable residents
- No. and ages of occupants
- Property rarely unoccupied/only used for residential reasons
- Able to manage energy bill costs
- Technically capable
- Installation of the system.
- Any planned renovations, structural work or expect to move property
- No. of rooms and radiators
- Mortgage type (No leasehold mortgages)

Those deemed suitable would be invited to consent to a technical survey of their property

18.4.In-Home Suitability Surveys

Note only 9 of the 11 homes who consented to a home survey are detailed, the following are excluded;

- The initial installation, which was a pilot home. This heat pump was installed in December 2018 and used to test that the control strategy was suitable for in-home installations, following extensive testing in a test environment. This home did not go through the same formal process as the other homes.
- A home which consented to survey, but the decision was taken to cancel their visit after it was revealed that the owner had a leasehold mortgage raising legal concerns with regards to making physical changes to the property.

All homes surveyed had some level of compromise to meet the constraints of the trial scope, budget and timescale. This ranged from minor packaging inconveniences such as using space in a garage or loft, through to major building work required for pipe runs requiring structural surveys. A summary of the results is as follows:

Home	Type	EPC Rating	Pass/Fail	Brief Notes
1	Mid-Terrace	C	Pass	Feasible and suitable for installation
2	Semi-Detached	D	Pass	Suitable home and understanding participant
3	Semi-Detached	Unknown	Pass	External cabinet required
4	Detached	D	Pass	Ideal property, very few negatives
5	Detached	C	Borderline	Suitable following additional work, installed then removed (detailed on page 13)
6	Semi-Detached	D	Fail	Failed noise requirements
7	End-Terrace	D	Fail	No secure location for heat pump, high property disturbance
8	End-Terrace	C	Fail	Insufficient space for components
9	Detached	E	Fail	Large property, structural concerns, packaging constraints

Table 2: Summary of the different survey outcomes for those assessed for a heat pump

2. Heat Pump Surveys (for excluded homes)

Borderline Home (Installed but later removed)

Home 5: Detached House (EPC Rating Band C)

Location for heat pump:

- Centre of property within enclosed rear garden.
- Nearby drain available for defrost.
- Unit will sit on level and sturdy wooden decking which may create noise issues. No other location available for ASHP.

Pros to installation:

- Garage space available for installation of major componentry.
- Clear space within enclosed rear garden and drain available for ASHP position.
- Most radiators appear over-sized for conventional system currently installed. No complaints of underheated areas from residents' feedback.

Cons to installation:

- Potentially unreliable boiler with poor quality installation currently installed.
- Major disturbance and surface mounted pipework to install within occupied utility room.
- Larger property – 4 bed detached with conservatory that may require a larger unit than 8.5kw.
- ASHP install location is on wooden decking, which is within Mitsubishi guidelines, however, increases noise vibration bringing the potential of noise complaints.

Installation conclusion:

- Combined with the resident's uncertainty and potential for high levels of noise from the heat pump, this property is not recommended for installation.
- The property may require a higher output unit than the standard 8.5kw. An uninhabited garage space does provide an ideal location for the large and unsightly system components. However, a great deal of pipework (3 sets of circulation pipework and electrical power wiring) being installed throughout the utility room creates a high level of disturbance and increase in cost than is practical for the purposes of the install.

ESC Decision:

- Following the recommendations from the installer, further discussions were held with the homeowner and it was jointly agreed that with some changes to the proposed install (e.g. addition of a concrete plinth to replace a section of decking to resolve possible noise issues) the homeowner would proceed with the install.
- Post-installation the homeowner asked for the heat pump to be removed for several reasons including the space taken by components and pipework, sight of the heat pump and noise concerns. This was removed on Monday 11th March 2019

4. Unsuitable Homes

Home 6: Semi-Detached House (EPC Rating Band D)

Location for heat pump:

- Location partially obstructed
- Requires 5m clearance from neighbour, but there was only 3.6m, meaning the location failed noise requirements

Pros to installation:

- None

Cons to installation:

- Multiple upsized radiators required from resident feedback (3 minimum). High ceilings, large spaces such as vaulted kitchen/diner. 3-story property.
- Requires reposition of outdoor bib tap and electrical socket.
- Due to space requirements, bulk of componentry would need to be installed within children's bedroom – Noise level concerns from pumps and Glycol flow/turbulence.
- Home had original wood floors so no access to floor voids, creating need for surface mounted cabling and pipework around exterior, within bedroom cupboards and children's bedroom.
- No direct route to 'Break in point' (Area of existing system pipework where boiler is split from the Central Heating). Creating extensive run with many changes in direction and Upsizing of standard pipework and pumps.

Installation conclusion:

- No practical space available for installation
- Contractor would not be prepared to provide an installation.

ESC Decision:

- Installation not progressed in line with Contractor's recommendation

Home 7: End-Terrace House (EPC Rating Band D)

Location for heat pump:

- No suitable, secure location

Pros to installation:

- None

Cons to installation:

- Attempting installation would result in many areas of high disturbance and result in vast surface mounted pipework and cabling within occupied spaces such as the Kitchen, Living room, bedrooms and hall.

Installation conclusion:

It's almost always feasible to find a way to provide the installation as compromises in design, practicality and aesthetics can be made. The extreme compact size of this property leaves no space, voids or even straight runs for all circulation pipework, cabling and components.
Contractor would not consider providing the installation due to the nature of the project/installation.

ESC Decision:

- Installation not progressed in line with Contractor's recommendation

Home 8: End-Terrace House (EPC Rating Band C)

Location for heat pump:

- Left Hand side of property away from neighbouring property.

- Initial thoughts were on the front of property back to back with Boiler (within utility room), however, noise calculation proved insufficient distance from neighbouring inhabited spaces.

Pros to installation:

- Short run from heat pump to other componentry
- Small property of which 8.5kw unit may suffice
- Radiators seem adequately sized for current system from residents' feedback

Cons to installation:

- Questionably tight installation space for main components within Utility/Downstairs WC washroom. (Pumps, Flow setter, isolations, expansion vessel, filling loop, majority of valves and pipework)
- Soak away required for ASHP involving ground works.
- ASHP not enclosed by property and directly accessible and visible to the front street.
  Possible high heat loss materials – Noted single pain glazing, wood frame internal doors.

Installation conclusion:

- Not practical to install this type of system under the current circumstance. This is due to insufficient space to install all major componentry downstream of the heat pump outdoor unit and all other uninhabited spaces are not within the vicinity, rendering them impractical to reach and return from.

ESC Decision:

- Installation not progressed in line with Contractor's recommendation

Note this home was considered a borderline property at one point. The initial recruitment diagram details them as the home excluded due to her husband's pending operation and a need to minimise disruption.

Home 9: Detached House (EPC Rating Band E)

Location for heat pump:

- Left hand side of property within enclosed rear garden.
- Large space available and well within noise calculations. Suitable base available on existing flagged walkway. Nearby drain available for defrost discharge.

Pros to installation:

- Large and enclosed location in rear garden for heat pump
- Airing cupboard containing unvented cylinder and existing system zone valves, expansion vessel, first and last tee of S-Plan (Point of connection to existing system)

Cons to installation:

- Questionably tight main components in installation space within airing cupboard
- Minimum of 14kw unit required – From a basic heat loss calculation 14kw should be sufficient down to 3 degrees.
- 17 rooms within property. High level ceilings. Large Conservatory.
- Extensive heat pump circulatory pipework run from heat pump to airing cupboard.
- Large Property Band E efficiency combined with extensive heat pump circulatory pipework installation creates large demand on the heat pump pumps and increases pipework diameter to 35-42mm
- Large diameter pipework may exceed drilling allowance in property joists
- As a minimum 19mm wall insulation is required and the best-case scenario results in a 73mm diameter pipe which cannot be insulated by knotching floor joists. Instead joists would have to be

drilled in the centre. Structural calculation would be needed to prove this is within maximum drilling tolerances. Pipework would then be insulated between joists.

Installation conclusion:

- Not practical to install the heat pump in this property due to:
- Minimal space to install all major componentry downstream of the heat pump outdoor unit (all other uninhabited spaces being too far out of reach).
- Scale of the property.
- Buildings heat loss and efficiency coming under band E of the EPC.
- Large diameter pipework required.
- Length of the heat pump circulatory installation.

ESC Decision:

- Installation not progressed

18.5. Pre installation materials

Figure 29a: Example of pre-installation materials sent to participants

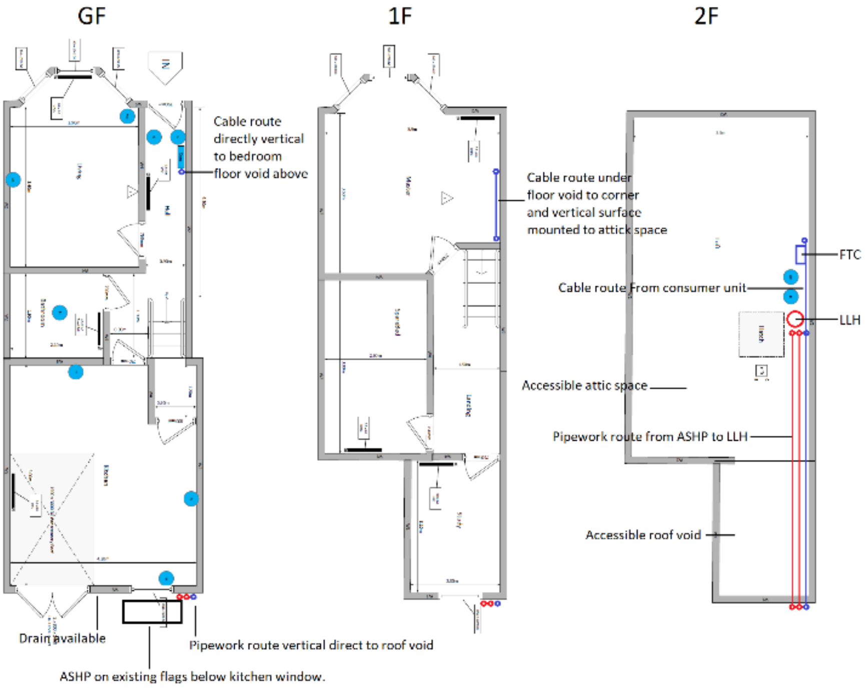


Figure 29b: Example of pre-installation materials sent to participants

19. Appendix E: Data analysis methods

This research involved a range of data collection and analysis methodologies, each designed to help researchers address a complex range of research goals. The following sections detail the methods used and the rationale behind the methodology selected.

19.1.1. Quantitative and qualitative data collection methods

Understanding participants' attitudes and behaviours in detail required a wide range of qualitative and quantitative methodologies, which included the ability to:

- Carry out standardised surveys to understand the outlooks and behaviours of the entire group;
- Hear responses directly from participants;
- Discuss participants' responses in order to explore their motivations further;
- Follow up trends that emerged in surveys to understand the impacts in the wider group;
- Capture and interpret sensor data relating to time, temperature, space

Qualitative data collection methodologies

Indeemo was used to create an ongoing research blog. This allowed the researchers to capture spontaneous qualitative feedback from the entire sample over the course of the trial.

The photo and video capabilities of the online blogging tool made it possible to form more of an idea about what was being experienced in participants' homes. This helped to build a relationship between participants and researchers and for richer information to be gleaned than would not have been possible through simple text reporting.

The blogging tool also allowed live screen recording of what participants were doing, so it was possible to see how they used the user interface to construct and manage their heating schedules first-hand. It is likely that some of these insights would not have been captured in participants' written blogs.

Researchers spoke directly to participants when carrying out activities such as the pre-installation interviews. This approach meant it was possible to disseminate complex information and get participants' qualitative feedback. It also meant that participants were able to provide ad hoc comments and for the researchers to discuss participants' responses with them. These interviews were conducted on the phone as this created a balance between developing rapport, collecting in-depth information and being efficient.

At-home interviews were used because this provided a deeper understanding of the physical components of participants' perceptions of 'comfort' in their own homes and allowed researchers to better understand the experience of living with the technology in their home. Researchers were able to see the layout of participants' homes, experience the temperatures and examine physical characteristics of the homes and heating systems; this provided a rich understanding of the environment and the household situation. These insights were used to inform trends in the broader sample.

Quantitative data collection methodologies

Online surveys were used to gather quantitative data from the entire sample in order to ascertain general awareness and understanding satisfaction surveys, segmentation and discernment metrics. Numerical data was gathered at various points during the research in order to:

- Benchmark participants' attitudes and awareness of low carbon heating technologies
- See whether they experienced comfort around the home any differently after the heat pump was installed

Online surveys were an efficient use of time and enabled standardisation across participants.

Periods of interest with similar weather. For each of the studied house, important milestones that will affect the Heat Pump performance have been defined. In particular, for some houses, the occupiers had an interview to discuss the performance of the Heat Pump, and this interview has led to some change in the usage. Therefore, it is important to not compare time periods mixing data of those different phase.

Using weather data information stored in the HESG system, periods in each different phase of the trial were defined such that the external weather was comparable, individually for each studied house. These periods should be sufficiently long, even though for some scenarios, only one comparable week was available. They should also include the same number of weekends and weekdays, as it is known that behaviours are different during specific day of the week. Additionally, days where data were missing or where the heating system was not used due to warm weather have been excluded.

In order to find comparable external weather, the observed temperatures from the closest weather station were used, and the calendar was scanned to find periods showing a similar shape in average daily temperature. The standard deviation and IQR outliers were also displayed. Differences between the shape was used to exclude obvious incompatibility. Due to the reduction of choice imposed by respecting the constrains, the number of possibilities was reduced, and a sensible choice was done by visually comparing them.

Usage of gas boiler and heat pump. When exploring the period prior to the heat pump installation, a procedure to extract the data from the online raw HESG data was developed. Due to technical issues, the state of the Heat Pump device (on or off) was not recorded in the HESG data that was extracted. The information was retained but was unavailable for analysis whilst the trial was ongoing. In order to know the state of the heat pump, the log files of the homes were saved, and these files used to extract this information. Due to the need to rotate log files because of their limited storage capacity, some log files were lost. The corresponding missing intervals are therefore not accounted for, but in the worst case, they account for less than 5% of the total time.

After discovering this issue, an improved extraction procedure was developed, with the new output no longer missing these intervals and the present data now proving to be identical to the log data. However, this new approach was completed late in August and, as implementing it would have required re-writing code, too late to implement for this report.

Performance of the heating device and the decision algorithm. Using the data discussed in the previous point, it was possible to define, for each room in each house, the number of minutes which a target temperature was requested. The override events were removed, because they do not involve any prediction i.e. it is an immediate request to change the temperature. It was also possible to distinguish situations where the ambient room temperature was satisfying the requested temperature, and situations where this was not the case. For the latter, if it is at the beginning of the heat scheduled, it is considered as a failure of the pre-heating. All other instances are considered as a situation where the temperature was satisfying the requested target but fell below due to the room cooling.

Using the periods defined previously, the percentages can be compared between the different periods.

Number of Warm Hours. We looked at the number of warm hours used in a household each week. Data on the target temperatures the home hub attempted to provide to each room was used to determine if any room was at or above 10 degree (9 to 11 target range) and not at the frost protect range for each minute. If that was the case, they were counted as a warm minute. The total number of warm minutes for a period was summed and then divided by 60 to get the number of warm hours per household.

While it is possible to schedule heating in all rooms, scheduling heating in a room with no radiator had no effect. So, for the purposes of this analysis rooms without radiators were ignored.

Number of overrides and Warm Hours. Using the data discussed in the previous points, it was also possible to count the number of override events and the number of warm hours used.

The number of override events ignore the “suspend” events and will ignore any event occurring within five minutes after another one of same type in the same room.

Energy consumption analysis: Only a preliminary short study was performed. The stored HESG data containing the gas and electricity meter readings was used. The periods where these readings were invalid or suspicious were ignored. This includes the missing sensor reading, the flat-lining readings, or the suspicious readings. Suspicious readings are the ones showing a constant regular increase with absolutely no variation or that correspond to a gas or electricity usage orders of magnitude away from the typical usage band. When the usage was drastically different from the past usage observed for the same household, the information was also excluded from the analysis. Finally, important changes in the household between different periods (renovation of the house, change of meter) were also accounted to exclude those comparison from the analysis.

Gas and electricity consumptions were compared for similar weather periods, defined as described before. Information on gas boiler and heat pump usage from the previous study were also used.

19.2. Temperature clusters

Portions of the pie chart represent the duration of requested heat spent at the specific temperature.

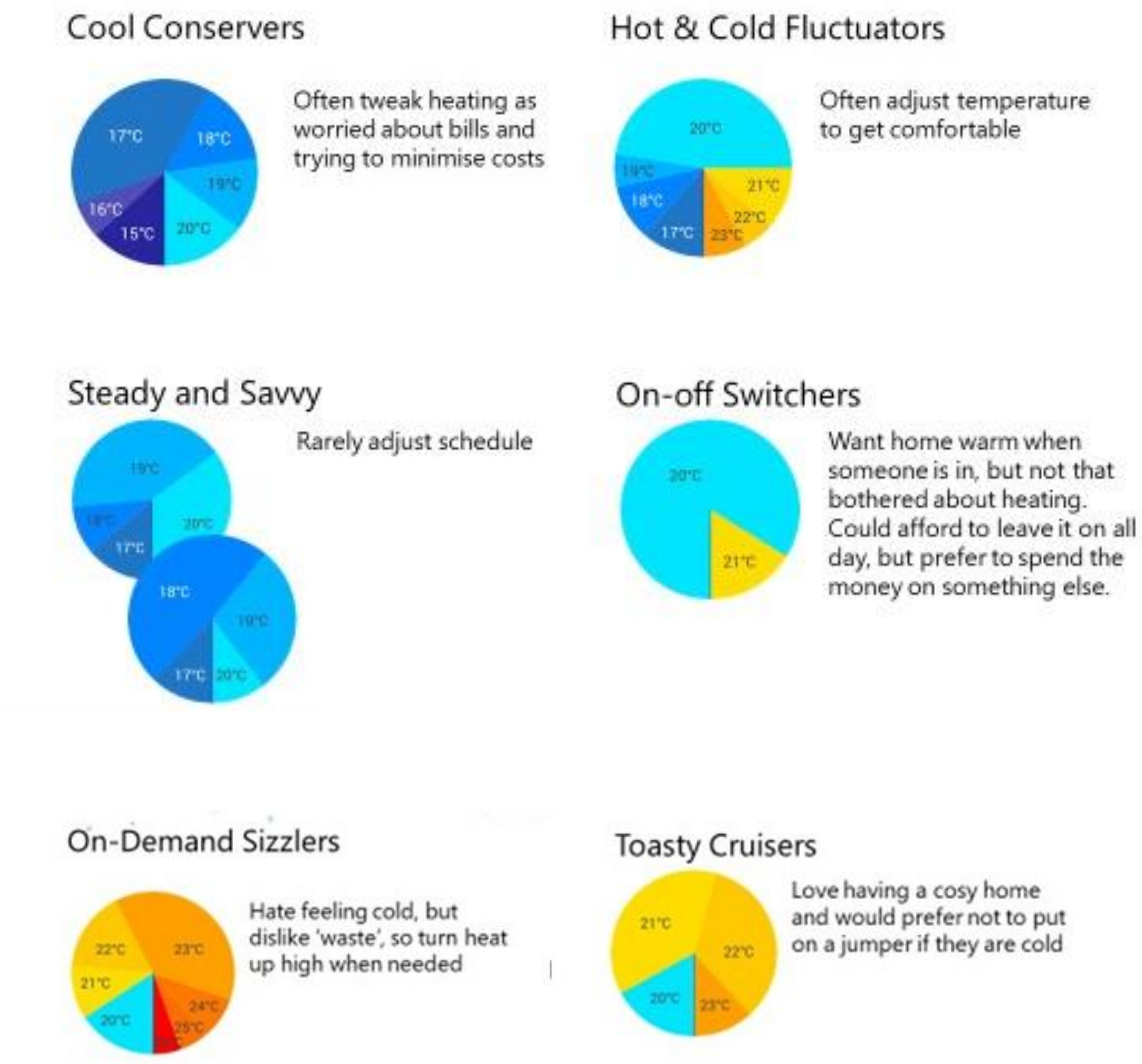


Figure 30: Clusters temperature behaviours observed from winter trial 17/18 [4]

19.3. Research task list, participant journey

Note participants took part in many tasks as part of the broader trial which are detailed in full in the winter trial report 2018/19 [7]. The tasks detailed below are those specific to homes with heat pumps or that had specific questions inserted for this group of participants.

Tasks were conducted with all 5 of the homes with a Hybrid Heating System, except where the table states otherwise.

	Task	Description	When
#1	Online Blog	Ongoing feedback from participant about their experiences over the course of the trial	September - May
#2	Getting Started*	Discuss awareness of low carbon alternatives and propensity to consider replacing their heating with one in the future – amongst other topics	November
#3	Comfort rating	Self-reported comfort score taken three times. Once prior to installation, after using the new heating system for a few months and again at the end. Further investigation into specific rooms and any differences observed also discussed.	December - May
#4a	Post-Install interview	Short telephone interview to explore early perceptions and experiences.	January - March
#4b	Post-removal interview**	Short telephone interview with the one home who requested to have the heat pump removed	March
#5	Home Interview	Face to face interview exploring experience of a heat pump. How the proposition/journey could be improved. Reveal performance data. Test the concept of a heat service.	April - May
#6	Closing survey	Online survey. Summarise trial experiences, opinions of heat service/fixed price and other concepts introduced during the trial.	June

Table 3 demonstrates the different research activities conducted with participants

* Task dispatched to all living lab homes
** Task conducted with one home only

20. Appendix F: Technical report

HESG Heat Pump Integration

Technical Summary – Project ESC0149 – HESG / HHP Integration

Warwick Brown

ICT Analyst

Publication date: 30th September 2019

Document control

ESC programme name	SSH2
ESC project number	ESC0149 – HESG / HHP Integration
Version*	1.0
Status	First version: Updated following internal review.
Restrictions*	Confidential
Release date	30/09/2019
External release ID	n/a

* Refer to the [Information Classification Policy]

Review and approval

	Name	Position
Author	Warwick Brown	ICT Analyst / Hardware
Reviewer(s)	Gary Marshall	Project Manager - Innovation
Approver	Dr Andrew Barton	Systems Development Manager

Contents

20.1. Executive summary

The objective of this document is to provide a technical overview of the Hybrid Heat Pump solution developed between Mitsubishi and the ESC.

The objective is to demonstrate control of a heat pump using HESG. A hybrid heating solution has been chosen to provide the greatest flexibility in trialling new propositions while minimising the risk of the participant having an unacceptable heating performance.

This required the development and implementation of a control system based around the ESC Living Lab HESG able to ensure the operational constraints of both boiler and heat pump could be met.

A Mitsubishi Ecodan Air Source Heat Pump (ASHP) was selected and the control system designed so that the selection of the heat source – gas boiler or heat pump – was invisible and not controllable by the participant. The control system was also designed to allow modification to the performance of the system as knowledge and experience grew.

Figure 31: Mitsubishi Ecodan Air Source Heat Pump

20.2. System Requirements

HESG is configured to have two boiler control units, one for the gas boiler, one for the heat pump. The control strategy is to use the higher output power gas boiler to carry out the initial heat function, and the heat pump to maintain the temperature once the target is achieved by the boiler, using a control algorithm developed for HESG.

The Mitsubishi ASHP component parts used are shown in Table 4.

Item	Part Number / Model	Description
Heat Pump – Outdoor Unit	PUHZ-W85VAA	943h x 950w x 360d mm
Controller Unit FTC2B	PAC-IF032B-E	Includes pipe thermistorsTHW1/2 278h x 336w x 69d mm
Control Panel	Supplied with FTC2B board	Approx. 100h x 100w x 20d mm

Table 4: Component Parts of the Mitsubishi ASHP

The high-level requirements are summarised below:

- Control the gas boiler for the initial heating cycle and for heat boost if room / home temperature drops below requested / set level.
- Control the heat pump to take over from boiler once the room / house set temperature is achieved.
- Protect the heat pump from the high flow temperature of the boiler and ensure pump over-runs are efficient.
- Ensure the boiler and heat pump cannot be switched on at the same time.
- Ensure Heat pump has minimum water volume for its defrost cycle.
- Ensure water is directed around the heating circuit efficiently.

Detailed Design Solution

A simplified diagram showing the functionality of the Hybrid Heating System is given in Figure 32a.

HESG Functionality includes:

- HESG providing heat pump "Call for Heat" signal which connects to the Programmable Logic Relay (PLR).
- HESG providing gas boiler "Call for Heat" signal which connects to the PLR.
- HESG monitoring of Flow / Return pipes from a Low Loss Header (LLH) to radiator circuit.

A Programmable Logic Relay, (PLR), provides the additional logic needed to ensure correct operation of the system motorised valves and interface to the gas boiler and heat pump control unit.

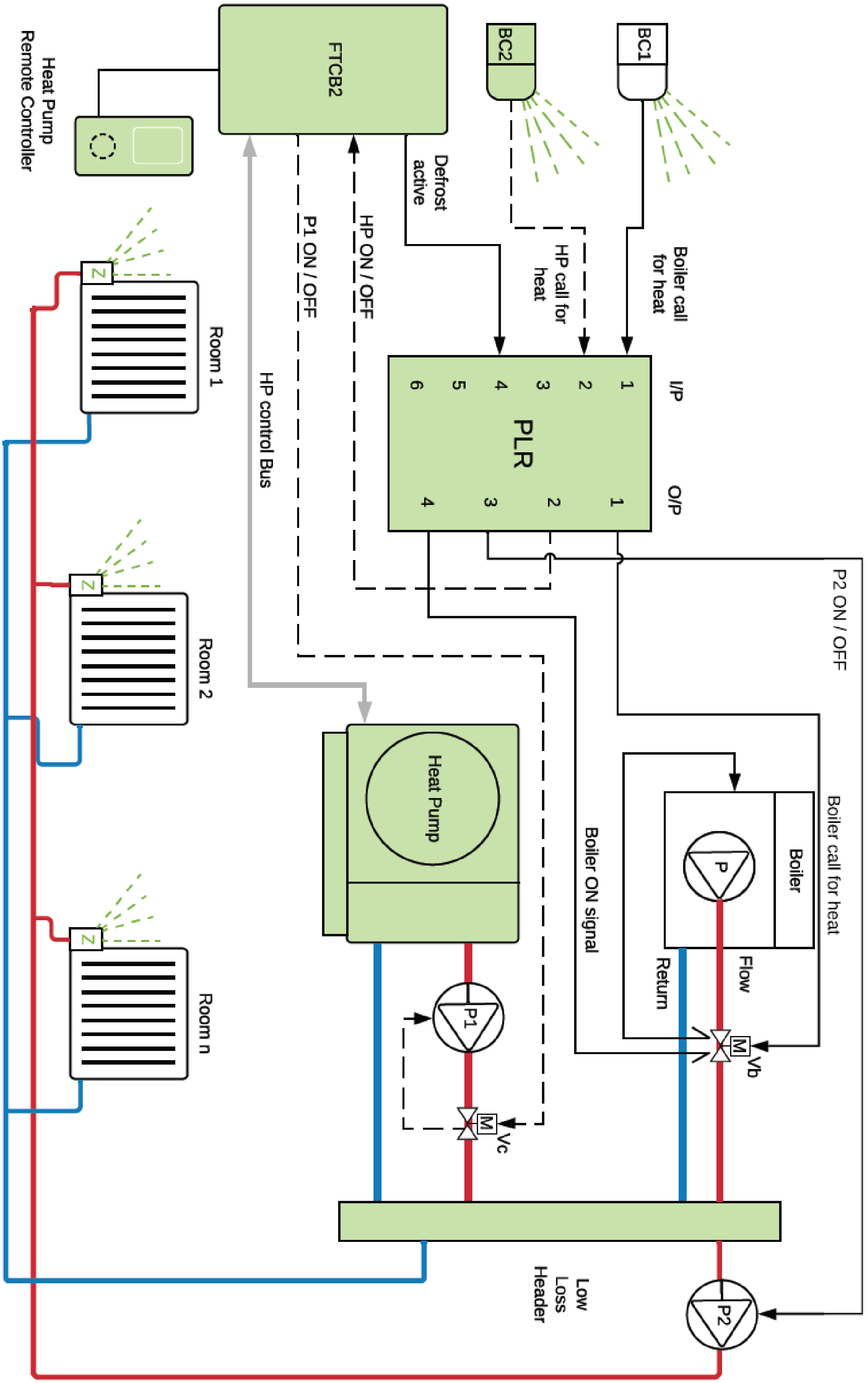


Figure 32a Hybrid Heating System Diagram

The programmable logic relay (PLR) incorporates the following functionality needed to ensure correct operation of the system:

- Monitoring of the heat pump defrost condition in order to ensure the minimum water volume can be managed by keeping the P2 pump running during a defrost cycle.
- Ensuring the "P2" pump is always ON during the defrost cycle. This will provide a robust defrost condition since low loss headers do not contain the minimum water volume needed.
- Controlling the "P2" secondary pump for the radiator circuit with overrun facility.
- Providing appropriate turn-on / over-run timer functions to ensure the pumps do not run against closed valves.
- Providing an interlock to prevent the boiler and the heat pump being active at same time.
- Ensuring "P2" pump is always ON during the defrost cycle. This will provide a robust defrost condition since low loss headers do not contain the minimum water volume needed.
- Isolating valves in the flow pipe from the heat pump to prevent hot water passing through the heat pump outdoor unit during a boiler cycle.

Further details on these functions are given in the following sections.

Design Implementation Details

The programmable Logic Relay is an off-the-shelf component available from RS-Components, part number RS 468-4444. The manufacturer is Schneider Electric, part number: SR2 A101FU. The associated USB programming cable, SR2USB01, also available from RS-Components, part number RS 615-2365. Figure 32b.

Figure 32b: Programmable Logic Relay SR2 A101FU and Programming Cable

The PLR has six logic inputs and four relay outputs, which can be configured for switched 240Vac Live or volt free according to the connectivity required.

The logic arrangement for the PLR is shown in Figure 32c. The design is implemented in Ladder Logic, programmed using the USB interface cable SR2USB01.

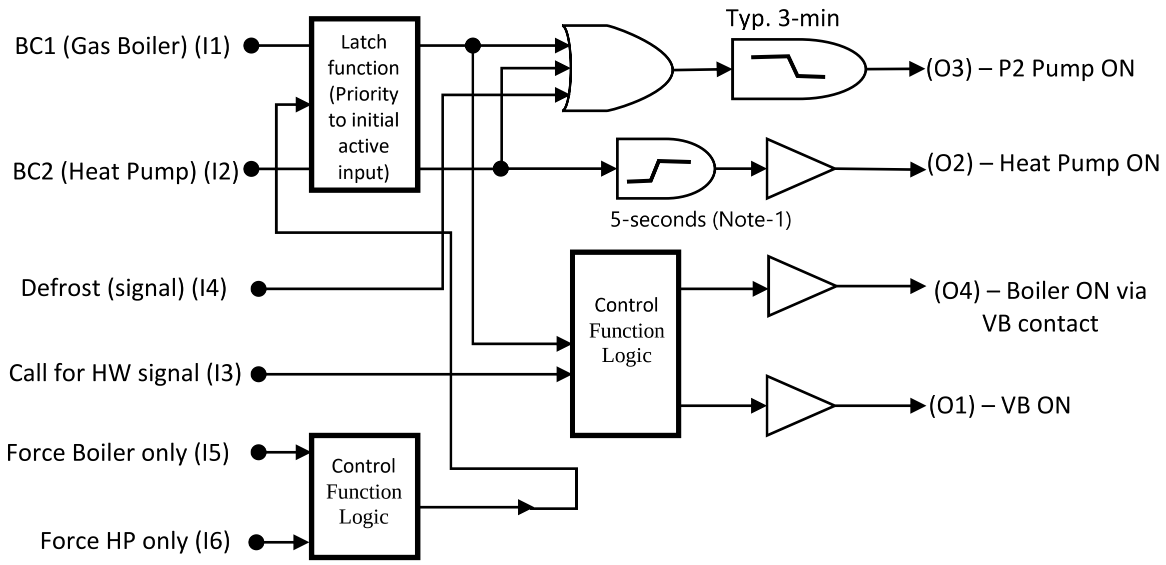


Figure 32c: PLR Logic Functional Diagram

The PLR design implementation makes use of motorised valves, as is common practice for heating systems. This ensures a circulation pump can only be turned ON if the flow path is open. There are effectively three heating / water circulation paths in this Hybrid Heating System, one for the gas boiler, one for the heat pump, and one for the radiator circuit.

a. **Heat Pump control:** The call for heat to the heat pump is made from the PLR to the heat pump FTC2B control unit. The FTC2B control unit then sends a command to open valve Vc. This causes activation of the circulation pump P1. By connecting the pump through the valve, it is not possible for the pump to be running against a closed valve which could damage it. Refer to Figure 32d.

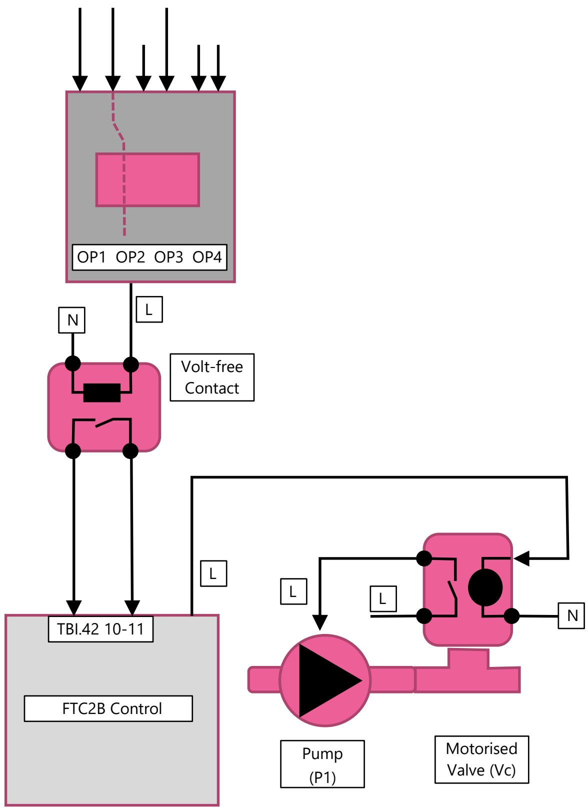


Figure 32d: Heat Pump Call for Heat management

b. **Gas Boiler control:** The PLR controls the call for heat to the boiler by sending an open command to the isolating valve Vb. This causes the contacts in the valve to close connecting the boiler call for heat input to the PLR and activating the boiler. When the PLR removes the call for heat signal it keeps the valve Vc open which allows the circulating pump in the boiler to overrun. Failure to do this may lead in damage to the boiler unless a bypass valve is installed.

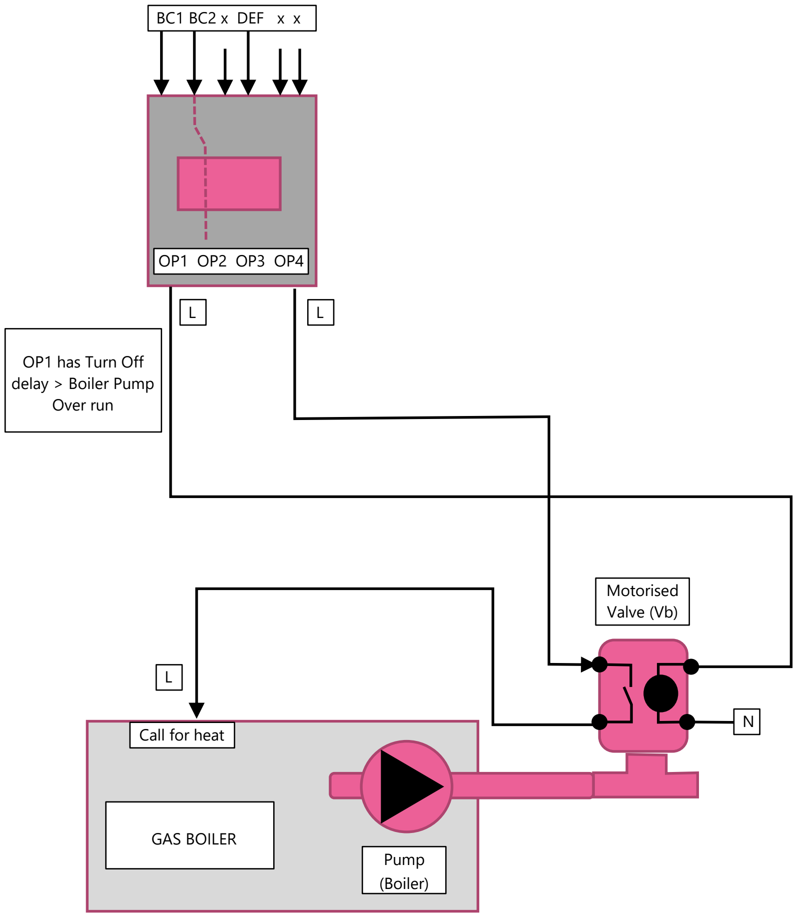


Figure 32e: Boiler Call for Heat management

The system also manages the following requirements:

- ***Heat Pump Return temperature limit***: The temperature of the return water is monitored to ensure that the flow into the Heat Pump is <65°C. Any temperature above this may cause the heat pump to shut down / cause damage to the unit. When the system is installed, the boiler is configured to a flow temperature of 65degC which should prevent the issue. However, the system also monitors the return temperatures and if they are above a configured value (nominally >65°C), the heat pump call for heat will be inhibited, whilst P2 pump remains active in order to speed up the cooling of the return flow to the level needed for heat pump operation. Below the configured value, the heat pump call for heat will be active as required. This is required because the maximum condensing pressure is at a temperature above +65ºC. Therefore, if the return temperature exceeds this, the unit will shut down and raise an error code on the display panel with Fault Code "U1". Manual reset of the system is required if this occurs.

- ***Prevent Boiler and Heat pump being switched on at the same time****:* If the boiler and heat pump are activated at the same time, there is a risk that damage may occur to the heat pump. To prevent this the HESG software is designed so that simultaneous switching of the boiler and the heat pump is not possible. However, it is also possible that both systems could be activated due to manual operation. The PLR implements a latch function as shown in Figure 32c that provides the failsafe, and is configured as follows:
    - If the boiler (BC1) is selected, and the heat pump (BC2) is then switched on, only the boiler is active. If the boiler is then cleared whilst the heat pump is still active, then the heat pump would then be selected after the turn on delay.
    - If the heat pump is selected, and the boiler is then switched on, only the heat pump is active. If the heat pump is then cleared whilst the boiler is still active, then boiler would be selected immediately.

- ***P1 Pump can only be activated after flow path is open.*** To prevent damage to the pump, the pump can only be turned on once the appropriate vales are open as described earlier**.**

- ***Defrost and freeze protect*** will function as required but the heat pump with P1 managed by the heat pump control circuit.

Heating System Water Volume

It is important to ensure the correct water / glycol mix is used to prevent the heating water freezing and damaging the system. A minimum of 25% glycol in the heating system water will provide freeze protection to -15ºC. A typical home will require around 12L – 15L of antifreeze. For UK installations it is usual to rely on the antifreeze rather than the freeze protect heat pump control circuit as this can result in high running costs as a result of the heat pump always being on if the ambient temperature is < +5ºC.

In the event that the freeze protect circuit is used, a minimum of 37L of water is required to produce correct operation for the heat pump model chosen. Less than this may result in the water freezing and damage to the heat pump.

Notes:

- *A typical home with 10 radiators will have a total volume of around 50 – 70 Litres. As the radiators are controlled by TRVs (thermostatic radiator valves) or WRVs (wireless radiator valves) only those that are not so fitted can be guaranteed to be open and should be included in the volume calculation*
- *The Low Loss Header can be used to add extra minimum volume capacity if needed.*

Mitsubishi Controller Unit

The heat pump is configured and can be managed if required via the Mitsubishi control unit. Normal operation of the hybrid system does not require interaction with this unit.

The Control and Monitoring unit functionality is shown in Figure 32f.

Figure 32f: Mitsubishi Heat Pump Control and Monitoring Panel

20.3. Heat Pump Configuration and Commissioning

Mitsubishi Document "Flow Temp. Controller 2B (Cased) PAC-IF032B-E" provides full details of how to configure and operate the Heat Pump, including the Main Controller functionality.

20.4. HESG Control Algorithm Description

The HESG heat pump control algorithm has been designed to be conservative to as to minimise the risk to participants of having a negative heating experience. The boiler is used at the start of any heating schedule to achieve the target temperature. Once the actual temperature is within the operating range, ±1degC of the target temperature by default, then the heat pump takes over and maintains the temperature. If the actual temperature falls by more than a configurable value below the target temperature, then the boiler takes back control. If a participant requests a heating override, then the boiler takes back control irrespective of any other conditions.

In addition to this, the system has been designed so that if the external temperature falls below a configurable temperature the boiler alone will be used.

In order to optimise the control of the heat pump and gas boiler and modify performance as experience is gained, several run time configurable parameters can be set via the HESG management interface as shown in Figure 33a.

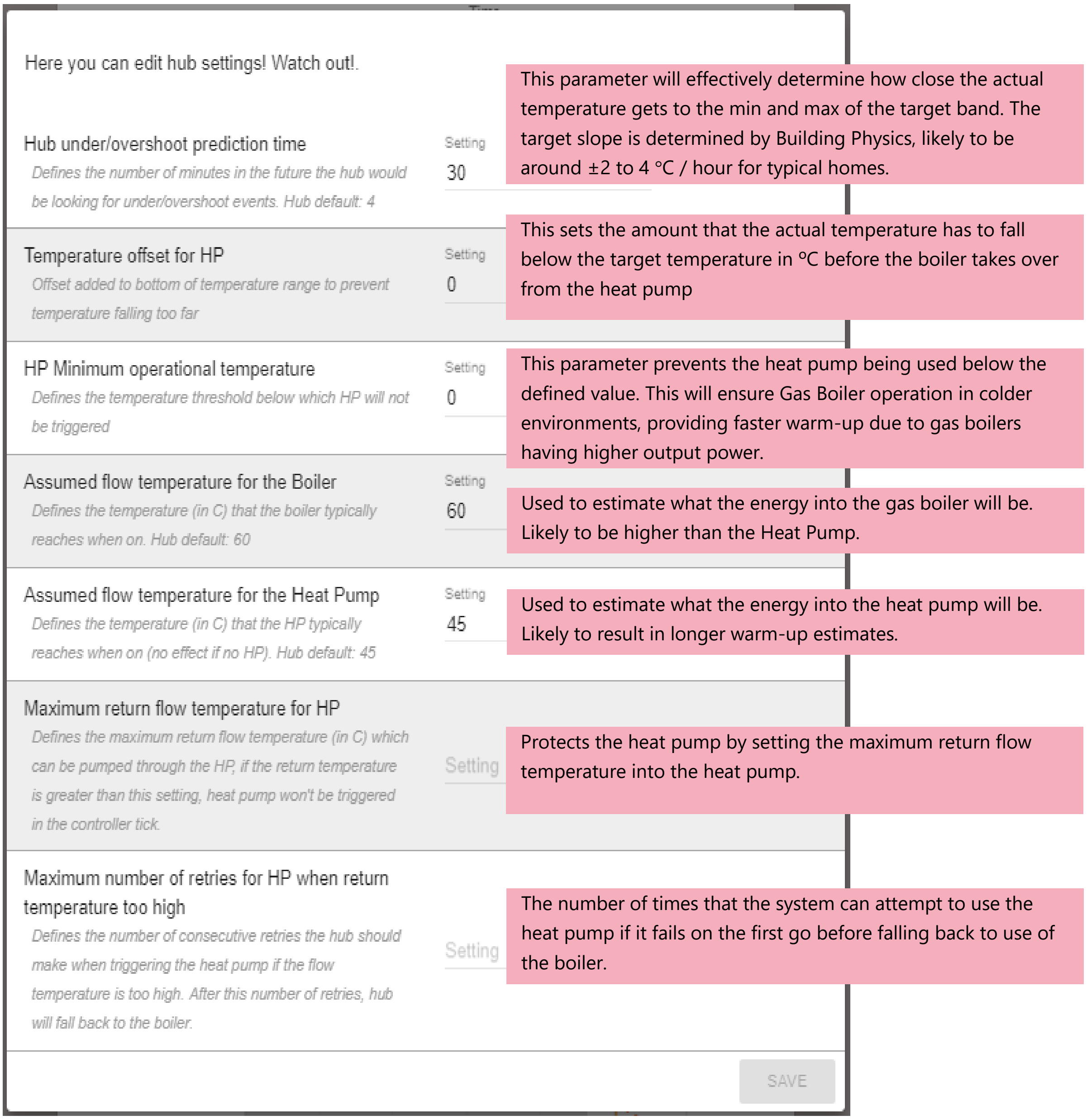


Figure 33a: Hub Settings available via the HESG management interface

Some examples of how the first two parameters will affect the boiler / heat pump performance are shown in Figures 34a, 34b and 34c. (LBP: learned building physics).

Figure 34a: The relatively long value of “t” will result in the control temperature being maintained in the centre of the control band. However, this will result in a relatively high heat pump switching cycle / WRV operations. All heating activity in the control band will be by the heat pump.

Figure 34b: The relatively short value of “t” will result in the control temperature being between the control band extremes. This will reduce the number of switching cycles / WRV operations. All heating activity in the control band will be by the heat pump.

Figure 34c: The effect of having a temperature offset for the heat pump will result in frequent use of the boiler to maintain temperature if the value “t” is relatively short.

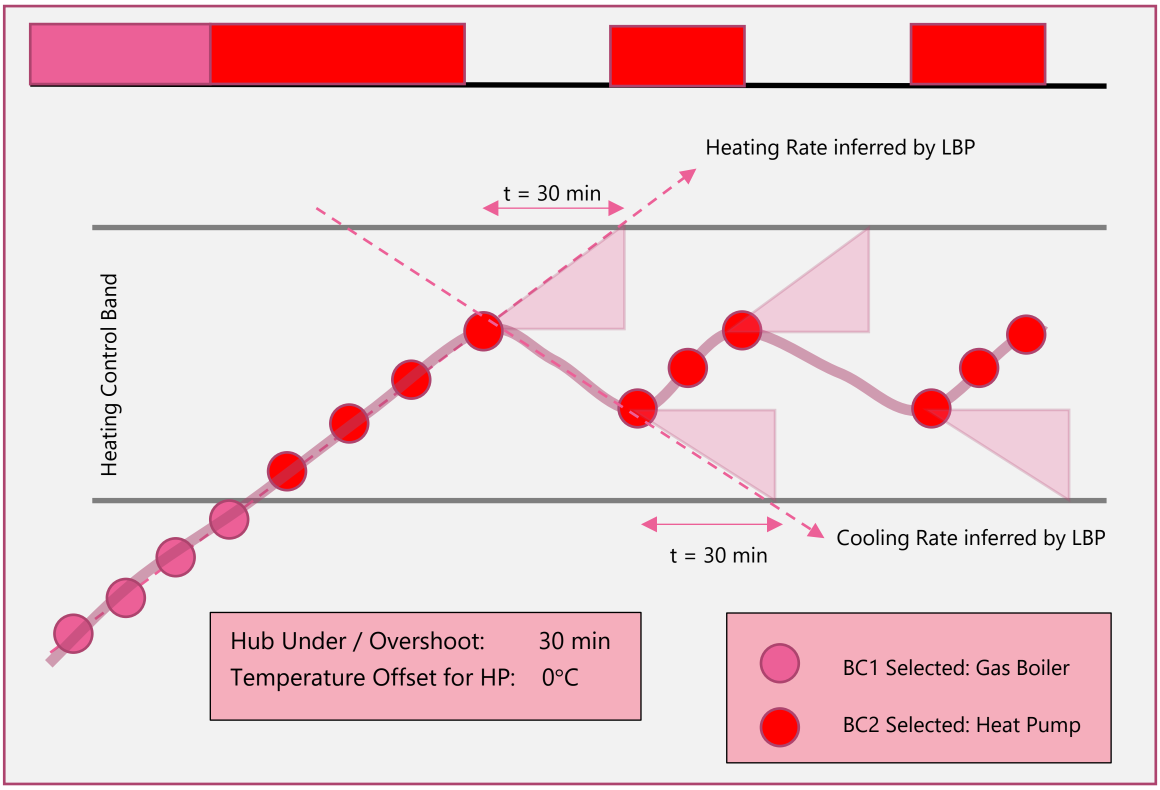


Figure 34a: Control Algorithm for Heat Pump Activity (Set to 30 min and 0°C)

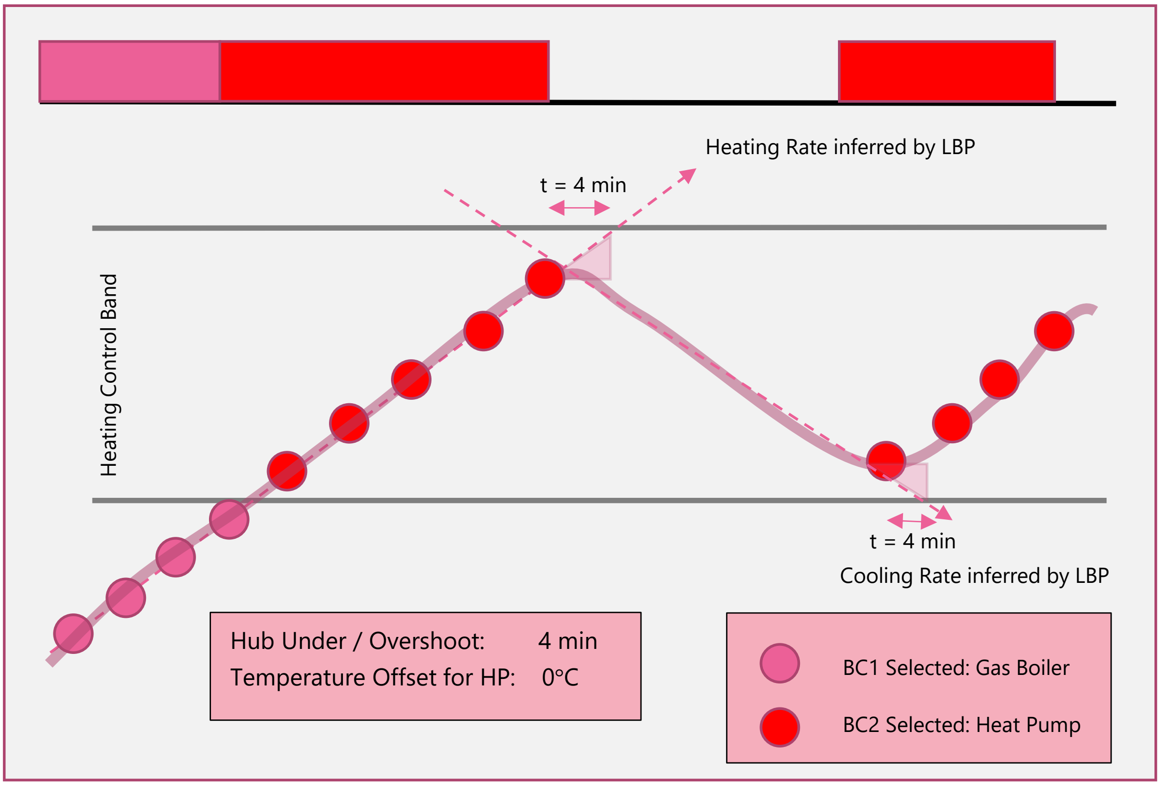


Figure 34b: Control Algorithm for Heat Pump Activity (Set to 4 min and 0°C)

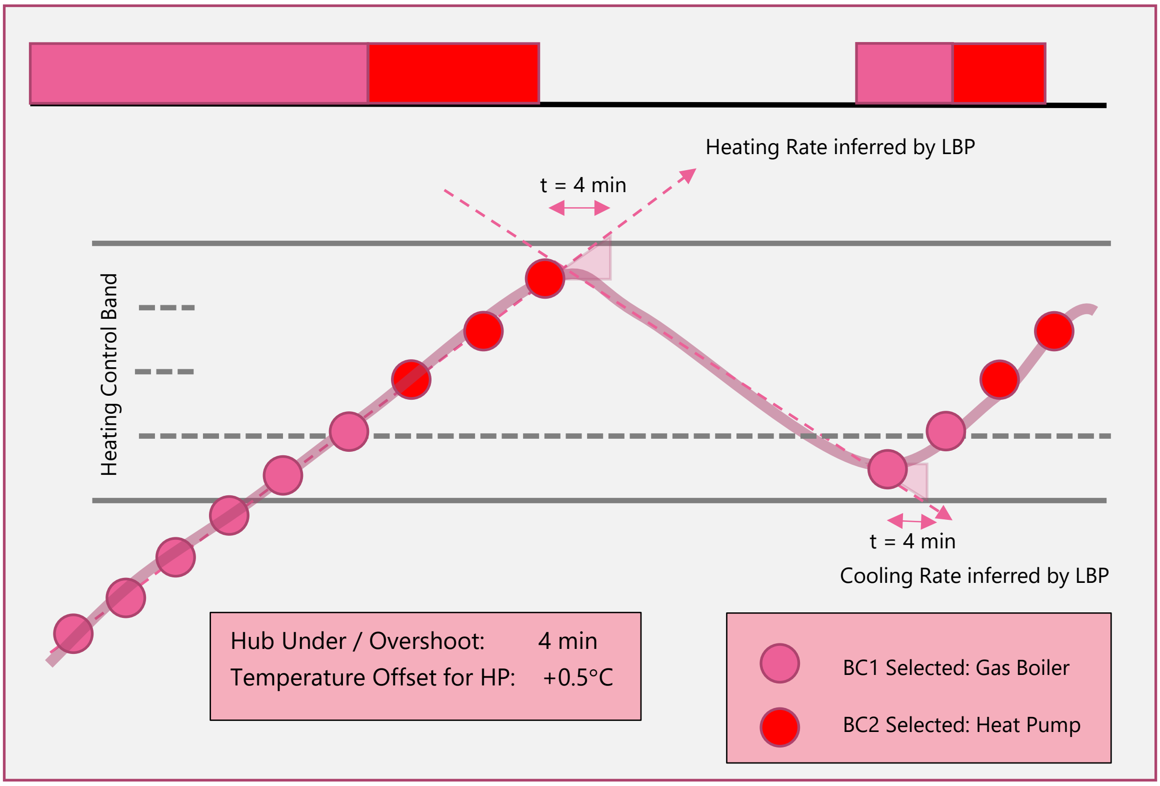


Figure 34c: Control Algorithm for Heat Pump Activity (Set to 4 min and +0.5°C

Example Home Performance

In attachment is a "real house" example.

It is from a specific room of the house, for two different days, one when only the boiler was used (Boiler-only system), one when the hybrid system was used (Boiler + heat pump). Both days had a very similar weather pattern.

This example demonstrates the boiler / heat pump use. Refer to Figure 35:

1) The pre-heating phase is performed by the gas boiler in both cases.
2) The heating cycle includes heating decisions based on predicted temperature.
3) For the hybrid system, the boiler is used when the temperature falls below the target band, with the heat pump taking over as soon as the room temperature is back in the target band.

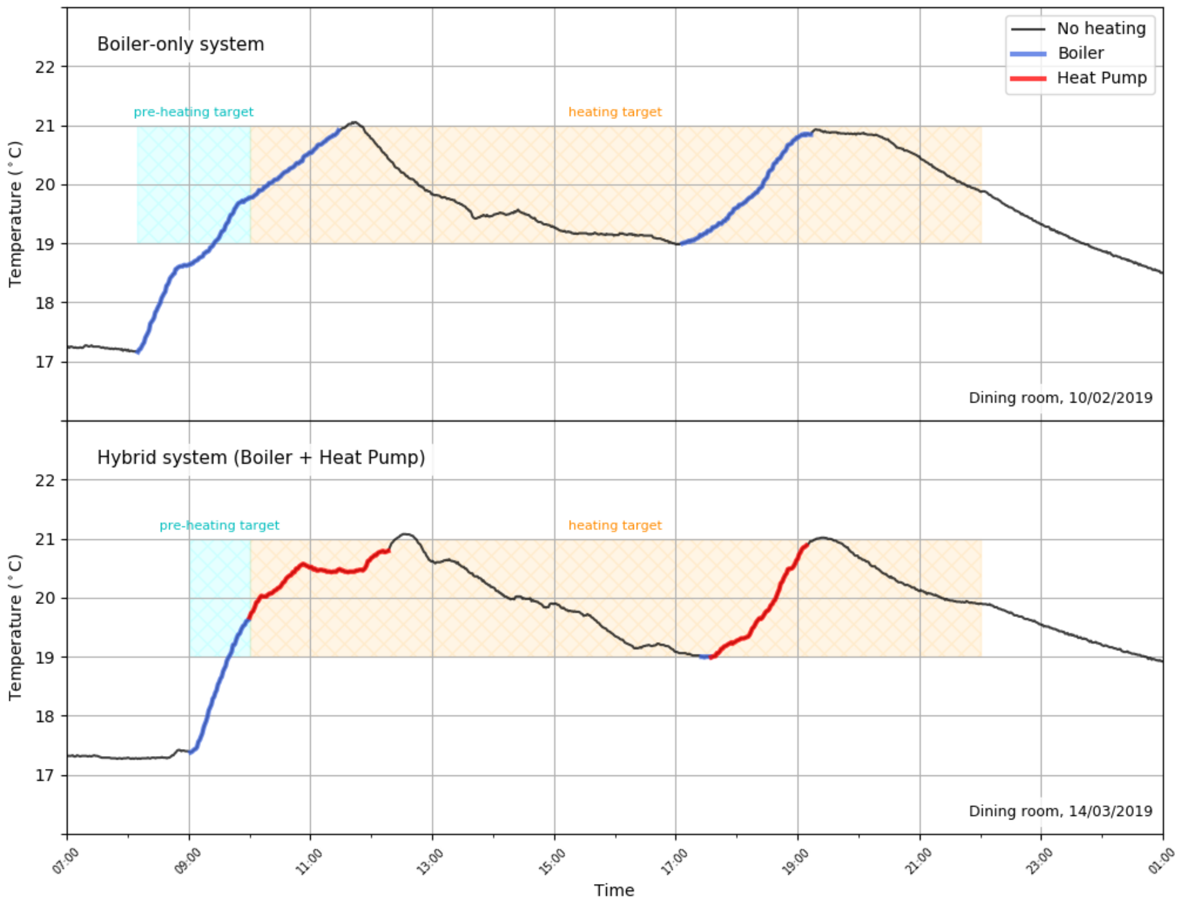


Figure 35. Real-home example of Hybrid Heating System

LICENCE/DISCLAIMER

Energy Systems Catapult (ESC) Limited Licence for [REPORT NAME]

ESC is making this report available under the following conditions. This is intended to make the Information contained in this report available on a similar basis as under the Open Government Licence, but it is not Crown Copyright: it is owned by ESC. Under such licence, ESC is able to make the Information available under the terms of this licence. You are encouraged to Use and re-Use the Information that is available under this ESC licence freely and flexibly, with only a few conditions.

Using information under this ESC licence

Use by You of the Information indicates your acceptance of the terms and conditions below. ESC grants You a licence to Use the Information subject to the conditions below.

You are free to:

- copy, publish, distribute and transmit the Information;
- adapt the Information;
- exploit the Information commercially and non-commercially, for example, by combining it with other information, or by including it in your own product or application.

You must, where You do any of the above:

- acknowledge the source of the Information by including the following acknowledgement:
- "Information taken from [REPORT NAME], by Energy Systems Catapult";
- provide a copy of or a link to this licence;
- state that the Information contains copyright information licensed under this ESC Licence.
- acquire and maintain all necessary licences from any third party needed to Use the Information.

These are important conditions of this licence and if You fail to comply with them the rights granted to You under this licence, or any similar licence granted by ESC, will end automatically.

Exemptions

This licence only covers the Information and does not cover:

- personal data in the Information;
- trademarks of ESC; and
- any other intellectual property rights, including patents, trademarks, and design rights.

Non-endorsement

This licence does not grant You any right to Use the Information in a way that suggests any official status or that ESC endorses You or your Use of the Information.

Non-warranty and liability

The Information is made available for Use without charge. In downloading the Information, you accept the basis on which ESC makes it available. The Information is licensed 'as is' and ESC excludes all representations, warranties, obligations and liabilities in relation to the Information to the maximum extent permitted by law.

ESC is not liable for any errors or omissions in the Information and shall not be liable for any loss, injury or damage of any kind caused by its Use. This exclusion of liability includes, but is not limited to, any direct, indirect, special, incidental, consequential, punitive, or exemplary damages in each case such as loss of revenue, data, anticipated profits, and lost business. ESC does not guarantee the continued supply of the Information.

Governing law

This licence and any dispute or claim arising out of or in connection with it (including any noncontractual claims or disputes) shall be governed by and construed in accordance with the laws of England and Wales and the parties irrevocably submit to the non-exclusive jurisdiction of the English courts.

Definitions

In this licence, the terms below have the following meanings: 'Information' means information protected by copyright or by database right (for example, literary and artistic works, content, data and source code) offered for Use under the terms of this licence. 'ESC' means Energy Systems Catapult Limited, a company incorporated and registered in England and Wales with company number 8705784 whose registered office is at Cannon House, 7th Floor, The Priory Queensway, Birmingham, B4 6BS. 'Use' means doing any act which is restricted by copyright or database right, whether in the original medium or in any other medium, and includes without limitation distributing, copying, adapting, modifying as may be technically necessary to use it in a different mode or format. 'You' means the natural or legal person, or body of persons corporate or incorporate, acquiring rights under this licence.