Making heat cheaper, smarter and greener

Paul Rogers and Michael Hamer – January 2023

Background

National Energy Action is the national fuel poverty charity working across England, Wales and Northern Ireland, and with sister charity Energy Action Scotland (EAS), to ensure that everyone can afford to live in a warm, dry home. In partnership with central and local government, fuel utilities, housing providers, consumer groups and voluntary organisations, NEA undertakes a range of activities to address the causes and treat the symptoms of fuel poverty. Its work encompasses all aspects of fuel poverty, but in particular emphasises the importance of greater investment in domestic energy efficiency.

This project was carried out by the Innovation and Technical Evaluation team at NEA:

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Table of contents

1. Project overview

1.1 Introduction

North Devon Homes is considering suitable technologies to retrofit rural off-gas grid properties, to reduce heating costs and improve thermal comfort for their customers. Many of these homes have traditional storage heaters which offer poor control and are expensive to run.

This project trialled a heating technology developed by Boxergy, which combined a high temperature air-source heat pump with energy storage with the aim to improve thermal comfort and reduce running costs. The Boxergy Hero system used a Vaillant aroTHERM plus heat pump. There was also an external 'Hero' box which contained a Sunamp heat battery, an Alpha ESS electrical battery along with control systems and monitoring.

7 households in Witheridge with storage heaters received a new wet central heating system and a Boxergy Hero system. These were the first Boxergy Hero installations in England and in socially rented properties. Installations took place in 5 semi-detached or end-terraced bungalows and 2 mid-terraced houses.

The project included an evaluation carried out by National Energy Action (NEA), investigating resident satisfaction, ease of use, running costs and reliability. Performance was also compared to the resident's previous energy consumption, and against comparable households selected as control properties. These included 2 households with low-temperature air-source heat pumps, a property with infrared heating panels and another with storage heaters and a Tesla Powerwall 2 battery charging using off-peak electricity.

The evaluation will be published on the NEA website, and dissemination will include sharing of learning among AdvantageSW members, presentations at events and articles in journals and the media.

1.2 Project targets

The project was led by North Devon Homes and NEA and achieved the following:

- Installed wet central heating systems in 7 off-gas grid socially rented homes owned by North Devon Homes which had electric storage heaters
- Installed 7 Boxergy Hero systems which combine a high temperature air source heat pump with an electrical and heat battery
- Monitored pre-installation electricity consumption in the homes during the previous heating season
- Monitored electricity consumption in the homes after installation of the Boxergy system
- Monitored electricity consumption of 4 comparable control properties which were heated using air source heat pumps, infrared heating panels and storage heaters with a battery
- Assessed levels of satisfaction before and after installation of the Boxergy Hero system
- Considered challenges associated with deployment and operation of the technology
- Produced an evaluation report and disseminated results from the innovation project

1.3 Context

In 2020, there were about 44,316 households in North Devon and the proportion of fuel poor households was estimated to be 12.3%. In the Witheridge ward of North Devon there were 1,081 households and the proportion who were fuel poor was 13.2%[1]. Rates of fuel poverty are higher in off-gas grid areas and in social housing and will have increased following the energy price rises of 2021/22.

North Devon Homes Ltd is the main social landlord in the district and rents 3,263 homes. There are 459 properties in areas where mains gas is unavailable, and 610 properties have Economy 7 heating. Of these, 186 have been upgraded to high heat retention storage heaters. About 6,475 households in North Devon had Economy 7 meters in 2020 and the average (mean) electricity consumption was 6,618 kWh[2]. In Witheridge, in the two postcode areas where the installations and controls were located, the mean electricity consumption for the Economy 7 meters was estimated to be 10,068 kWh in 2020[3].

Many tenants in off-gas grid homes have traditional storage heaters. There is dissatisfaction with the thermal comfort, ease of use and running costs with these heaters. Landlords and households looking to replace traditional storage heaters typically have the option of replacing them with modern high heat retention storage heaters or fitting an air source heat pump with a new wet central heating system.

Modern high heat retention storage heaters have the advantages of a digital thermostatic control and emitting less heat at times when heating is not required. However, running costs can still be expensive and they may not provide whole house heating. Some households can struggle to understand the more complicated controls.

A heat pump is likely to have lower running costs than storage heaters if a well-designed system is fitted in an appropriate property. The seasonal coefficient of performance (SCOP) is likely to be 3 or more, meaning that each unit of electricity produces on average 3 units of heat. There are challenges with fitting a new wet central heating system in a property and where the levels of insulation and airtightness are poor.

The Boxergy Hero system combines an air source heat pump with an electrical and a heat battery. The household stays on a time of use tariff and the electrical battery charges during the off-peak periods and supplies cheaper electricity to the household during peak rate periods. This means that the heat pump can be powered by off-peak electricity for some of the expensive peak rate period. Maximising the use of off-peak electricity should mean the Boxergy heating system has lower running costs than a standard air source heat pump and storage heaters.

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[1] Department for Business, Energy and Industrial Strategy, Sub-regional Fuel Poverty England 2022 (2020 data) https://www.gov.uk/government/statistics/sub-regional-fuel-poverty-data-2022 (Accessed 22 Nov 22)

[2] Department for Business, Energy and Industrial Strategy, Sub-national electricity consumption statistics 2005-2020 https://www.gov.uk/government/statistics/regional-and-local-authority-electricity-consumption-statistics (Accessed 22 Nov 22)

[3] Department for Business, Energy and Industrial Strategy, Postcode level electricity statistics 2020 (experimental) https://www.gov.uk/government/statistics/postcode-level-electricity-statistics-2020-experimental (Accessed 22 Nov 22)

1.4 Project timeline

The project started at the beginning of March 2020. The first lockdown due to COVID-19 began on 23rd March, shortly after the start of the project. Restrictions were gradually reduced between 13th May and 4th July 2020. Recruitment and surveys of suitable properties took place once home visits were possible again from June until October. Monitoring equipment for temperature/humidity and electricity consumption was fitted at the end of October 2020.

The second COVID-19 lockdown across England took place from 5th November 2020 until 2nd December 2020. Two additional control properties were recruited in December 2020 and monitoring equipment fitted. The third COVID-19 lockdown across England started on 6th January 2021 and restrictions were gradually reduced between 12th April and 19th July 2021 as part of a 4-step plan.

The first installation took place in late June, with the storage heaters removed and wet central heating system completed by 17th June 2021. The Boxergy system comprising the Vaillant aroTHERM plus air source heat pump and Sunamp heat battery was commissioned on 25th June 2021. It was not possible to fit the Alpha ESS electrical battery at this time due to supply chain issues.

The second Boxergy installation was commissioned on 25th November 2021. This included both the Sunamp heat battery and a 10.1kWh Alpha ESS electrical battery.

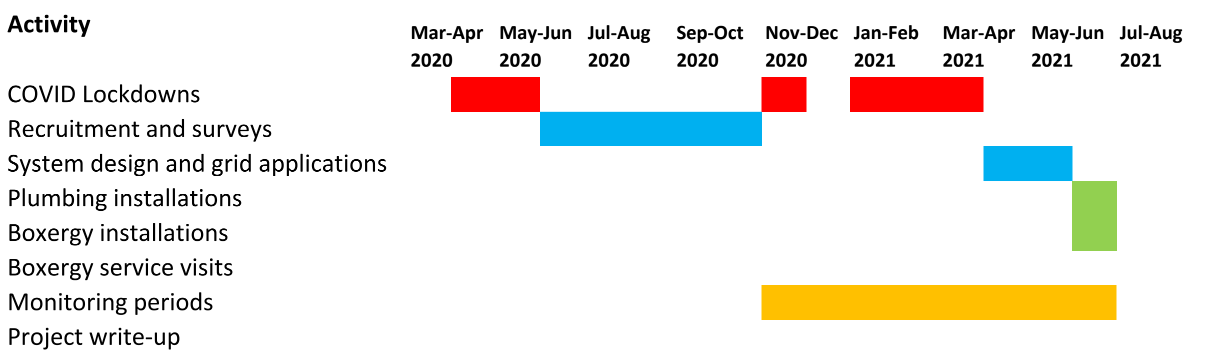


Figure 1.1 a Project timeline – March 2020 to August 2021

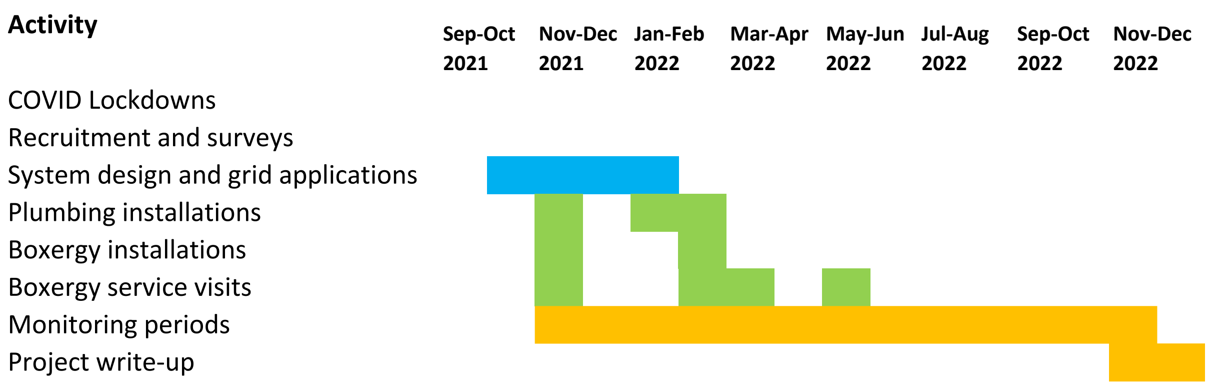


Figure 1.1 b Project timeline – September 2021 to December 2022

The remaining 5 installations took place in January and February 2022. Three installations were commissioned on 28th January 2022 and the remaining two installations were commissioned on 10th and 11th February 2022.

There were service visits during the second week of March 2022, the third week of May 2022 and the second week of July to address issues with systems and to fit components which were unavailable at the time of commissioning.

Household interviews to assess satisfaction with the new heating system took place at the end of October 2022 and the project was written up in November and December.

1.5 Recruitment of households for installations and monitoring

- Witheridge was identified as a suitable location for the installations having a significant number of NDH properties that were on Economy 7 and had traditional storage heaters
- These included semi-detached or terraced bungalows and terraced houses
- A shortlist of suitable properties in the village was drawn up and recruitment letters were sent to households with information about the project and the Boxergy heating system
- A tenant liaison officer and a staff member from NEA also phoned residents to see if they were interested in having an installation and willing to have a survey
- A mix of properties were selected for installations that included houses and bungalows
- Surveys of the properties to have installations were carried out in Autumn 2020
- This enabled room by room heat loss calculations to be made and for Boxergy to specify the radiators and heat pump
- Properties which would make interesting control households were identified
- Letters were sent to households as well as contacting them by phone and in person
- A total of 4 households were selected as controls with 2 households having existing air-source heat pumps, 1 having infrared heating panels and another storage heaters and a Tesla Powerwall 2 battery
- All households were interviewed at the start of the project before monitors were fitted and at the end of the project
- All households that had installations and were control properties were provided with £50 in shopping vouchers during the final interview as an incentive for assisting with the study

1.6 Factors affecting the project plan

Issue	Description and mitigation
Change to number of households benefiting from installation	Originally, the project aimed to have the 7 Boxergy Hero installations providing heating for 9 homes. It was intended that semi-detached bungalows could share a Boxergy Hero installation, allowing 2 installations to supply 4 homes. The potential for a shared installation was discussed with the Distribution Network Operator (DNO). It was not possible for the battery with the Boxergy Hero system to supply both homes and there would have been complexities with metering if the heating was powered by 1 home and supplied 2 homes. Another alternative was for the Boxergy Hero system to have its own electricity supply and the battery to only power the heat pump and not also a home. The battery would have provided less benefit to households, with little benefit in summer when the heat pump was little used. The DNO also had concerns about installing a new electricity supply for such a system. They wanted to check there would be full electrical separation of the systems. They also wanted lines to be inserted into the property deeds protecting the electricity supply and heat pump installation should the properties be sold in the future under right-to-buy. The concern was that a new owner might request that the Boxergy system and electricity supply be removed and install alternative heating. North Devon Homes also noted that the properties selected were still mortgaged and the lender might have restrictions on what could be done at the property and may be unhappy with a shared system. The above complications and budget considerations meant that the Boxergy Hero systems were only installed at and provided heating for 7 individual properties.
Delays and complications due to COVID-19	The project started at the beginning of March 2020 shortly before the first lockdown due to COVID-19. There were multiple impacts to the project as a result of COVID-19. Initial surveys and recruitment were delayed and most household visits were carried out using protective masks. Trials to confirm the heat pump operated with the heat battery were not possible during lockdowns. Household visits and installations were not possible during certain time periods. Installations were completed within 2 years of the start of the project, but a 9-month extension was required to get all aspects of the Boxergy Hero systems operational and to allow a period for monitoring of performance and an evaluation report to be written.
Supply chain issues	There were delays due to supply chain issues which resulted from the COVID pandemic. Manufacture of the Boxergy Hero enclosures was delayed. Obtaining suitable chips for the Boxergy Hero controller was difficult and also led to a redesign. There were delays in obtaining other components such as the Vaillant

	sensoNET gateway, which meant an installation having this fitted only in May 2022. There was also difficultly obtaining Alpha battery modules. It took over 6 months to get a replacement 10.1kWh module after a unit failed.
Wet central heating installation cost	The cost of the wet central heating installations and removal of the old storage heaters was considerably more than had been originally budgeted for. The cost of the first wet central heating installation was more than double the original quote. This was partly due to additional staff time, higher specification materials being required and the addition of a volumizer and expansion vessel for the Vaillant system. A review of the costs was made and another contractor was selected for the plumbing for the remaining installations. It was however also necessary to use all the contingency budget for grid connections and plumbing/installation issues.
Clearance of lofts	In the bungalows, the pipework for the wet central heating systems ran through the loft and pipes were dropped down walls in locations near to where the radiators were fitted. It was necessary for the lofts to be clear for the plumbers to work. While North Devon Homes sometimes lock the loft hatch to ensure that the lofts are kept clear, for several of these properties belongings had to be moved from the loft. Unfortunately, some items were damaged when moved by a contractor at 1 property which led to a disagreement with the resident. At another, a major clearance of the loft and house was necessary for plumbers to have access to the loft and to be able to fit radiators.
Limited post-installation monitoring	Although it was possible to collect extensive data from winter 20/21 before the installations, there was a limited period of cold weather for monitoring 5 of the systems after the installation. Additional complications included technical issues with some of the installations. Also, Storm Eunice blew the outhouse roof off for a household with an installation and a control household. This meant the residents had to be moved out for a period. There was a period of 18 days between the storm and the Boxergy heating system being back online.

2. Social evaluation and impacts

2.1 Details of the properties

2.1.1 Location of the installations

Figure 2.1 Location of the Boxergy installations and control properties in North Devon

All the installations and control properties were in Witheridge, a village with a population of about 1,300. It is off the gas grid and located on the B3137 between South Molton and Tiverton. It has an elevation of 188m, which makes it more prone to cold weather in winter. Wikipedia notes that the name of the village may be derived from the Old English for “Weather Ridge” and suggests this could be due to the exposed location[4].

2.1.2. Building types and characteristics

Figure 2.2 (a) Example installation at bungalow (b) Mid-terraced house

[4] Witheridge, Wikipedia https://en.wikipedia.org/wiki/Witheridge (Accessed 22 Nov 22)

There was a total of 7 Boxergy Hero systems installed in Witheridge. 5 of the installations were in 2-bedroom bungalows which were either semi-detached or end-terraced and dated from about 1965. The other 2 installations were in mid-terraced houses which were built between 1945 and 1950.

There were 2 control properties which had air-source heat pumps. These were 1-bedroom brick bungalows of a similar design and age to the bungalows which had the Boxergy installations. The control property with infrared heating panels was another comparable 2-bedroom semi-detached bungalow. The control with storage heaters and the battery was a mid-terraced house which was in the age band 1965-1975.

Each property in the study was given a technical reference number. The technical reference number for households having Boxergy Hero installations started with B, while those which were control properties started with C. Table 2.3 shows characteristics of different properties in the study including the dwelling type, number of bedrooms, floor area and the type of heating system at the start of the project. It also shows the energy score for the Energy Performance Certificate before and after the Boxergy installation.

The control properties do not include a value for the energy score as the EPCs available did not reflect the current heating system installed.

Technical Reference Number	Dwelling Type	Number of bedrooms	Floor area (m^2)	Wall Type	Heating at the start of the project	Pre-install Energy Score	Date Boxergy commissioned	Post-install Energy Score
B-01	Bungalow	2	55	Filled cavity	Storage heaters	57	25-Jun-21	76
B-02	Bungalow	2	55	Filled cavity	Storage heaters	60	25-Nov-21	76
B-03	Mid-terrace house	3	100	Filled cavity	Storage heaters	46	28-Jan-22	76
B-04	Bungalow	2	55	Filled cavity	Storage heaters	56	28-Jan-22	76
B-05	Bungalow	2	55	Filled cavity	Storage heaters	58	28-Jan-22	76
B-06	Bungalow	2	55	Filled cavity	Storage heaters	61	10-Feb-22	76
B-07	Mid-terrace house	2	87	Filled cavity	Storage heaters	54	11-Feb-22	75
C-01	Bungalow	2	57	Filled cavity	Infrared panels		-	
C-02	Mid-terrace house	3	88	Filled cavity	Storage heaters		-	
C-03	Bungalow	1	51	Filled cavity	ASHP		-	
C-04	Bungalow	1	50	Filled cavity	ASHP		-	
Average			**64.4**			**56.0**		**75.9**

Table 2.3 Details of properties where a Boxergy Hero heating system was installed and also the control properties in the study

2.2 Details of monitored households

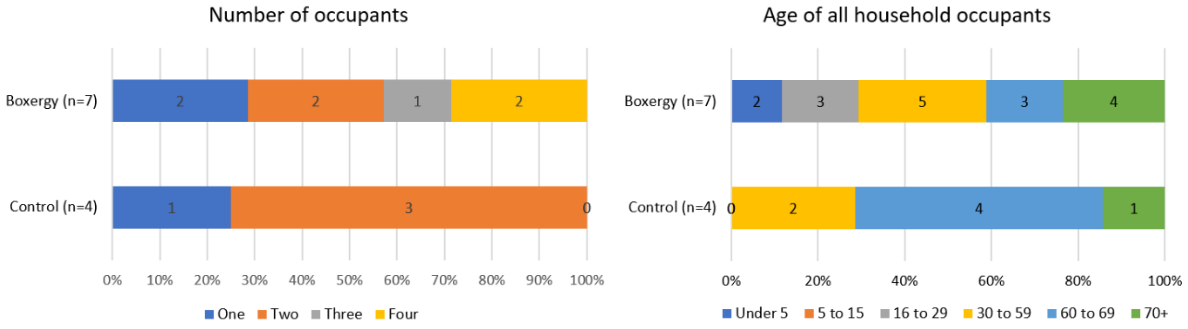


Figure 2.4
(a) Number of occupants per household (b) Age of all household occupants

At the time of final interviews for the study, 2 of the 7 households that received a Boxergy Hero installation had a single resident (figure 2.4). There were 2 households with 2 residents, a single household with 3 residents and 2 households with 4 residents. Over the course of the project, the total number of residents had fallen from 18 to 17. There was the birth of a baby and a new person who moved in, while 3 people had moved out.

Among the control households, there was 1 single person household and 3 households with 2 residents at the time of the final interview. A few weeks prior to that interview, a resident moved out from a household that was recorded as 2-person and so could be classed as a 3-person household for much of the study.

Many of those who lived in the properties which had Boxergy Hero installations were over 60 years old, with 3 in the age band 60 to 69 and 4 who were over 70. There were only 2 children living in these properties who were both under 5 and lived in the same household. There were 3 residents in the age band 16 to 29 and 5 residents who were between 30 and 59 years old.

There were 7 residents in the control households. There were no children and young adults among these residents with a single person over 70 years old, 4 in the age band 60 to 69 years and 2 residents who were between 30 and 59.

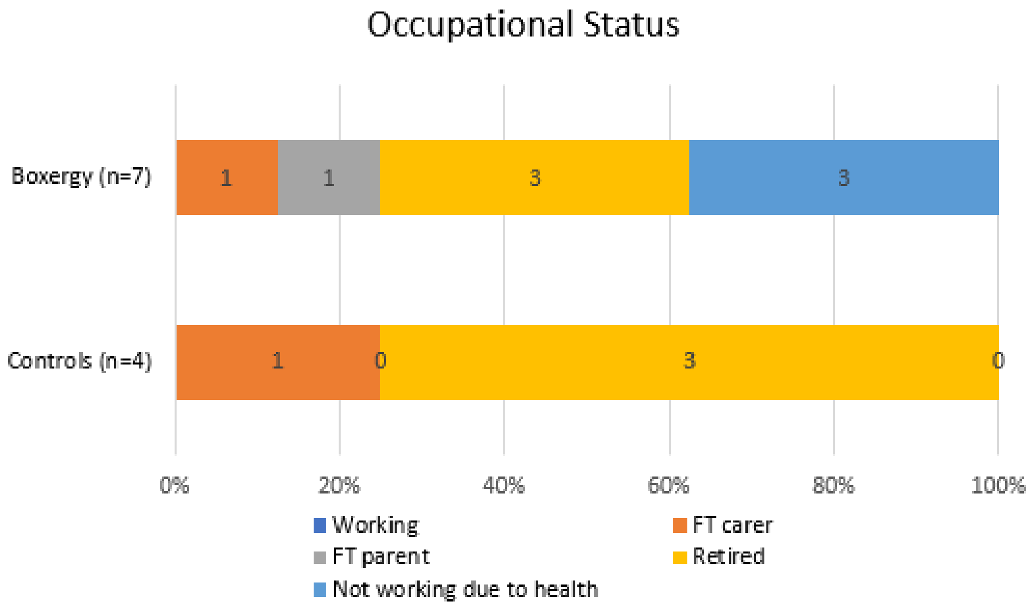
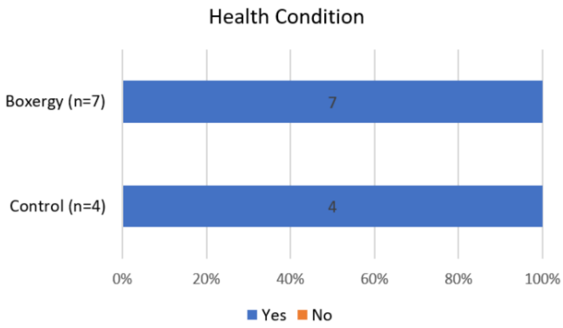


Figure 2.5 Number of occupants per household

Among the household members who were interviewed, none with a Boxergy Hero installation and none of the control household members were working. There were 3 households with Boxergy Hero installations where a resident was not working due to health or a disability and a further household where the interviewee was a full-time carer. A resident who was not working due to health was also a full-time parent. The interviewee was retired for 3 of the households which had a Boxergy Hero installation.

For the control households, the interviewee was retired for 3 of the households and was a full-time carer in the other.



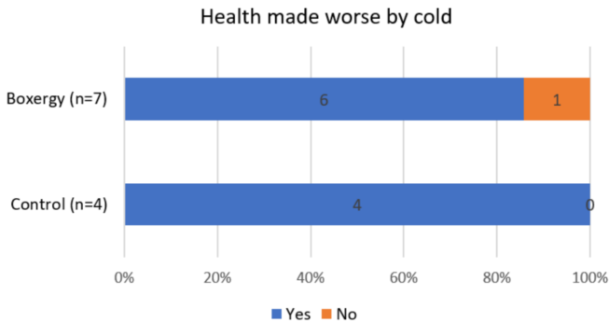


Figure 2.6
(a) Households with a health condition (b) Households where health made worse by cold

All the households that had a Boxergy Hero installation and were control properties had members who had a health condition or limiting long-term illness (figure 2.6). These conditions included: Addison's disease angina, arthritis, asthma, cancer, COPD, diabetes, fibromyalgia, heart condition, M.E. and mobility issues. Each of these households apart from 1 who had a Boxergy installation felt that their health was made worse by cold living conditions.

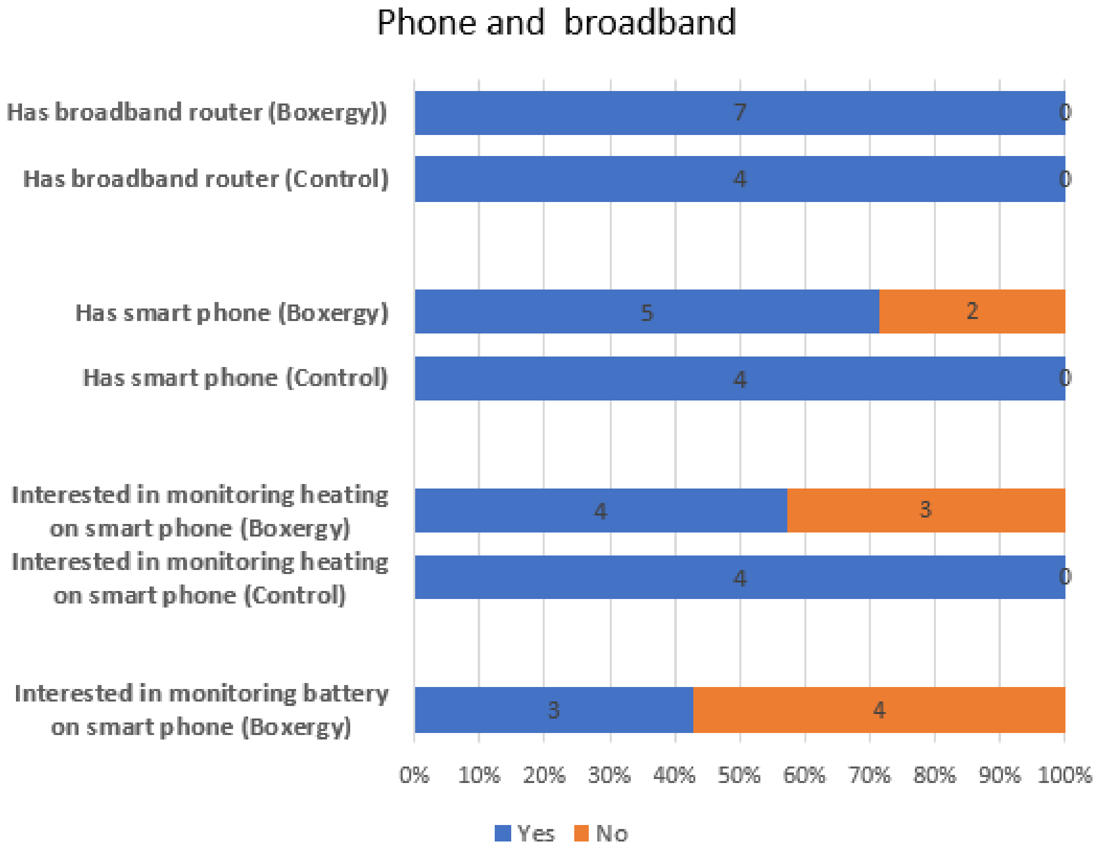


Figure 2.7 Home broadband and smart phone availability and use

All 7 of the households that had a Boxergy Hero installation had home broadband. This was a requirement for the installation. The control households also all had home broadband and a WIFI router. 5 out of the 7 households that had a Boxergy Hero installation had a smart phone. Among these, 4 households said they were be interested in monitoring their heating system with their smart phone and 3 said they would be interested in monitoring the battery for the Boxergy system with their smart phone. During the study, only Boxergy and NEA had access to monitoring of the heat pump and the Alpha ESS battery system.

All 4 of the control households had a smart phone and were interested in the idea of being able to monitor their heating system with an app on the smart phone.

2.3 Affordability of energy bills

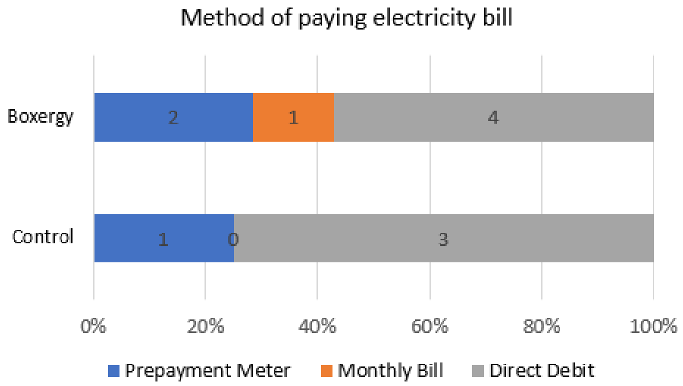


Figure 2.8 Method of paying for electricity bill

The majority of the households who took part in the project were paying for their electricity by Direct Debit. 4 of the 7 households with Boxergy Hero installations and 3 of the 4-control household paid be Direct Debit. There were 2 households with Boxergy Hero installations and 1 control household who were paying by pre-payment meter. A single household was paying by monthly bill, but this was due to a dispute with their electricity supplier.

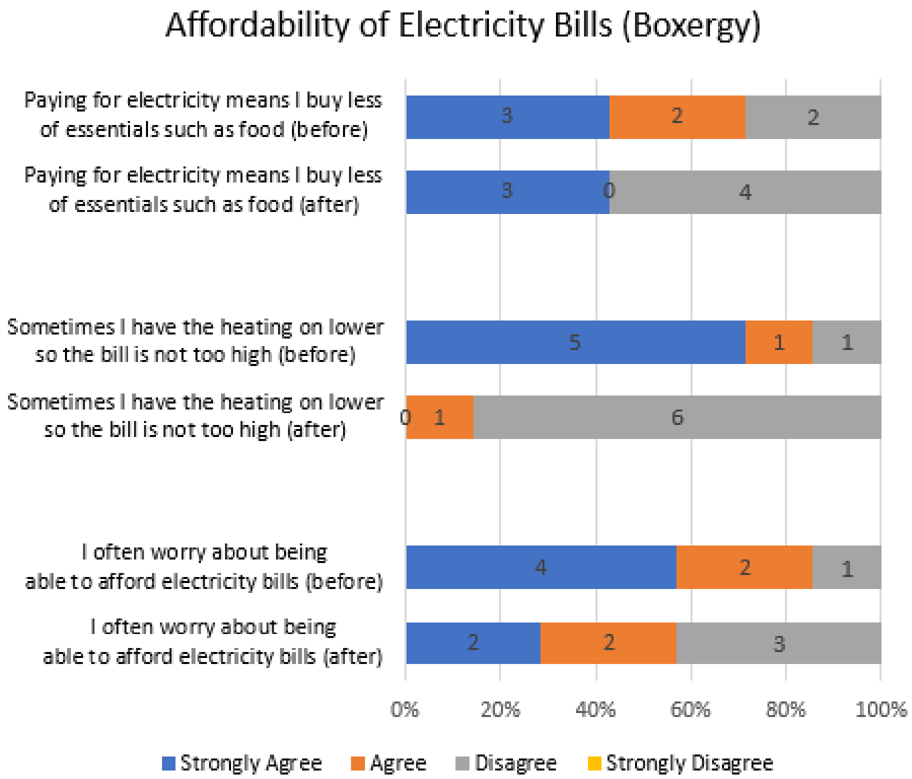


Figure 2.9 Affordability of electricity bills before and after the Boxergy Hero installation

The steep rise in electricity prices during 2021/2022 makes it difficult to assess the impact of installing the Boxergy Hero heating system on the affordability of electricity bills. Responses from households are likely to be affected by price rises over the project.

Households were asked at the start and end of the project whether paying for electricity meant that sometimes they could not afford to buy or bought less of other essentials such as food. At the start of the project, 3 of the households that had a Boxergy Hero installation strongly agreed with that statement with a further 2 agreeing and 2 disagreeing (figure 2.9). By the end of the project, 3 households still strongly agreed with the statement, but 4 now disagreed. There was an improvement in this response despite electricity prices rising.

For comparison, 4 of the control household disagreed with the statement at the start. By the end, 3 still disagreed, but 1 household had changed their response to agreeing with the statement (figure 2.10). The control households included 2 with air-source heat pumps, 1 with infrared heating panels and 1 with traditional storage heaters and a Tesla Powerwall 2 battery charging on the off-peak tariff and discharging during the peak rate period.

Households were also asked at the start and end of the project if they sometimes had their heating on lower so that the bills were not too high. Before they had the Boxergy Hero installation, 5 households strongly agreed with this statement and a further household agreed. A single household disagreed. After having the Boxergy installation there was a marked shift, with only 1 household agreeing that they had the heating on lower and 6 disagreeing (figure 2.9).

With the control households, there was the reverse shift (figure 2.10). At the start of the project, 1 household agreed that they sometimes had the heating on lower so that the bill was not too high while 3 of the 4 households disagreed. By the end of the project, 1 household strongly agreed and 3 agreed with the statement. There had been no change in their heating system, only in electricity prices over this period.

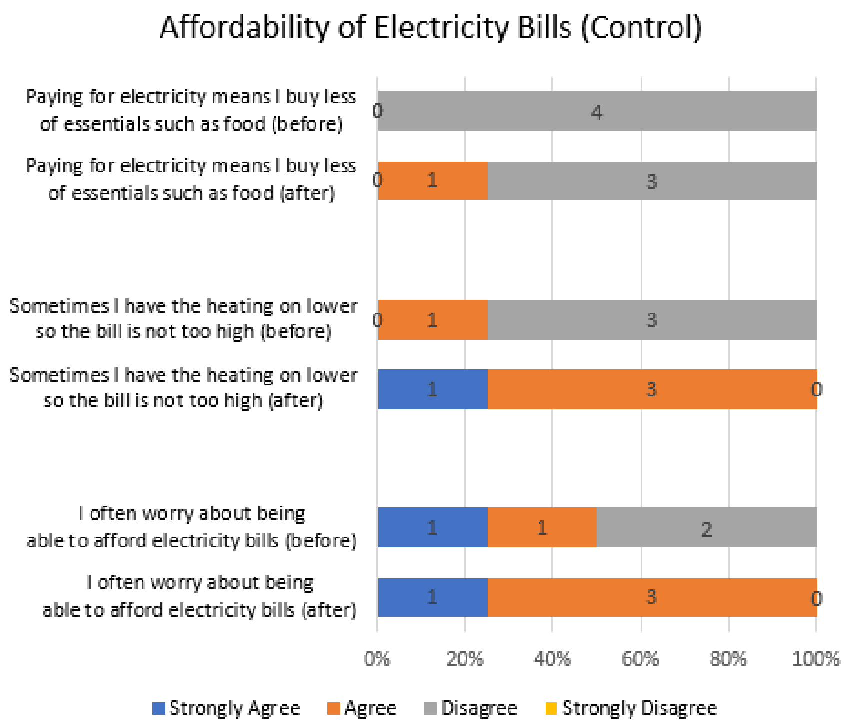
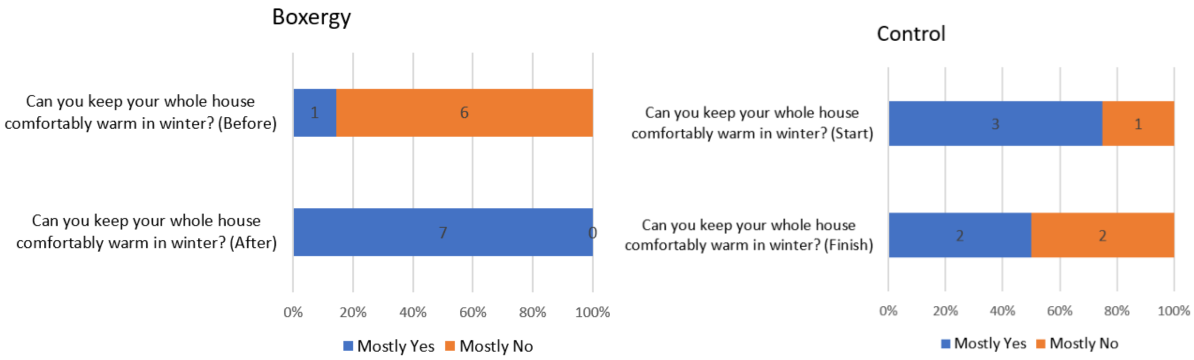


Figure 2.10 Affordability of electricity bills at the start and end of the project for the control households

Each of the households were asked at the start and end of the project if they often worried about being able to afford their electricity bills. Figure 2.9 shows that among the households having a Boxergy Hero installation, there was a decrease in this concern over the course of the project.

Before the installation 4 of the households strongly agreed that they often worried about being able to afford their electricity bills with a further 2 agreeing with the statement and only 1 disagreeing. By the end of the project, the number strongly agreeing had decreased from 4 to 2. Those agreeing remained the same at 2, but those disagreeing that they often worried about the affordability of their electricity bills had increased from 1 to 3.

In contrast, concern about affordability of their electricity bills increased among the control properties (figure 2.10). At the start of the project 1 household strongly agreed that they often worried about the affordability of their electricity bills, 1 household agreed and 2 disagreed. By the end, 1 household still strongly agreed, but the number agreeing with the statement had risen to 3 households and none of the households now disagreed.



(a) (b)

Figure 2.11 Ability to keep whole house comfortably warm at start and finish of the project

Residents were also asked at start and finish of the project whether they were able to keep the whole house comfortably warm during winter or when it was cold outside. The options were mostly no or mostly yes. For those who answered mostly no, they were asked whether it was due to the cost of keeping the heating on for long enough or whether it was due to issues which were not financial such as the heating system or level of insulation or whether it was a combination of cost and issues with the house.

When they had storage heaters prior to the Boxergy Hero installation, 6 of the 7 households said they were mostly unable to keep the whole house comfortably warm (figure 2.11 (a)). Out of these 6 households, 4 said it was due to a combination of cost and non-financial issues, while 1 household said it was purely due to the cost and another that it was due to issues with the house. After the Boxergy Hero system was installed, all 7 of the households said they were mostly able to keep their whole house comfortably warm.

For comparison with the control properties (figure 2.11 (b)), 3 of the households at the start of the project said they were mostly able to keep the whole house comfortably warm in winter. The household which responded ‘mostly no’ was C-02 with storage heaters and a

Tesla battery. This was due to a combination of both cost and issues with the house/heating. At the end of the project, C-02 again responded 'mostly no', but one of the control households with an air-source heat pump also switched to 'mostly no'. This was due to draughts from the front door and the thermostat for the heat pump being poorly located in the hallway and affected by the draughts. The front door was scheduled to be replaced a few months after the final interview.

2.4 Times when residents feel it is important to have a warm home

All the households with Boxergy Hero installations and who were control properties said on average they were at home all day (figure 2.12). The combination of having health conditions and being at home throughout the day meant that having a suitable heating system was important.

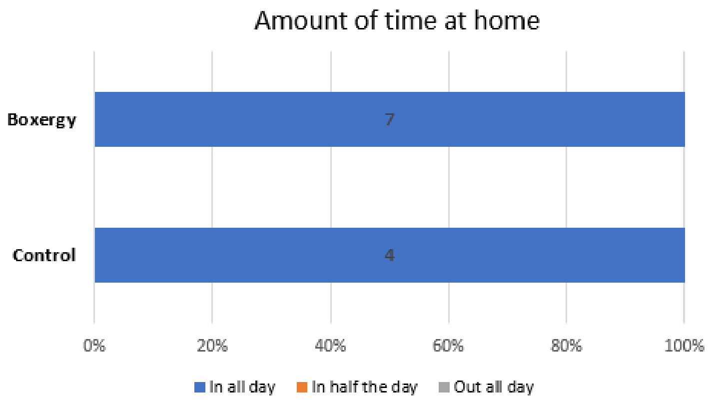


Figure 2.12 Amount of time typically at home

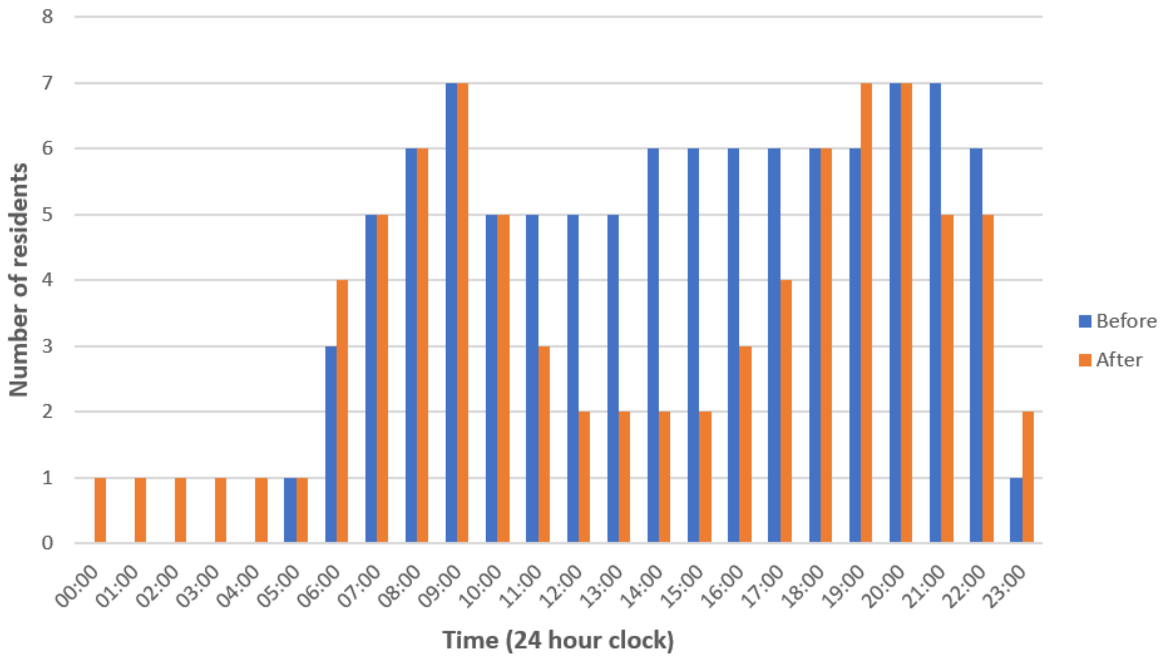


Figure 2.13 Times when residents said it was important to have a warm home (Before and after Boxergy Hero installation)

During the interviews before and after the Boxergy Hero installation, residents were asked what times of day they felt it was most important for their home to be warm. Before the installation, when the households had storage heaters, the numbers wanting to be warm rose from 5am to a peak with all the households at 9am. 5 or 6 households felt it important to be warm throughout the middle of the day, until another peak at 8pm and 9pm when all 7 households wanted to be warm. The number wanting to be warm dropped to 1 household by 11pm.

After the Boxergy Hero installation, there was a household wanting to be warm 24 hours a day due to a health condition and getting up during the night. The rise in the number wanting to be warm in the morning up until 9am was comparable to the response before the installations. However, during the middle of the day, there was a decrease in residents feeling it was important to be warm. This might be due to the residents experiencing improved thermal comfort with the Boxergy Hero heating system and not feeling the need for extra heating. From 4pm the number feeling it was important to be warm rose and reached a peak with all 7 households at 7 and 8pm and then decreased later in the evening.

2.5 Resident satisfaction with their heating system

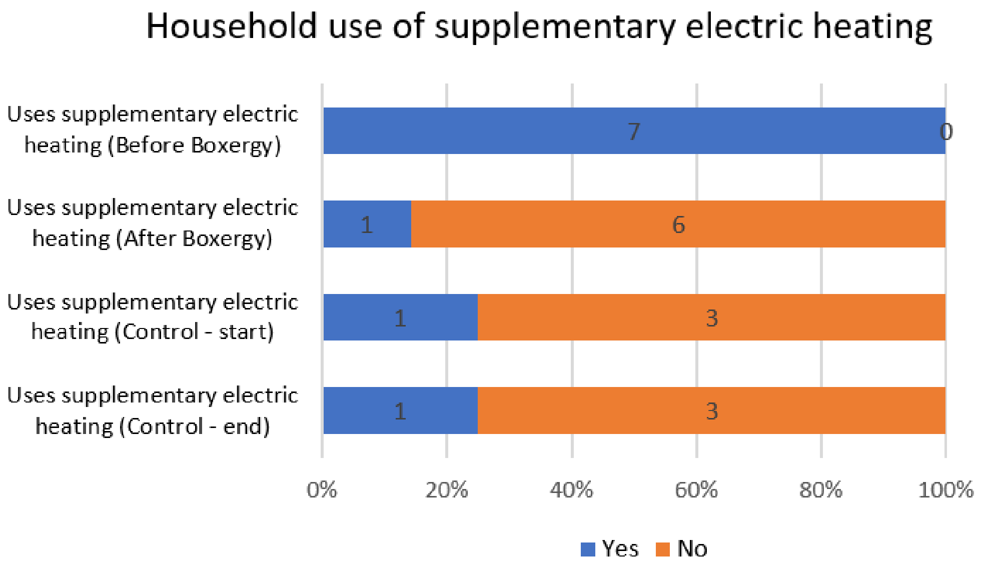


Figure 2.14 Household use of supplementary electric heating at the start and end of the project

Households were asked about their use of additional heating to the main heating system during the interviews at the start and end of the project. When they had electric storage heaters, prior to the installation of the Boxergy Hero heating system, all 7 households noted they used supplementary electric heating. This was often on a daily basis in winter for an hour or more a day. This included use of oil-filled electric radiators, an electric hearth fire, fan heaters and the boost on the storage heaters. In addition to this, a household was using a bottled gas heater and another was often using an open fire.

After the Boxergy Hero installation, 6 of the households said they no longer used supplementary electric heating, while 1 household noted they might use it for a short period. During occasional periods when the Boxergy Hero heating system broke down, households would still need supplementary electric heating. Household B-01 liked to have an open fire and still liked to do this in December after the installation due to the form of heat and cosy feel.

There was no change in the reported use of supplementary electric heating for the control properties during the project. Household C-01 heated the home with infrared panels. These provided heat when required and some of the panels also had a thermostat. As a result no further supplementary heating was required. Households C-03 and C-04 both had radiators with an air-source heat pump and did not use additional supplementary heating. Household C-02 had storage heaters and a Tesla Powerwall 2 battery which charged overnight during the off-peak time and provided power to the home during peak rate periods. This household occasionally used the boost function for their storage heaters which worked as an electric panel heater, but could be powered by the Tesla battery if it had sufficient charge.

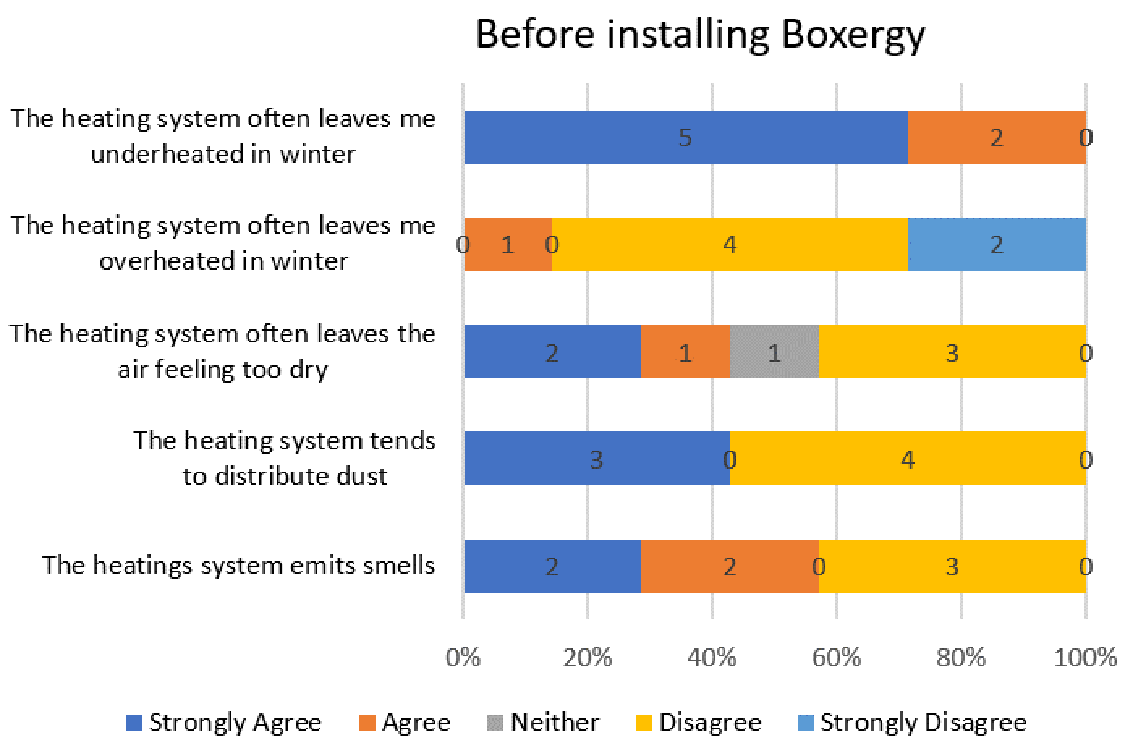


Figure 2.15 (a) Agreement with statements about their heating system at the start of the project (Before installing Boxergy Hero system)

During the interviews at the start of the project, households were asked how much they agreed or disagreed with a series of statements about their heating system. Prior to having the Boxergy system installed, 5 of the 7 households strongly agreed that their storage heaters often left them underheated in winter, with the other 2 households agreeing with the statement (figure 2.15 (a)).

Traditional storage heaters have a reputation for providing too much heat in the morning and getting cold by the evening or providing too much heat when a cold day is followed by a mild day. The households were asked their agreement with the statement ‘the heating system often leaves me overheated in winter’. Only 1 household agreed with the statement while 4 disagreed and 2 strongly disagreed.

2 of the households strongly agreed that the storage heaters often leave the air feeling too dry. A further household agreed with the statement while another neither agreed nor disagreed and 3 households disagreed. There were 3 households who strongly agreed that the storage heaters distributed dust while 4 households disagreed. A resident with a lung condition noted that the dryness of the air and dust made breathing difficult.

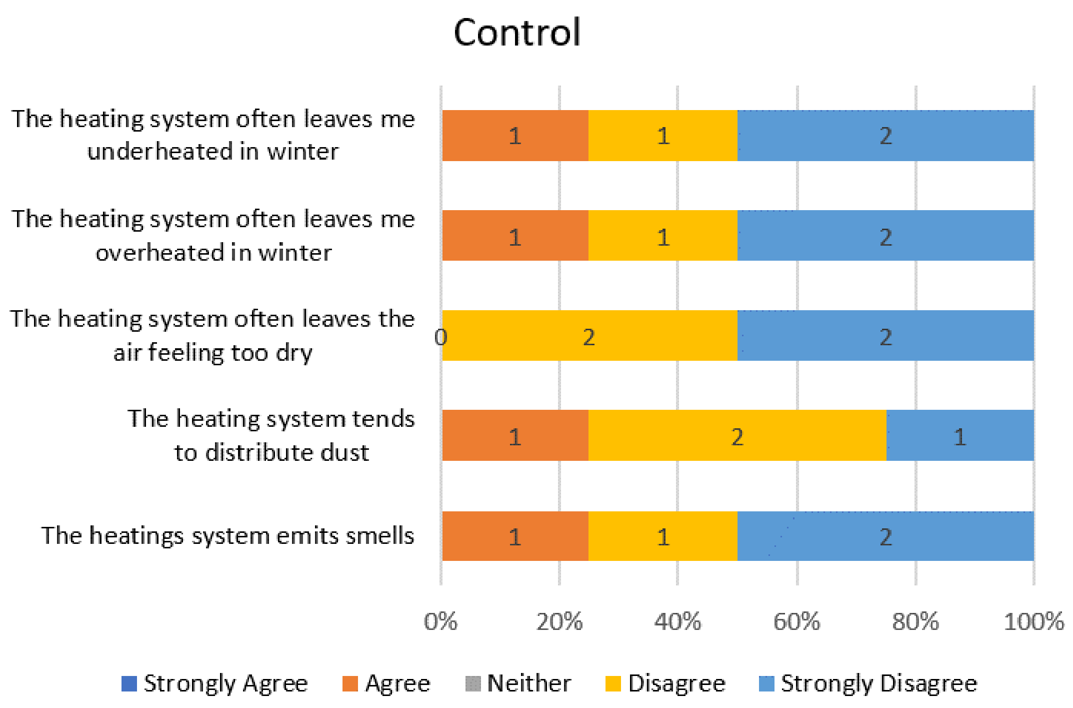


Figure 2.15 (b) Agreement with statements about their heating system at the start of the project (Control households)

The control households were also asked their agreement with the same set of statements about their heating system at the start of the project (figure 2.15 (b)). Only a single household agreed that their heating system left them underheated in winter and this was household C-02 which had storage heaters and a Tesla battery. Household C-03 with an ASHP disagreed and Household C-04 with an ASHP strongly disagreed along with C-01 with infrared heating panels.

Household C-01 with the infrared heating panels agreed that the heating system often left them overheated in winter. Household C-03 disagreed while household C-02 (with the storage heaters and battery) and C-04 with the ASHP strongly disagreed.

None of the control households thought that the heating system left the air feeling too dry with 2 households disagreeing and 2 strongly disagreeing with the statement. C-02 with the storage heaters and battery was the only control household that agreed that the heating system tended to distribute dust and emitted smells. Other households with storage heaters among those which had Boxergy Hero installations also agreed or strongly agreed with these statements. Household C-01 with the infrared panels strongly disagreed that the heating system distributed dust or emitted smells. Both households with ASHPs disagreed that their heating system distributed dust and 1 household disagreed that their heating system emitted smells while the other strongly disagreed.

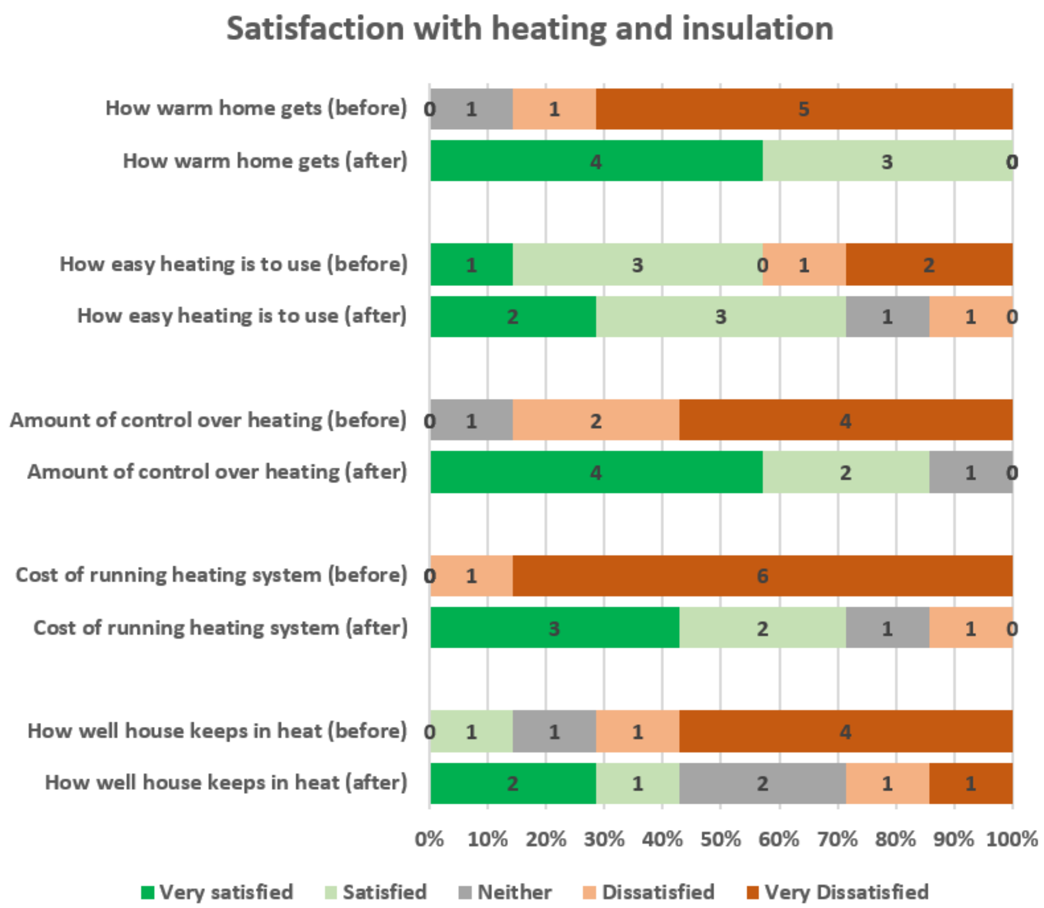


Figure 2.16 Household satisfaction with their heating and insulation before and after Boxergy Hero installation

Households were asked how satisfied they were with several aspects of their home heating and insulation at the beginning and end of the project. Figure 2.16 illustrates the responses for the households that had Boxergy Hero installations.

Prior to installation of the Boxergy Hero heating system, when all 7 households had storage heaters, residents were asked how satisfied they were with how warm their home gets when it is cold outside. 5 of the households said they were very dissatisfied; a further household was dissatisfied and the remaining household was neither satisfied nor dissatisfied.

There was a significant improvement after the Boxergy Hero heating system was installed with 4 of the households very satisfied and the other 3 households satisfied with how warm the home gets when it is cold. For the control households, C-01 with the infrared heating panels was very satisfied with how warm the home gets at the start and end of the project. C-02 with the storage heaters and Tesla battery was dissatisfied at the start and end. C-03 with the ASHP went from very satisfied at the start to satisfied. C-04, the other household with the ASHP went from satisfied with how warm the home gets to very dissatisfied at the end, most likely due to draughts from the front door and issues with the location of the thermostat.

At the start of the project, 1 household was very satisfied and 3 were satisfied with the ease of use of the storage heaters prior to the Boxergy Hero system being installed. 2 households were very dissatisfied with the ease of use and the remaining household was dissatisfied. After the Boxergy Hero system was installed, 2 households were very satisfied with how easy the heating system was to use, and 3 households were satisfied. The remaining 2 households were neither satisfied nor dissatisfied and dissatisfied. Many of the households found the Vaillant sensoCOMFORT smart thermostat difficult to understand and rarely adjusted it beyond making simple adjustments.

With the control properties, both household C-01 with the infrared heating panels and C-02 with the storage heaters and Tesla battery were very satisfied with how easy the heating system was to use at the start and end of the project. Households C-03 and C-04 with the ASHPs were very satisfied with how easy the heating system was to use in the interview at the start of the project and satisfied in the final interview.

There was a significant improvement in satisfaction with control over the heating after the Boxergy Hero installation (figure 2.16). At the start, when they had storage heaters, 4 households were very dissatisfied with the amount of control over the heating and a further 2 were dissatisfied. The remaining household was neither satisfied nor dissatisfied.

During the final interview, 4 of the households that had Boxergy Hero installations said they were very satisfied with the amount of control they had over their heating system, while a further 2 households were satisfied. Again, there was one household which was neither satisfied nor dissatisfied.

With the control properties, household C-01 with the infrared heating panels was very satisfied with the amount of control over the heating at the start and end of the project. Household C-02 with the storage heaters and Tesla battery was very dissatisfied at the start and end of the project. This was a typical response from the households with traditional storage heaters. Both households with ASHPs were satisfied with the amount of control at the start of the project. At the end, 1 of these households had changed their response from satisfied to neither satisfied nor dissatisfied while the other was unchanged.

The level of dissatisfaction with the cost of running the heating system was high for the households before they had Boxergy Hero installations. 6 of the 7 households were very dissatisfied with the cost of running the storage heaters and the other household dissatisfied. There was a notable improvement after Boxergy was installed. 3 of the households were very satisfied and 2 more were satisfied with the cost or running the heating system. Out of the other 2 households, 1 was dissatisfied and the other was neither satisfied nor dissatisfied.

For the control properties, household C-01 with the infrared heating panels was very satisfied with the cost of running the heating system at the start and end of the project. They previously had storage heaters and found them expensive and subsequently bought their own infrared panels which they thought were cheaper to run. Both households C-03 and C-04 with ASHPs were satisfied with the running costs of the heating at the start of the project, although the response of C-03 switched to neither satisfied nor dissatisfied at the end of the project. Household C-02 with the storage heaters and Tesla battery went from very dissatisfied with the cost of the heating to neither satisfied nor dissatisfied. This change might reflect variation in the responses rather than a significant change in satisfaction.

The final question looked at how satisfied households were with how well the house kept in the heat. This should primarily reflect the insulation and draught proofing of the property but can be affected by the effectiveness of the heating system and how quickly the warmth is lost from the system.

At the start of the project, only 1 household among those to have a Boxergy Hero heating system was satisfied with how well their house kept in the heat. 4 households were very dissatisfied with 1 household dissatisfied and the other neither satisfied nor dissatisfied. There was an improvement in satisfaction on how well the house kept in the heat after Boxergy Hero was installed. The number who were very dissatisfied went down from 4 to 1. There were 2 households who were now very satisfied and a further household that was satisfied. There were also 2 households that were neither satisfied nor dissatisfied and 1 household that was dissatisfied.

There was less change in satisfaction over how well the house kept in the heat among the control properties. The responses for households C-01, C-03 and C-04 did not change between the start and end interviews. Household C-01 with the infrared heating panels was very satisfied with how well the house kept in the heat. C-03 with the ASHP was satisfied and C-04 was dissatisfied, most likely due to draughts from the front door. Household C-02 with the storage heaters and Tesla battery was very dissatisfied in the start interview and dissatisfied in the final interview.

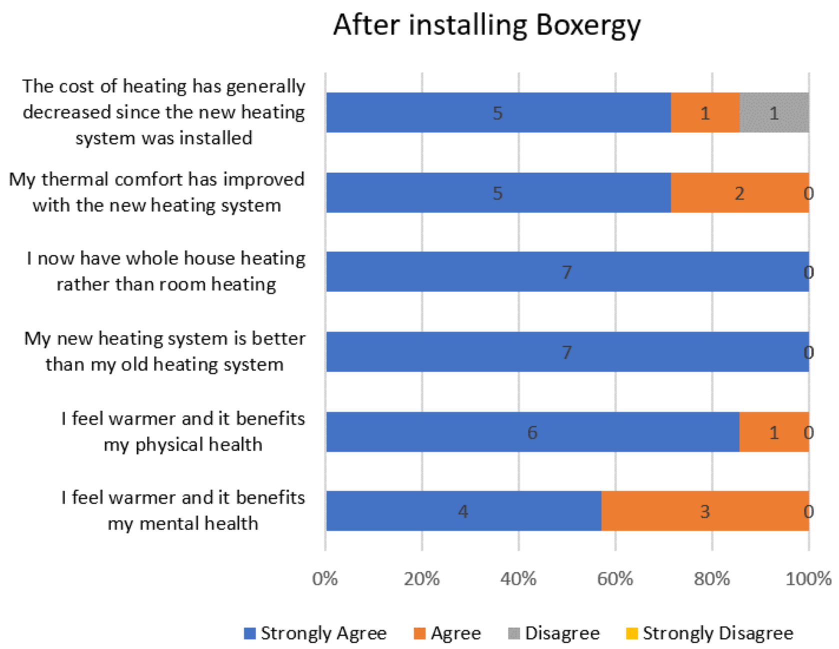


Figure 2.17 Agreement with statements about their heating system at the end of the project (After installing Boxergy Hero)

During the final interview, the households which had a Boxergy Hero installation were asked how much they agreed or disagreed with a series of statements about their heating system. These illustrated a significant improvement in thermal comfort after Boxergy was installed.

When asked if ‘the cost of heating has generally decreased since the Boxergy Hero system had been installed’, 5 of the households strongly agreed. A further household agreed with the statement and the remaining household neither agreed nor disagreed.

5 of the households strongly agreed that their thermal comfort had improved since the Boxergy Hero system had been installed with the other 2 households agreeing with the statement.

All 7 households strongly agreed that they now had whole house heating rather than room heating. They also all strongly agreed that their new heating system was better than their old heating system.

6 of the households strongly agreed and the other household agreed that they felt warmer, and it benefited their physical health. 4 of the households strongly agreed and the other 3 households agreed that they felt warmer, and it benefited their mental health.

2.6 Comments about the heating system before and after installation

Residents were asked to describe their feelings about their heating system before and after the Boxergy Hero heating system was installed.

Household	At start of the project (Storage heaters)	At the end of the project (Boxergy)
B-01	Don't like the running costs, not efficient and a lack of control.	Extremely satisfied. Warm all the time. Easy to use. Definitely better than the storage heaters and a massive improvement.
B-02	Had a Dimplex Quantum in the living room and hall which are better than the other traditional storage heaters. However, would like a heating system that provided heat when needed. Storage heaters are expensive.	Completely different heating to night storage heaters and 100% better. The house feels warm whichever room you go in. There is no longer an issue of the heating being cold in the evening
B-03	Not fit for purpose and not cost effective. Takes up space as they are fat bulky heaters. Can't control when you have heat.	Whole house is warm and not confined to a single room to keep warm. A better, easier to control thermostat would be better which does not rely on internet access.
B-04	The storage heaters are old and don't work properly. They were fitted in the wrong places. The dry heat and dust affect breathing due to a health condition.	Now have control over the heating and get heating when we want it. The radiators give off a better heat. Over the moon with the new heating system and was fighting to get a new one for several years.
B-05	It is absolutely useless, and you have no control over it at all. You need to be able to predict the weather 48 hours in advance. The storage heaters are too hot in the morning. They run out of heat in the evening, and you need to use Boost or convector heaters to keep warm and the rest of the house is cold.	Get heat when it is wanted. The new heating system produces a steady heat 24 hours a day
B-06	Not enthusiastic about the storage heaters. Quite bulky and struggled to get the furniture past them.	The heating system is a lot cleaner. There is no smell and have less dust. Previously felt cold in the evening, but that no longer happens with the new heating system.
B-07	Hates the system. There are no advantages. The storage heaters are cold by 5pm. Thinks the Dimplex Quantum's are a health hazard as child got burnt. The panel heaters and fan heaters upstairs are very expensive to run.	Is a lot better than the old system and can heat the whole house. The radiators look nicer. Don't dread coming into the kitchen in the morning or having a bath due to the cold. Can dry clothes on the radiators.

Table 2.18 Comments from households about their heating system before and after Boxergy Hero installation

3. Installations, technologies and monitoring

3.1 Overview of the technology

3.1.1. Boxergy Hero System

Boxergy is a Scottish company focused on making low carbon heat affordable for all. They install solar PV, batteries and heat pumps[5] and developed a product that combined a heat pump with electrical battery, hot water storage and control systems.

The Boxergy 'Hero' system combined a high temperature air-source heat pump (ASHP) with another external unit know as a Hero box. This enclosure contained an electrical battery along with a heat battery and control units and metering for the system. Figure 3.1 shows a Boxergy Hero installation before the enclosure lid was fitted on the Hero Box. The heat battery was fitted on the left of the Hero Box and had insulation board fitted around it. On the right of the Hero Box was the battery inverter at the front and the battery module behind it. There were meters and control units above the battery. There was a Hero controller in the Hero enclosure which allowed bi-directional communication with the unit, updating firmware on the meters and inverter and carrying out other remote maintenance and monitoring. The Boxergy installation cost was £17,000 + VAT and had a 2-year workmanship warranty. These were the first Boxergy Hero system installations in England and the first in social housing.

Some of the components could be fitted into the Hero Box before going on site. Reasons for using the Hero Box were to limit the components to be fitted in the home, saving them space, reduce disruption to the household and speed up the installation for Boxergy.

Figure 3.1 Boxergy Hero installation showing components within the Hero Box.

[5] Boxergy, https://boxergy.com/ (Accessed 2 Dec 22)

A high temperature air-source heat pump was used with the system. This meant the heat pump had a high level of efficiency even with a flow temperature of 55˚C. It was suitable to use in situations where the home was not necessarily highly insulated. It was also capable of achieving a sufficient temperature to melt the phase change material in the heat battery provided with the system.

The system required the following connections into the home:

- Plumbing connections
  - Cold mains
  - Domestic hot water
  - Central heating flow
  - Central heating return
- Electrical connections with AC isolators for
  - Heat Pump
  - Hero unit and electrical battery

The Boxergy Hero system operates with the household on a time of use electricity tariff, such as Economy 7, Octopus Go or Agile. The battery charges during the lower cost off-peak period and provides power to the home and the ASHP during the more expensive peak rate period until the battery is discharged. The aim is to lower the running costs compared to an ASHP in a home with a single rate electricity tariff.

Figure 3.2 Boxergy Hero installation showing the system with the Hero Box covered

3.1.2. Air-source heat pump

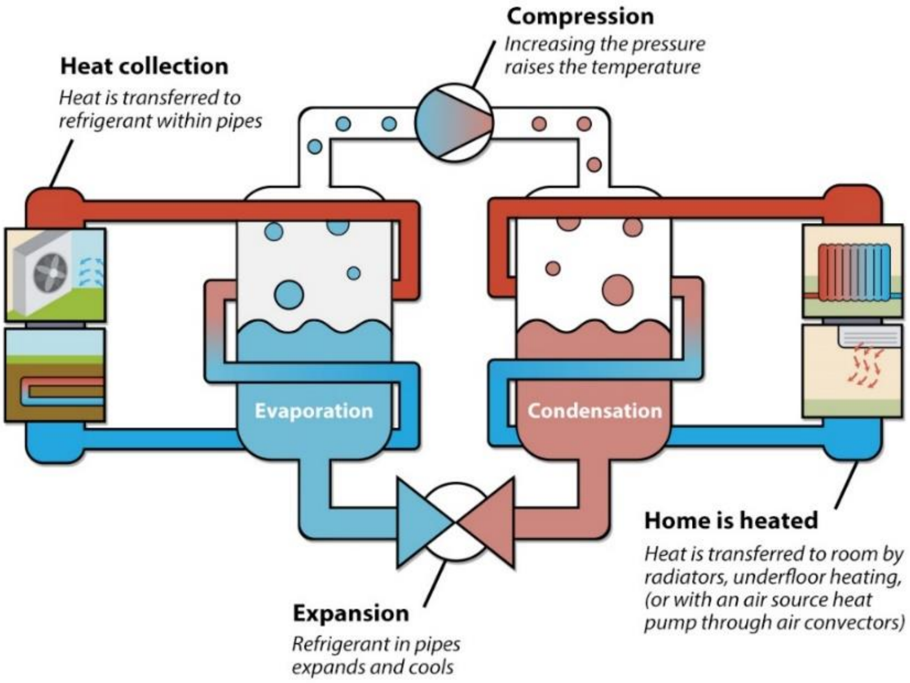


Figure 3.3 Diagram showing how a heat pump works[6]

An air-source heat pump is able to extract heat from the air outside to warm a home. It operates like a refrigerator or air conditioning unit in reverse. Air is drawn into the outdoor unit of the air-source heat pump by the fan and blows over pipes with refrigerant which transfers heat into the evaporator. This causes low temperature liquid refrigerant to evaporate. The refrigerant is compressed, causing the temperature to rise. As the refrigerant passes into the condenser, cooler water from the central heating system absorbs heat from the refrigerant and is transferred to heat emitters in the home such as radiators. The refrigerant condenses back to liquid, passing through an expansion valve so it expands and cools. It goes back into the evaporator for the cycle to begin again.

For a well-designed air-source heat pump system, for each unit of electricity consumed by the heat pump (powering components like the compressor and pumps), about 3 units of heat are likely to be produced. For this reason, a heat pump is more efficient than other forms of electric heating where 1 unit of electricity may produce about 1 unit of heat.

The air-source heat pump selected for this project was a Vaillant aroTHERM plus which is a high temperature heat pump. It uses R290 (propane) as the refrigerant, which has a Global Warming Potential (GWP) of only 3. This means the release of 1kg of refrigerant would be equivalent to 3kg of CO_2. Older heat pumps have sometimes used R410A which has a GWP of 2,088, while some other heat pumps have used R32, a refrigerant with a GWP of 675. This means the Vaillant aroTHERM plus is more environmentally friendly through lower carbon emissions while operating and also with the refrigerant used.

[6] Air source heat pumps, http://www.airsourceuk.org/air-source-heat-pumps.html (Accessed 30 Nov 2020)

Figure 3.4 Vaillant aroTHERM plus 7kW air-source heat pump

The 7kW Vaillant aroTHERM plus high temperature air-source heat pump is 1100mm wide, 965mm tall and 449mm deep and weighs 133 kg. The rated maximum current is 15A. The seasonal coefficient of performance (SCOP) for a 55˚C flow temperature is 3.39[7]. The heat pump has a 7-year warranty.

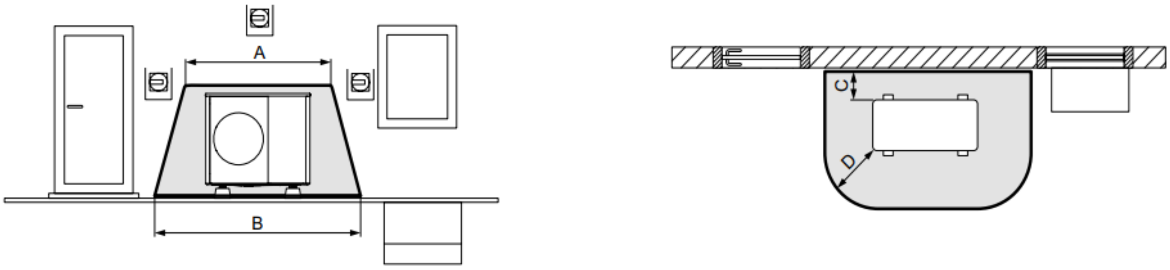


Figure 3.5 Protective zone around Vaillant aroTHERM plus air-source heat pump[8]
A=2100mm, B=3100mm, C=200/250mm, D=1000mm

Since propane is used as the refrigerant for the heat pump, there are additional regulations connected with installation. Figure 3.5 shows the protective zone required around the heat pump where there should be no sources of ignition such as plug sockets, lamps or rotary isolation switches. A drain within the protective zone needs to be airtight as shown to the left of the heat pump in figure 3.4. There also needs to be a condensate soak away to a depth of 100mm. The heat pump did not need an internal unit, but an expansion vessel was required.

[7] Vaillant aroTHERM plus specification sheet, Be ready for the energy change, https://www.vaillant.co.uk/downloads/aproducts/renewables-1/arotherm-plus/arotherm-plus-spec-sheet-1892564.pdf (Accessed 1 Dec 22)
[8] Vaillant aroTHERM plus, Installers Quick Start Guide, https://www.vaillant.co.uk/downloads/aproducts/renewables-1/arotherm-plus/arotherm-plus-1/quick-guides/new-5/installers-quick-guide-arotherm-plus-1949445.pdf (Accessed 1 Dec 22)

Figure 3.6 (a) Vaillant sensoCOMFORT thermostat (b) Vaillant sensoNET internet gateway

The thermostat used with the Vaillant aroTHERM plus heat pump was the Vaillant sensoCOMFORT smart thermostat. To provide online control and monitoring of the heat pump, a Vaillant sensoNET internet gateway was installed in the Boxergy Hero enclosure[9]. Supply chain issues meant there were delays in obtaining Vaillant sensoNET units for a couple of the installations.

Vaillant has produced an online simulation of the menus for the sensoCOMFORT smart thermostat. This is useful for consumers and installers to be able to learn how to use the system[10].

3.1.3. Electrical battery

The electrical battery selected for the installations was manufactured by Alpha ESS. This comprised of a Smile 5 hybrid inverter[11]. This has a nominal maximum charging/discharging power of 5,000W. It is 610mm wide x 236mm deep and 615mm tall. This unit was fitted on the right-hand section of the Boxergy Hero enclosure with battery modules fitted next to it.

There were major supply chain issues for batteries during the project. This meant that it took a number of months to replace a battery module which had failed. 3 of the installations had a single SMILE-BAT-10.1P module, which had a total capacity of 10.1kWh and a 90% depth of discharge (usable capacity of 9.09kWh). The module was expected to last 8,000 cycles.

The other 4 units each had 2 x SMILE-BAT-5.7. These had a total capacity of 5.7kWh and a depth of discharge of 96% (usable capacity of 5.47kWh). The lifespan of these modules was 10,000 cycles under specific test conditions. The Alpha inverter has a 5-year warranty while the battery modules have 10-year warranties.

The units could be IP21 (indoor) or IP65 (outdoor) rated. Both models were used on the project due to difficulties with supply.

[9] Vaillant senso Range, https://www.vaillant.co.uk/for-installers/products/latest-innovation/senso-range/ (Accessed 1 Dec 22)

[10] Vaillant sensoCOMFORT simulation, https://simulator.vaillant.com/vrc720/ec/#/simulator (Accessed 1 Dec 22)

[11] Alpha ESS Smile 5 hybrid inverter data sheet, https://www.waxmanbatterystorage.co.uk/wp-content/uploads/2020/04/Alpha-ESS-Smile-5-datasheet.pdf (Accessed 1 Dec 22)

Alpha ESS provides monitoring of the battery system via an app and a monitoring portal[12]. This shows performance of the battery and the household electricity consumption. An Acrel ACR10R electricity meter was used with the batteries for these installations. The resolution and settings required for this meter meant that monitoring for the battery only had a resolution of 1.2kWh. Daily totals for consumption were therefore in integers of 1.2kWh.

Figure 3.7 Boxergy Hero unit with an Alpha ESS Smile 5 hybrid inverter and 2 x SMILE-BAT-5.7

3.1.4. **Heat battery**

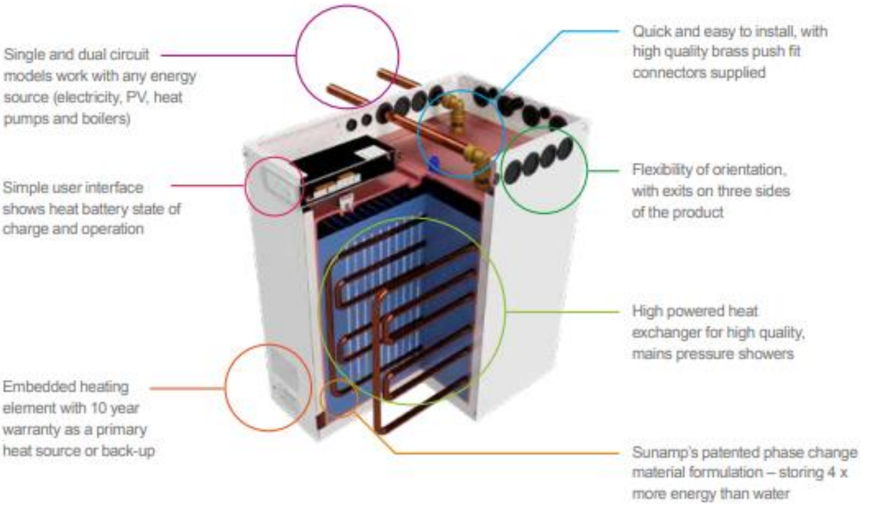


Figure 3.8 Sunamp 3rd generation UniQ heat battery (in Hero Box and schematic diagram)[13]

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12 Alpha Cloud monitoring portal https://cloud.alphaess.com/login (Accessed 1 Dec 22)
13 Compact thermal storage for heating and hot water, UniQ product brochure, Sunamp

The Boxergy Hero enclosure included a Sunamp heat battery to store heat for domestic hot water. Heat batteries do not store water directly, which removes the risk of legionella. They can be up to 4 times smaller than the equivalent hot water cylinder and are a more convenient rectangular shape. They use a phase change material (PCM) which releases heat when it changes from liquid to solid. In order to fully charge the heat battery, the high temperature heat pump needed to be capable of a flow temperature of 65˚C. The Vaillant aroTHERM plus heat pump was tested with the Sunamp heat battery prior to the installations to confirm it was compatible.

The heat battery used on the installations was a 3rd generation Sunamp UniQ HW + iPV. This was able to be charged by the heat pump, but could have been capable of being charged by solar PV with a suitable solar immersion controller like the myenergi eddi.

The models fitted for these installations were either the UniQ HW 9+ iPV-VT or the UniQ HW 12+iPV-VT. Characteristics of these heat batteries are shown in Table 3.9. The heat batteries had a heat storage capacity of 9.5 kWh for the size 9 unit and 12.6 kWh for the size 12 unit when used with a high temperature heat pump. They had a low heat loss of 32W or 35W, which is equivalent to either 0.77 or 0.84 kWh per day. The ErP rating for the model was A+. There was also additional insulation put around the heat batteries in the Boxergy Hero Box.

The heat batteries used in the Boxergy Hero enclosure were 175 or 220 kg net weight. The significant weight and lack of points to grip the units made fitting the heat batteries in the Hero Box on-site a challenge.

Heat Battery Model	Height (mm)	Depth (mm)	Length (mm)	Net weight (kg)	Heat storage capacity	Equivalent Hot water cylinder size	Heat loss
UniQ HW 9+iPV-VT	856	365	575	175	9.5 kWh	212 litres	0.77 kWh per 24h
UniQ HW 12+iPV-VT	1070	365	575	220	12.6 kWh	284 litres	0.84 kWh per 24h

Table 3.9 Characteristics of the Sunamp UniQ heat batteries fitted in the Boxergy Hero unit[14]

The properties had their existing hot water cylinders removed, as part of the installations. All initially had electric showers. Mixer showers were fitted in addition to these at 4 of the properties. The water supply rather than being gravity feed with a tank in the loft was changed to a mains pressurized system. Many of the households noted the mixer showers provided hot water at a good pressure. The longer distance between the hot water storage and the taps meant the water needed to be run for longer before it came through hot. This led to some negative feedback from households.

[14] Sunamp UniQ eHW+iPV & HW+iPV Heat Battery Installation and User Manual

3.2. Methods of monitoring

3.2.1. Temperature and humidity

Figure 3.10 Lascar EasyLog EL-USB-2 temperature and humidity data logger

The room temperature and relative humidity was recorded in the living room and main bedroom of the properties having installations and the control properties. A battery powered Lascar EasyLog EL-USB-2 data logger was used to record readings at 30-minute intervals.

The temperature and humidity loggers collected data during a pre-installation heating season and a period after installation of the Boxergy systems. Data was only available after it was downloaded from the logger. Analysis was carried out using Lascar's EasyLog USB software or through analysis of the data in a spreadsheet.

3.2.2. Electricity

Several methods were used to monitor the electricity consumption of the households in this project. These were:

- Tinytag View 2 data logger with a current clamp
- Electricity meter readings and smart meter data
- Alpha ESS battery portal
- Vaillant sensoCOMFORT heating control and sensoAPP
- Smart plugs
- Wibeee data logger

3.2.2.1. Tinytag View 2

The household electricity consumption during peak and off-peak periods was monitored using Tinytag View 2 data loggers with a Chauvin Arnoux current clamp. One logger was fitted over the meter tail for the heating circuit while another was fitted around the meter tail for the 24 hour circuit. Data was recorded at 15-minute intervals. The data was downloaded from the logger after collection using the Tinytag Explorer programme. It was analysed using Tinytag Explorer or in a spreadsheet.

![NEA logo]

Figure 3.11 Tinytag View 2 data logger with Chauvin Arnoux current clamp

3.2.2.2. Electricity meter readings and smart meter data

Electricity consumption data was obtained from a variety of sources. Readings were regularly recorded from electricity meters during the project. Historic meter readings were obtained from past electricity bills and energy suppliers. Monthly consumption values were obtained from smart meter in-home displays or Liberty 110 SMETS1 meters.

Smart meter data was also obtained from electricity suppliers. This was in the form of daily meter readings for peak and off-peak consumption or half-hourly electricity consumption. Some residents signed up for the Carbon Coop PowerShaper Monitor. This provided daily and monthly consumption graphs and access to half-hourly consumption data.

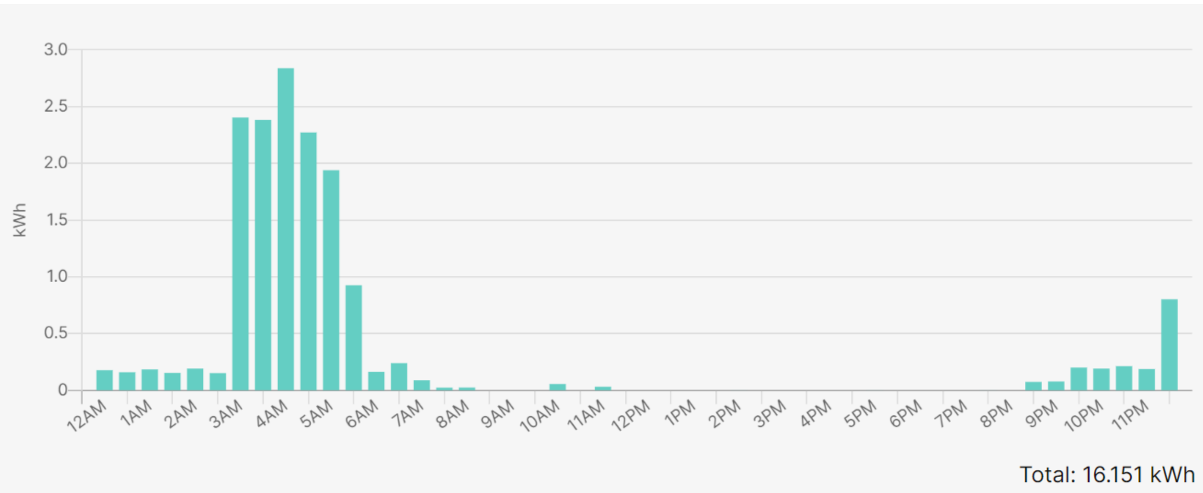

Figure 3.12 Example of graph from the Carbon Coop PowerShaper Monitor service

3.2.2.3. Alpha ESS battery monitoring portal

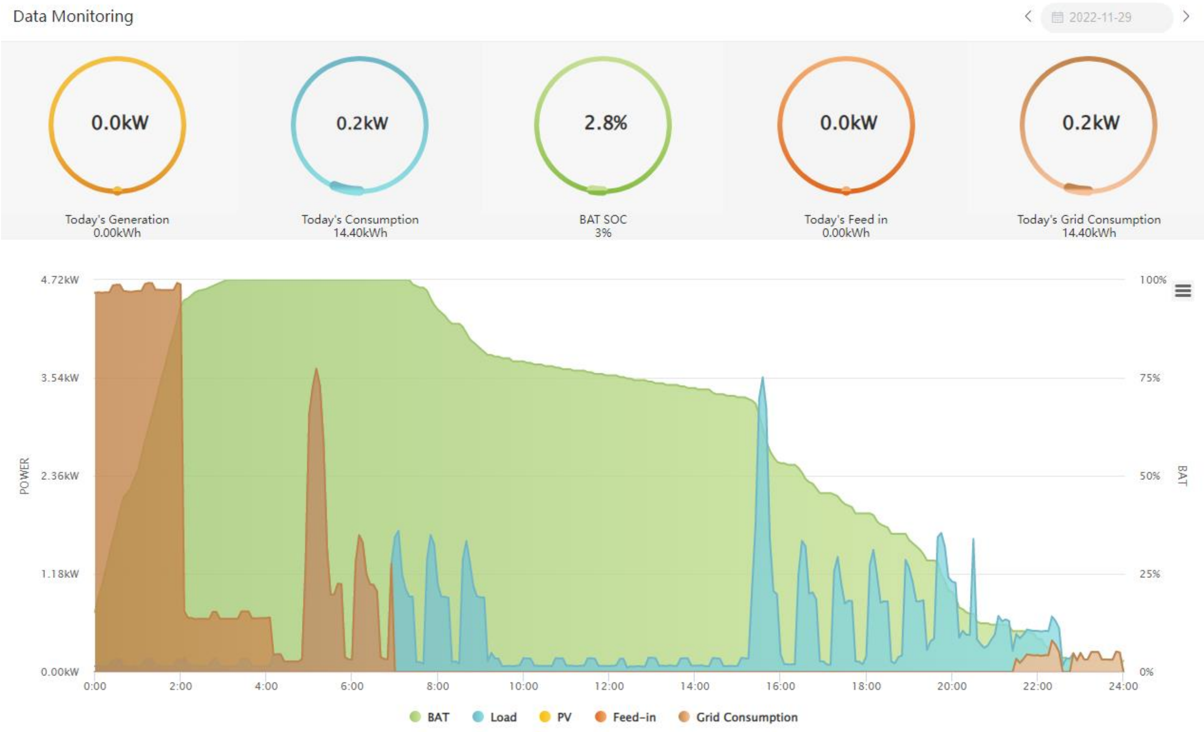

Figure 3.13 Power diagram from the Alpha ESS battery monitoring portal

The Boxergy Hero unit included an Alpha ESS battery system. As the installations did not include solar PV, the batteries charged purely from the grid during the off-peak period for Economy 7. Installations had either a single 10.1kWh or 2 x 5.7kWh Alpha batteries.

Alpha ESS provides a phone app and a monitoring portal for their batteries and NEA had access to the monitoring portal for the evaluation. Figure 3.13 shows an example of one of the daily power diagrams which are available on the portal. The parameters shown on the graph are:

- BAT (in green) – showing the percentage charge level of the battery (%)
- Load (in blue) – electricity being consumed in the home (kW)
- PV (in yellow) – solar PV generation
    - Not used on this project as no solar panels were fitted
- Feed-in (in red) – electricity being exported to the grid
    - Normally recording data on this project as no solar panels were fitted
- Grid consumption (in brown) – amount of electricity being imported from the grid (kW)

In the example shown in figure 3.13 the battery charge (shown in green) rises overnight to 100%. The battery discharged from 07:00 (start of the peak rate period) until it was depleted.

The grid consumption by the household is shown in brown. Between midnight and 2am in figure 3.13, the grid consumption was about 4.5kW as the battery was charging and consumption from the grid continued until 07:00. The household load is shown in blue and for periods where no grid consumption is shown, this was powered by the battery. In the example in figure 3.13, the home was powered by the battery between 07:00 and about 21:30. Much of this consumption was likely to be due to the heat pump, with the heating schedule set to 19˚C between 06:00–11:00 and 16:30–22:00 and setback to 15˚C at other times.

If you click on the three horizontal lines (or 'hamburger' symbol) at the top right of the graph, it is possible to download a PDF of the power diagram or a CSV or Excel file with 5-minute interval data.

The circles above the graph in figure 3.14 show data related to that day including the household consumption and grid consumption. The accuracy of the consumption data from the portal is limited for these systems. This is because values of consumption were recorded in intervals of 1.2kWh. This meant that values shown for grid consumption might typically be either 12.0kWh, 13.2kWh, 14.4kWh, 15.6kWh, 16.8kWh or 18.0kWh for example. The limited resolution was due to the accuracy of the Acrel ACR10R meter used and the meter CT ratio required for the settings on the battery system.

The Alpha ESS monitoring portal can also plot a Statistical Diagram with data from a month, year or since installation. A monthly plot is shown in figure 3.14 with data from each day in October 2022. The limited resolution of the monitoring is apparent with the load and grid consumption identical at 20.4 kWh on 10th, 11th, 12th, 15th, 18th and 19th October.

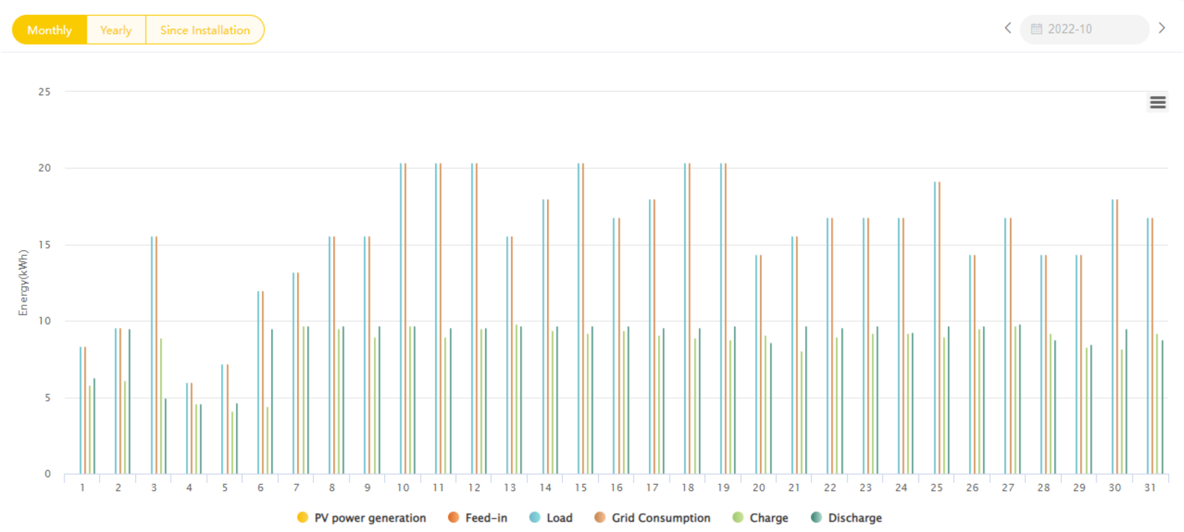

Figure 3.14 Statistical diagram from the Alpha ESS battery monitoring portal

3.2.2.4. Vaillant sensoCOMFORT heating control

The Vaillant sensoCOMFORT smart thermostat was used with the Vaillant aroTHERM plus heat pump.

Figure 3.15 Power consumption menu on the Vaillant sensoCOMFORT smart thermostat

It is possible to obtain an indication of the electricity consumption by the heat pump while providing space heating and domestic hot water. The sensoCOMFORT control will provide these values for:

- Current month
- Last month
- Current year
- Last year
- Total

The heating control will also provide an indication of the environmental yield. This is the amount of heat taken out from the air at a particular time (in kWh).

Heating output ≈ Environmental yield + Consumption

Coefficient of Performance, COP = Heating output / Consumption

The consumption and yield figures obtained from the sensoCOMFORT controller provide only an indication of consumption and heat generation. An accurate assessment would require separate MID approved electricity and heat meters as in a metering and monitoring service package (MMSP). Depending on the conditions such as outdoor and flow temperature, compressor speed and auxiliary components, the actual yield and consumption might vary by up to 20% from the value recorded by the Vaillant system[15].

The Boxergy heating system also included the Vaillant sensoNET internet gateway. This allows remote monitoring and control of the thermostat and heat pump via the Vaillant sensoAPP. The app allows the installer to set the heating schedule, check for faults and monitor performance of the heat pump.

[15] Simon Austin, Vaillant Group, Personal communication (1 August 2022)

Figure 3.16 (a) shows the initial control screen for the sensoAPP, where it is possible to set the thermostat to manual or auto control and the operating mode for the hot water. An example heating schedule for a property is shown on the app in figure 3.16 (b). In this case, the thermostat was set to 20˚C between 6:00 and 11:00 and 16:00 and 21:00. At other times the room temperature was set-back to 18˚C.

The sensoAPP also provided an indication of the electricity consumption by the heat pump. This could be accessed by pressing the information button at the bottom of the home screen. Data on the electricity consumption by the heat pump due to space heating, domestic hot water and the environmental yield is available. Graphs are available showing data from a day, week, month or year. Figure 3.16 (c) shows the approximate electricity consumption from the heat pump in April 2022 due to space heating, with each bar on the graph representing days in the month.

The sensoAPP sources the data from the sensoCOMFORT controller. There can be discrepancies between the app and the controller as the app only periodically updates and might lose connection. The data from the sensoCOMFORT controller is likely to be the more accurate as it is the source of the performance data.

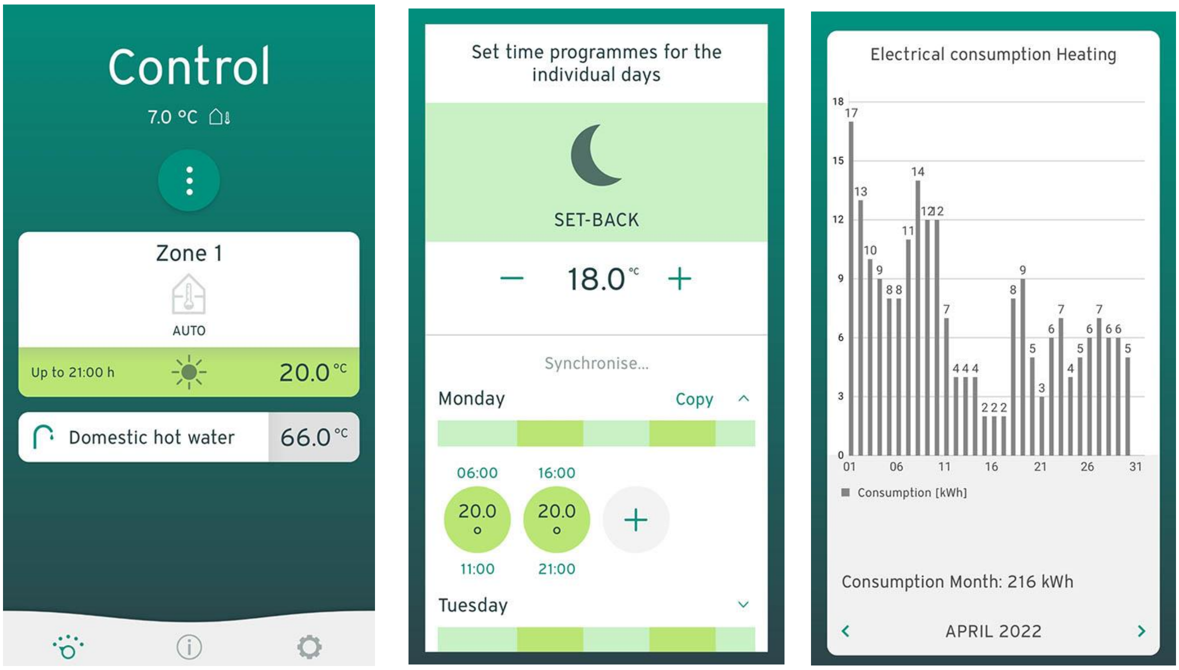

Figure 3.16 Screenshots from the Vaillant sensoAPP
(a) Main control screen (b) Heating schedule (c) Heating electrical consumption

The Vaillant sensoNET gateway was fitted in systems B-01 and B-02 on 23rd and 24th November 2021 and sensoAPP data was available from those dates. Installations B-03, B-04, B-05 and B-07 have sensoAPP readings dating from commissioning in January and February 2022. Due to supply chain issues, it was not possible to install the sensoNET gateway at household B-06 until a later service visit. The sensoNET was installed on 18 May 2022 and sensoAPP data was available from that date. There have been periods when some of the Boxergy systems have lost internet connection and there is the risk of data loss during those periods.

3.2.2.5. Knightsbridge smart plugs with energy monitoring

Figure 3.17 Example of a Knightsbridge smart plug

Figure 3.18 Data from the SmartKnight app

Control household C-01 used plug-in infrared panels for heating. We attempted to monitor the daily consumption of individual infrared heating panels by having panels plugged into Knightsbridge smart WIFI plugs which had energy monitoring. These devices connect to the home WIFI router and can be monitored and controlled via the SmartKnight app. A number of different manufacturers supply similar smart plugs which use the same format for monitoring.

The monitoring had mixed success as the smart plugs periodically lost connection with the WIFI router and the household replaced some of the panels during the study and the plugs were not reconnected. Once plugs went offline, it was not possible to access data from them. Data was collected between mid-November 2021 and the end of April 2022, with some of the plugs going offline during this period.

3.2.2.6. Wibeee Box data logger

Figure 3.19 Wibeee Box logger and CT clamp with images from the Wibeee Home app and portal

A Wibeee Box data logger was installed to monitor the electricity consumption of household B-03, a mid-terraced house with 3 bedrooms which had high electricity bills. The Wibeee logger had 3 CT clamps which were fitted in the consumer unit and each were able to monitor a particular electrical circuit. Circuit 1 monitored the household grid consumption, circuit 2 the downstairs sockets and circuit 3 the electric shower.

The Wibeee data logger was initially fitted in 2021 and used the Wibeee Home portal and app for monitoring. A combination of the household switching broadband supplier and Wibeee updating their monitoring portal from Wibeee Home to Wibeee Nest meant that it was necessary to set up a new account and previous data was lost. Data was available on Wibeee Nest between 19th May and 28th October 2022. After that date, the system lost connection due to the household switching broadband supplier again.

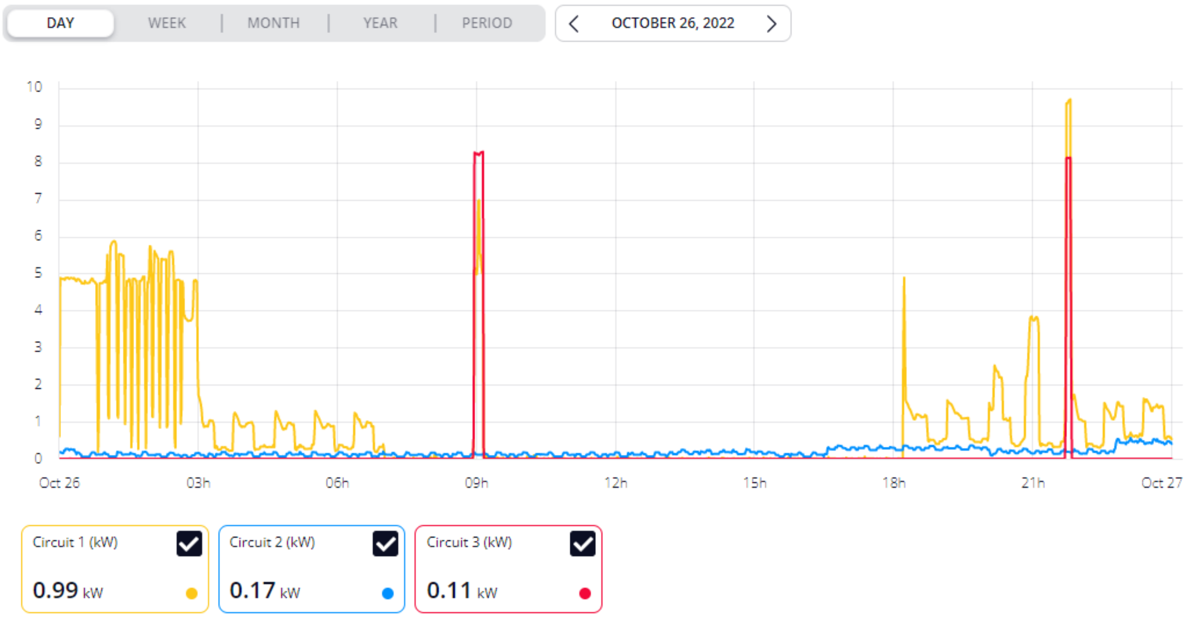

Figure 3.20 Example of graph from Wibeee Nest monitoring portal showing daily consumption for each of the 3 monitoring circuits (circuit 1 in yellow (household grid consumption), circuit 2 in blue (downstairs sockets) and circuit 3 in red (shower))

The Wibeee Nest portal can plot graphs showing consumption for each of the 3 monitoring circuits for individual days (figure 3.20), weeks, months and years. You can also select start and end dates for the graphs by selecting the period tab.

Data from graphs can also be downloaded by clicking on the icon with three horizontal lines on the top right of the graph. Data from a daily graph is in 1-minute intervals and provides the consumption in kW for each of the 3 circuits. Data from weekly graphs has average kW consumption in 15-minute intervals and data from monthly graphs has average kW consumption in hourly intervals. A download of data from a yearly graph provides average kW consumption data for each day. To convert these values into kWh consumption for the day for example requires the daily average value to be multiplied by 24.

The Wibeee Nest monitoring portal can also illustrate trends by plotting bar charts of the household consumption. This can be with plots that are for a day, month, year or a defined period (set start and end dates). A trend graph between 2nd and 4th October 2022 is shown in figure 3.21.

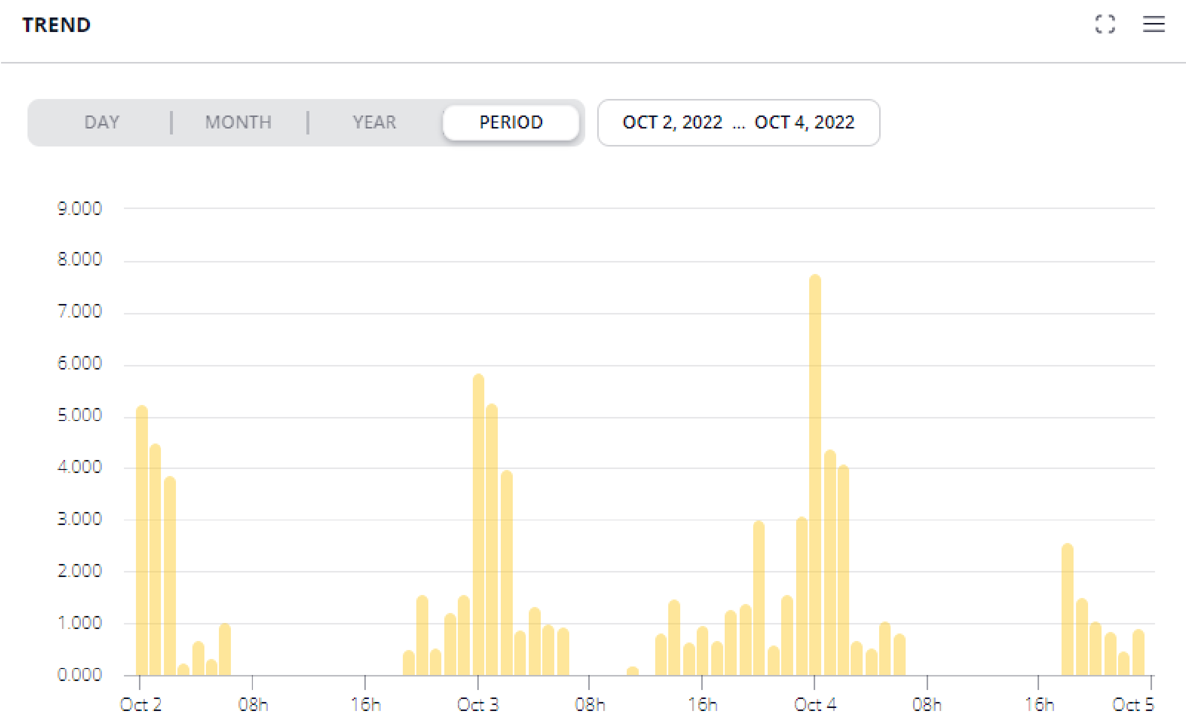

Figure 3.21 Trend plot from Wibeee Nest monitoring portal for the period 2nd to 4th October

Wibeee Nest can also illustrate patterns of behaviour with a 'Habits' plot. The level of consumption over a week or month is illustrated by blocks with different colours. Figure 3.22 shows a Habit plot for the week of 10th – 16th October 2022. There are 7 rows of 24 blocks, representing each hour of the week. Each block is coloured according to the level of consumption that occurred during that period.

It is apparent in figure 3.22 that there was greatest consumption on a daily basis between midnight and 03:00 (when the battery charged), with very limited consumption until 18:00. The level of consumption after 18:00 varied for the different days, with higher consumption on Tuesday and Sunday. It is possible to get the consumption in kWh by hovering over individual blocks.

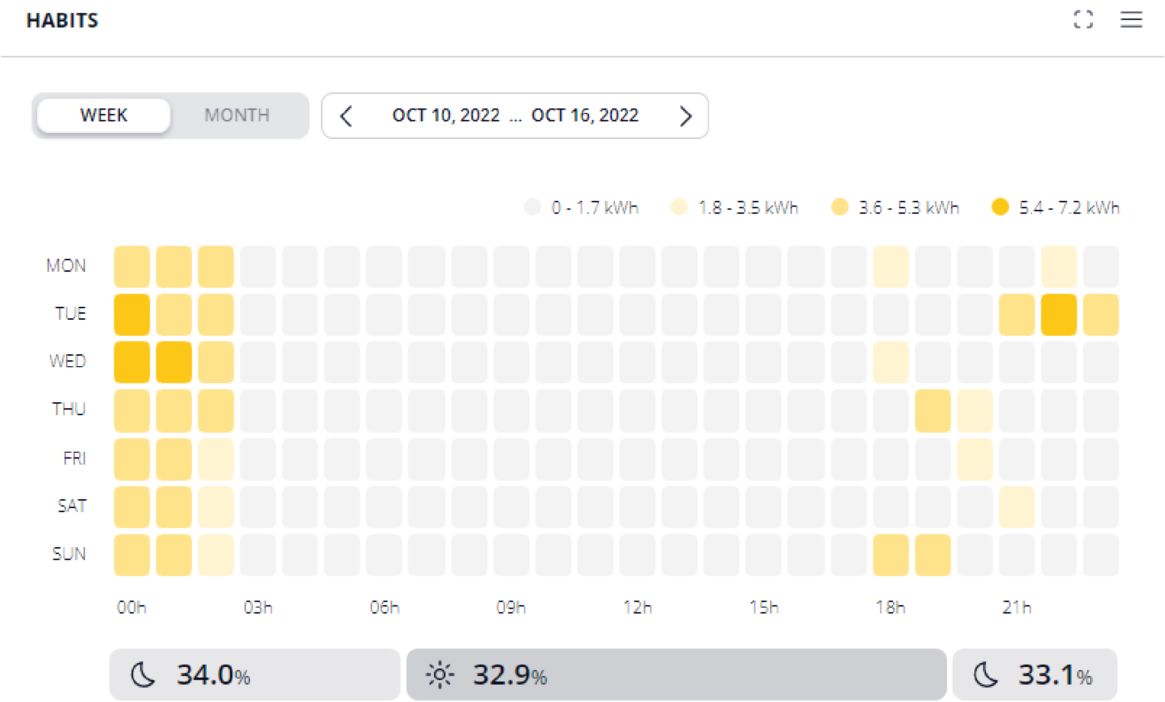

Figure 3.22 Habits plot from Wibeee Nest monitoring portal for the week 10th to 16th October

A summary of the different types of monitoring that was used for each of the properties in the study is provided in table 3.23. It also highlights the dates from which some of the types of monitoring was available from and whether there were periods of significant data loss.

Technical Reference Number	Meter readings	Smart meter data	Lascar USB-2 temperature loggers	Tinytag current clamps	Alpha battery portal	Vaillant sensoAPP	Smart Plugs	Wibeee Box logger
B-01	Y	Y	Y	Y	Nov-21	Nov-21	N	N
B-02	Y	N	Y	Y	Nov-21	Nov-21	N	N
B-03	Y	N	Y *	Y	Feb 22 *	Feb 22 *	N	May 22 *
B-04	Y	Y	Y	Y	Jan 22 *	Jan-22	N	N
B-05	Y	Y	Y	Y	Feb 22 *	Feb-22	N	N
B-06	Y	Y	Y	Y	Feb 22 *	May-22	N	N
B-07	Y	Y	Y	Y	Feb 22 *	Feb-22	N	N
C-01	Y	Y	Y	Y	N	N	Y *	N
C-02	Y	Y	Y	Y	N	N	N	N
C-03	Y	N	Y	Y	N	N	N	N
C-04	Y	Y	Y	Y	N	N	N	N
* Missing periods of data								

Table 3.23 Types of monitoring used at different properties in the study

3.3 Installation of Boxergy Hero systems and wet central heating systems

All the North Devon Homes properties which had Boxergy installations previously had electric storage heaters and a hot water cylinder. Before the Boxergy Hero system was installed, it was necessary for another contractor to remove the storage heaters and hot water cylinder and fit a new wet central heating system. The radiator sizes were determined by Boxergy following heat loss calculations. K2 model radiators were specified with a height of 600mm, with the output typically able to provide about 100W additional capacity to the room heat loss. A high level of insulation was required on pipework going to the Boxergy Hero system and in the loft. Installations in the bungalows had pipes dropping down from the ceiling and most of these were later boxed in.

Table 3.24 shows numbers of the storage heaters and panel or fan heaters there were in the different properties prior to installation of the wet central heating and Boxergy Hero system. It also shows the rate of heat loss that was calculated for the property during the system design stage and the number of radiators that were fitted.

Technical Reference Number	Type of storage heaters at start	Initial number of traditional storage heaters	Initial number of Dimplex Quantum storage heaters	Initial number of panel/fan heaters	Calculated heat loss	Number of radiators fitted
B-01	Traditional	5		1	3.09 kW	6
B-02	Quantum/Traditional	3	2	1	3.75 kW	6
B-03	Traditional	2		5	6.18 kW	9
B-04	Traditional	6		0	3.2 kW	6
B-05	Traditional	4		2	3.2 kW	6
B-06	Traditional	4		1	3.1 kW	6
B-07	Quantum/Traditional	2	1	3	5.34 kW	7
C-01	Infrared panels	0		6		
C-02	Traditional	4		0		
C-03	ASHP					4
C-04	ASHP					6

Table 3.24 Details of heat emitters before and after installation

Figure 3.25
(a) Example of radiator fitted in the hallway (b) Insulation on pipework to Hero unit

Since the Boxergy Hero unit had a heat battery which stored 9.5kWh or 12.6kWh of heat, the aim was also to also fit mixer showers. These would provide hot water at mains water pressure at a lower cost than the existing electric showers fitted in the properties. It was possible to fit 4 mixer showers during the project. A single household preferred not to have a mixer shower and to keep their electric shower due to the needs to a disabled family member. Another household was waiting for a wet room to be installed with a disabled facilities grant.

Table 3.26 shows details of which household had which size of electrical and heat battery and the date the air-source heat pump for the system was commissioned. The 4 households that had mixer showers are also shown. Among the control properties, C-02 had a 13.5kWh capacity Tesla Powerwall 2 battery along with traditional storage heaters. Household C-03 had a Daikin low temperature monobloc air-source heat pump with an output of about 4.4kW while household C-04 had a Daikin low temperature air-source heat pump with an indoor and outdoor unit and a nominal output of 6kW.

Technical Reference Number	Air-source heat pump model	Heat pump output	Electrical battery capacity	Heat battery capacity	Type of shower at end of project	Date ASHP commissioned
B-01	Vaillant aroTHERM plus	7 kW	10.1 kWh*	12.6 kWh	Mixer	25-Jun-21
B-02	Vaillant aroTHERM plus	7 kW	10.1 kWh	9.5 kWh	Electric	25-Nov-21
B-03	Vaillant aroTHERM plus	7 kW	11.4 kWh	9.5 kWh	Electric	28-Jan-22
B-04	Vaillant aroTHERM plus	7 kW	10.1 kWh	9.5 kWh	Mixer/Electric	28-Jan-22
B-05	Vaillant aroTHERM plus	7 kW	11.4 kWh	9.5 kWh	Mixer/Electric	28-Jan-22
B-06	Vaillant aroTHERM plus	7 kW	11.4 kWh	9.5 kWh	Mixer/Electric	10-Feb-22
B-07	Vaillant aroTHERM plus	7 kW	11.4 kWh	12.6 kWh	Electric	11-Feb-22
C-01	-		-	-	Electric	-
C-02	-		13.5 kWh	-	Electric	-
C-03	Daikin Altherma EDLQ05CAV3	4.4 kW	-	-	Electric	ca 2018
C-04	Daikin Altherma ERLQ006CAV3	6 kW	-	-	Electric	ca 2018

Table 3.26 Installations at the properties with Boxergy Hero systems and control properties

3.3.1. Phase 1 of installations

The system at household B-01 was first to be installed. The wet central heating system was installed during the 3rd week of June 2021 and the Boxergy installation was fitted the following week and commissioned on 25th June 2021.

The budget and initial estimated cost for fitting the wet central heating system in a 2-bedroom bungalow was £2,500. However, the final costs were considerably higher and this was influenced by several factors. The initial estimate planned to use plastic pipe and copper pipe was specified. A volumizer and expansion vessel was required for the Vaillant heat pump system. More expensive foiled lagging was specified for the pipework in the loft along with premium inhibitor. The more complex installation also led to extra time on site. This resulted in a cost of £5,995+VAT for the wet central heating system and further £1,135+VAT for electrical work such as disconnecting, removing and disposing of the old electric storage heaters and hot water cylinder. A new supply was also provided for the air-source heat pump along with a double pole isolator fitted externally close to where the heat pump was to be located.

The higher-than-expected cost for installing the first wet central heating system led to a review of the project budget and to an investigation of alternative plumbing contractors. It proved necessary to use all the contingency budget which was allocated for grid connections and plumbing on the installation of the wet central heating systems. Spare budget which had been hoped to be used for a couple of solar PV systems also had to be spent on plumbing costs.

Boxergy fitted the 7kW Vaillant aroTHERM plus air-source heat pump along with the Boxergy Hero enclosure. However, the Hero unit did not include the Hero controller, Vaillant sensoNET gateway and Alpha battery module due to supply chain issues. The heat pump and heat battery were however operational and a new mixer shower was fitted.

Boxergy planned to learn lessons from the first installation before installing the second system. This included some redesign work to the Hero unit casing.

3.3.2. Phase 2 of installations

2 Boxergy Hero systems were planned to be installed during the second phase of installations in November 2021. However, the wet central heating system for household B-02 proved to be the most complex of all the installations and this meant only a single wet central heating system could be fitted before the scheduled visit by Boxergy.

The restrictions due to having a propane refrigerant with the Vaillant aroTHERM plus heat pump meant that the heat pump had to be fitted next to an outhouse in the back garden, separated from the main building. Pipes from the loft exited the gable end of the house and were fed to the outhouse along a metal tray. They then passed through the outhouse, where an expansion vessel was fitted and connections were provided at the side of the outhouse for the Boxergy Hero system. In preparation for the Boxergy Hero installation, the ground was reinforced with a Kedel GeoGrid, which is a modular plastic grid which can withstand high loads after it is filled with fine gravel[16].

The installation for household B-02 was commissioned on 25th November 2021. This included the Vaillant sensoNET gateway which allowed online monitoring and control of the heat pump as well as the 10.1kWh battery module for the Alpha ESS Smile 5 hybrid inverter in the Boxergy Hero unit.

The plumbing work for this installation cost £5964+VAT, which was slightly cheaper than for the previous installation despite the additional high-level pipework. Installing the electrical supply and removing the storage heaters cost £525+VAT.

Upgrades were also carried out on the first installation for household B-01. A 10.1kWh Alpha battery module was installed in the Boxergy Hero unit, along with a Vaillant sensoNET gateway. The Alpha battery module was charged and left to operate, but developed a fault within a day. It was not possible to fit a replacement 10.1kWh battery module on this system until July 2022 due to supply chain issues.

[16] Kedel GeoGrid Specification and Installation Guide, https://www.kedel.co.uk/user/Kedel%20GeoGrid%20Install%20guide%20sm.pdf (Accessed 2 Dec 2022)

Figure 3.27
(a) External pipework for household B-02 (b) Installing the Hero unit for household B-02

3.3.3. Phase 3 of installations

The third phase of the installations took place between December 2021 and February 2022. A start was made on the wet central heating system at household B-04 in December, with some of the storage heaters being removed and radiators installed. The aim was to fit a wet central heating system each week during January for the 4 remaining households, with Boxergy installing the 5 remaining Hero systems during the last week of January.

Boxergy were able to commission the heating systems for households B-03, B-04 and B-05 on 28th January. Delays with the installations meant that the 2 remaining systems were commissioned on a later visit during the second week of February. During the period between the storage heaters being removed and the Boxergy Hero installation becoming operational, households were provided with supplementary heating and compensated for the additional running costs.

The cost of the wet central heating system installation and associated electrical work was £5,676+VAT for each of the last 5 properties.

3.3.4. Maintenance visits and upgrades

Visits were carried out by Boxergy in March, May and July to address maintenance issues and fit components that were unavailable at the time of the original installation.

Storm Eunice hit South West England on 18th February 2022 which led to power cuts in Witheridge and affected broadband connections. The outhouse roofs were blown off for households B-05 and C-03. The residents were moved out temporarily while the roofs and electrics were repaired.

Boxergy completed service visits on 8th March, which included addressing issues with installation B-05, ensuring it was operational again. There were issues with installation B-06 soon after commissioning, with unusual noises produced by the heat pump fan. Low voltage on the electricity network may have caused the heat pump to regularly go into restart mode and not produce heat and hot water. The storm led to a full cut-out of the system. Over this period, the residents were relying on supplementary heating. Engineers investigated other issues with the installations during this service visit such as problems with connections to thermocouples and the CT clamp connections for the batteries for 2 installations.

Household B-01 had a mixer shower fitted in June 2021. Further mixer showers were fitted by the plumbing contractor for households B-04, B-05 and B-06 on 7th and 8th March 2022.

A further service visit was completed on 17th to 19th May 2022. This included fitting the Vaillant sensoNET gateway on the installation for household B-06, allowing online monitoring and control of the heat pump. The Hero controller for household B-01 had gone offline and the controller was repaired. There were further thermocouple connection errors to be addressed. There were also issues with some of the batteries, such as for households B-04 and B-05 where the batteries were not discharging.

Another set of service visits was carried out by Boxergy between 5th and 7th July 2022. The replacement 10.1 kWh Alpha battery module was fitted for household B-01. The Vaillant heat pump had been fitted a year earlier, but a battery had only been operational for a few hours during that time before failing.

Household B-05 had experienced regular drops in pressure from the system and this had been caused by leaks. The pipework to and from the Boxergy Hero system used compression joints with rubber. Glycol had been added to the heating circuit, but the wrong specification had been used by the plumbers, which led to the rubber seals failing and leaks from the system. The seals on the joints were repaired at this time and replacement Glycol added.

Other health checks were performed on the systems and the Hero controller's software was updated. Issues with several of the batteries were resolved on this visit and 6 of the 7 batteries were operating as expect by the end of the visit.

There was still a problem with the installation for household B-04. The electrical wiring for the consumer unit meant that it was not possible to measure the full household consumption with the CT clamp for the battery. The system showed anomalous behaviour on the Alpha battery portal, with the battery charging overnight and rapidly discharging under a high load as soon as the battery was allowed to discharge. As a result, the battery charge level was controlled during August until a new consumer unit was fitted on 26th August. The upgrade allowed the Alpha battery system to correctly measure the household consumption and discharge the battery at appropriate times.

4. Technical evaluation and results

4.1. Introduction

The project began in March 2020 and households were recruited in October 2020. The electricity consumption and room temperatures were monitored for the properties with their original heating systems between October 2020 and April 2021. Replacement loggers were fitted for the following heating season in October 2021 and collected in October 2022.

The first Boxergy Hero installation, B-01 was fitted in June 2021. While the heat pump and heat battery were fully operational from commissioning, it took until July 2022 before the electrical battery was working. The second Boxergy Hero installation, B-02, was fully operational from 25 Nov 2021 with both the heat pump and batteries running.

The remaining 5 Boxergy Hero installations were fitted in January and February 2022. For several of the systems, the electrical battery was only fully operational and monitoring available on the Alpha ESS portal from July 2022. This meant that all 7 Boxergy installations were only operating together during the heating season from October 2022.

With the project ending in December 2022, this limited the analysis that was possible of the performance of the systems with both the heat pump and electrical battery operational.

4.2. Household B-01

4.2.1. Pre-installation period for household B-01

Prior to the new heating system being fitted, the household had 5 storage heaters. The storage heater in the living room was behind a sofa and not used. The heater in the second bedroom was not used either. The storage heaters that were used most were the ones in the hallway and main bedroom. Supplementary heating was typically used in the living room and bedroom, with the kitchen and bathroom unheated. The storage heaters were not extensively used however as the residents felt they were expensive to run.

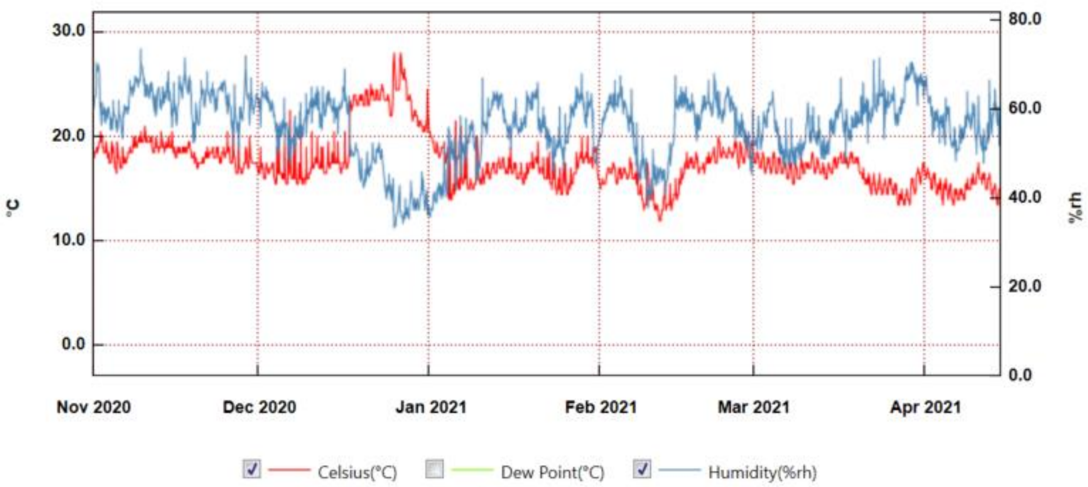

Figure 4.1 (a) Graph of living room temperature and relative humidity for household B-01 Property with storage heaters before Boxergy Hero installation

Figure 4.1 (a) shows a graph of the living room temperature and relative humidity over the winter heating season, while figure 4.1 (b) shows a graph for the bedroom.

The average room temperature in the living room with the old heating system was 17.48˚C over the full 24 hour period. This rose to 17.97 ˚C when only considering the period 17:00 to 21:00 when households typically want to be warm. The temperature of the living room was warmer during the second half of December due to the use of an open fire and additional supplementary heating, with a peak in temperature of 28˚C on 25 Dec 20 at 18:00. The room temperature was also very warm overnight during this period and was 26.5˚C on 27 Dec 20 at 03:00. If the period from 15 to 31 Dec 20 is ignored, the average living room temperature dropped from 17.48˚C to 16.9˚C and the maximum temperature recorded was 22.5˚C.

The average relative humidity in the living room between 1 Nov 20 and 15 Apr 21 was 56.3%. The minimum value of 33.5% occurred on 25 Dec 20 at 18:00 at the time of maximum temperature. The maximum value of relative humidity was 73.5% which occurred on 9 Nov 20. The optimum level for relative humidity is considered to be in the range 40 to 60%[17]

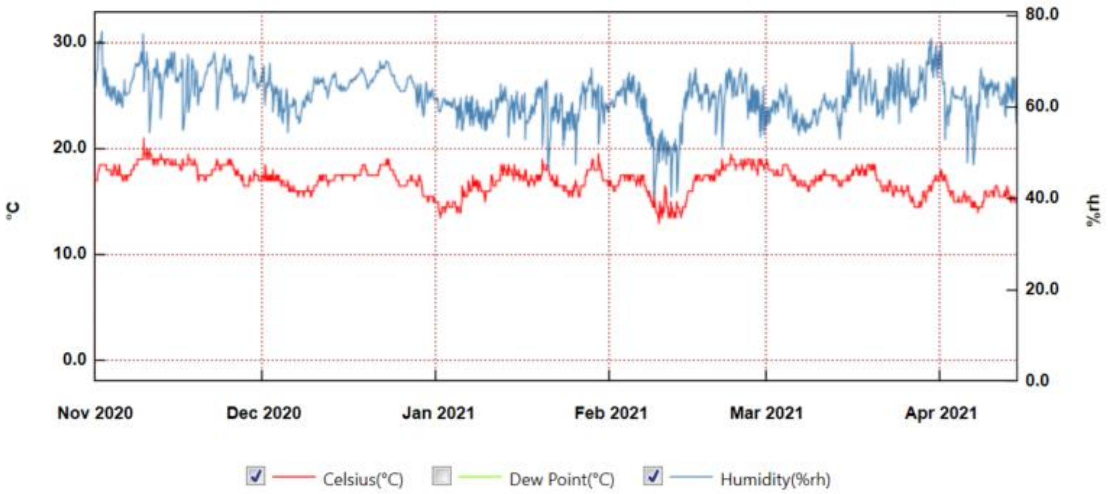

Figure 4.1 (b) Graph of bedroom temperature and relative humidity for household B-01 Property with storage heaters before Boxergy Hero installation

The average temperature in the bedroom was 16.97˚C between 1 Nov 20 and 15 Apr 21. The room temperature was quite consistent over a day, but varied more over longer timescales due to variation in the external temperature. There was a cold spell with days with 10 to 15 Degree Days[18] between 27 Dec 20 and 10 Jan 21. Another occurred from 5 Feb 21 to 14 Feb 21, with days having 10 to 18 Degree Days. These periods both correspond to dips in the bedroom temperature with the minimum bedroom temperature of 13˚C occurring at 18:30 on 9 Feb 21. The minimum temperature for the living room of 12˚C occurred at 20:30 on 11 Feb 21, during the same period of cold weather.

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[17] A.V. Arundel, E.M. Sterling, J.H. Biggen and T.D. Sterling, "Indirect health effects of relative humidity in indoor environments", Environ Health Perspect, 1986, http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/ (Accessed 19 Dec 22)

[18] Degree Days – An Introduction, https://www.degreedays.net/introduction (Accessed 18 Dec 22)

The humidity in the bedroom between 1 Nov 20 and 15 Apr 21 ranged from 40.5 to 76.5% with an average of 62.41%. Much of the time it was out of the optimum range of 40-60%. The minimum value of humidity occurred on 8 Feb 21 at 21:30 during the cold weather period when the bedroom and lounge temperatures both reached their minimum values.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Lounge 24 hours	17.48	28.0	12.0	2.44	56.3	73.5	33.5	7.16
Lounge 17:00 - 21:00	17.97	28.0	12.0		57.43	73.5	33.5	
Bedroom 24 hours	16.97	21.0	13.0	1.27	62.41	76.5	40.5	4.69
Bedroom 17:00 - 21:00	16.92	19.5	13.0		62.2	76	42.5	

Table 4.2 Household B-01 temperature and relative humidity between 1 Nov 20 and 15 Apr 21 Property with storage heaters before Boxergy Hero installation

The electricity consumption of the household was monitored using Tinytag View 2 loggers with current clamps fitted on the 24 hour and heating circuits. Figure 4.3 (a) shows the heating circuit between 1 Jan 21 and 6 Jan 21. On the mornings of 1 to 4 Jan 21 between 00:00 and 07:00, there was a consistent consumption of at least 10,000mA or about 2.3kW. This was probably due to use of the hallway storage heater.

On top of this baseload were a series of 13,000mA spikes in consumption overnight, briefly taking consumption to about 23,000mA. These were due to the 3kW immersion heater for the hot water cylinder initially bringing water in the cylinder to temperature and then maintaining it at temperature during the off-peak period.

On 5 Jan 21, a second 2.3kW storage heater was turned on, which doubled the baseload consumption during the off-peak period to 20,000mA. The storage heaters were used until 19 Mar 21 and again briefly from 6 to 12 Apr 21 during another period of colder external temperatures.

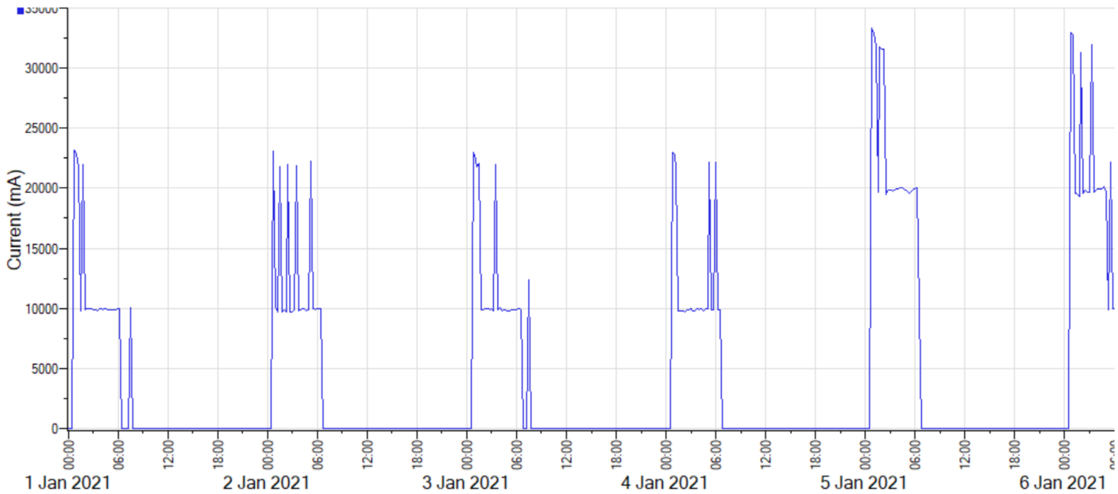


Figure 4.3 (a) Heating circuit consumption for household B-01 between 1 Jan 21 and 6 Jan 21 Property with storage heaters before the Boxergy Hero installation

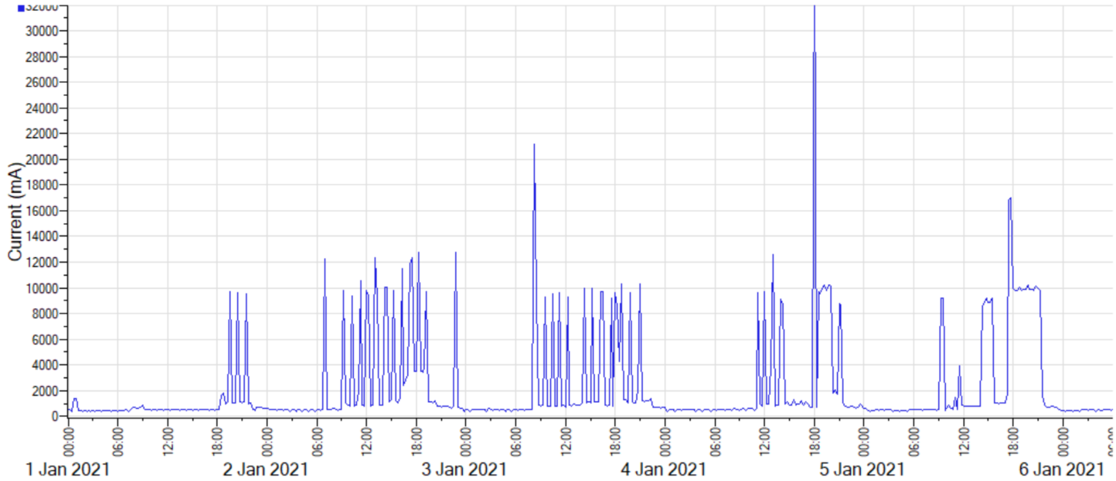


Figure 4.3 (b) 24-hour electricity circuit for household B-01 between 1 Jan 21 and 6 Jan 21 Property with storage heaters before the Boxergy Hero installation

The electricity consumption on the 24-hour circuit is shown in figure 4.3 (b). Between 09:00 and about 21:00 on 2 and 3 Jan 21, there were regular peaks in consumption of about 10,000mA. These peaks might be due to a supplementary heater with a thermostat running through the day. There was a sharp peak of 37,600mA at 18:00 on 4 Jan 21 which was due to use of an electric shower.

There was an initial peak in consumption of 17,000mA at 17:30 on 5 Jan 21 followed by consistent consumption of about 10,000mA (about 2.3kW) until 21:30. This electricity consumption was likely to be due to supplementary heating as it corresponded to a temperature rise in the living room over the same period. At 17:30 the living room temperature started to rise from 14.5˚C and reached 21.5˚C at 21:30 and started to decrease again from this time.

It is apparent that over the period from 1 Jan 21 to 6 Jan 21, household B-01 was using a combination of storage heater and supplementary electric heating.

During the pre-installation phase for household B-01, only a limited number of electricity meter readings were available. Table 4.4 shows that over the heating season between 29 Oct 20 and 27 Apr 21, the electricity consumption during peak rate times was 9.36 kWh/day and 18.37 kWh/day during off-peak times. 66.25% of the electricity consumption was on the off-peak rate primarily due to use of the storage heaters and water heating. The total consumption per Degree Day over the heating season was 2.88 using data from Dunkeswell Airport[19]. Over a 10-month period, the household consumption was 6,694.5 kWh, with 59.6% of the consumption from off-peak electricity.

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
29-Oct-20	27-Apr-21	180	9.36	18.37	27.72	66.25%	2.88
30-Jul-20	01-Jun-21	306	8.84	13.04	21.88	59.60%	2.96

Table 4.4 Electricity consumption for Household B-01 with storage heaters

[19] 03840 Dunkeswell Airport, Degree Days, https://www.degreedays.net/ (Accessed 20 Dec 22)

4.2.2. Post-installation period for household B-01

The 7kW Vaillant aroTHERM plus air-source heat pump was commissioned along with the Sunamp heat battery on 25 Jun 21. A mixer shower was fitted with the system at the same time. The Alpha electrical battery was not fully operational for over a year after the heat pump installation. This provides a year of data for the system with just the heat pump and heat battery running. A 10.1 kWh Alpha electrical battery was fitted on 23 Nov 21 but failed after about a day. Supply chain issues meant that a replacement 10.1 kWh battery could not be fitted until 5 Jul 22.

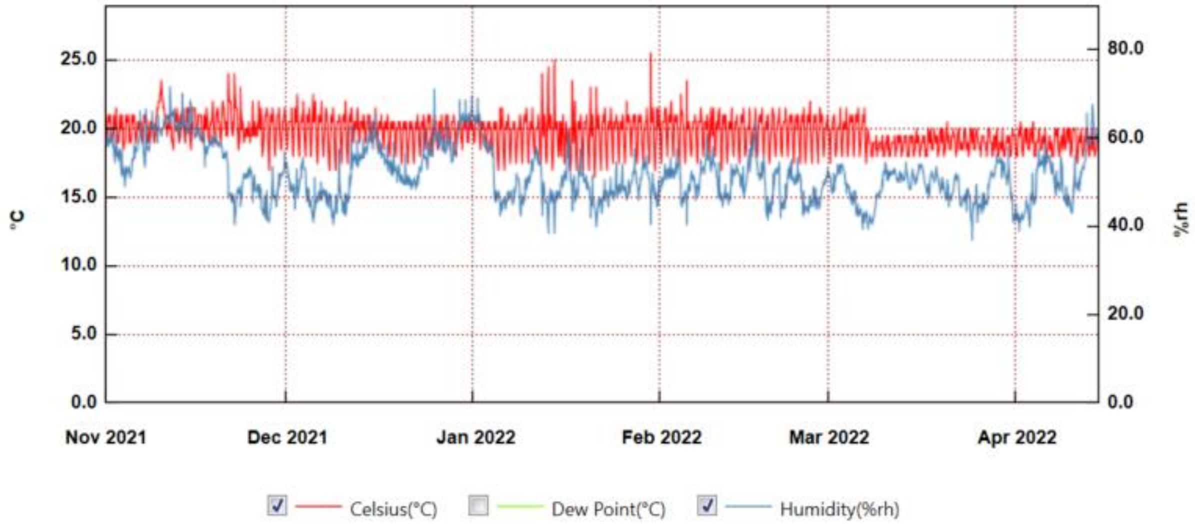


Figure 4.5 Graph of living room temperature and relative humidity for household B-01 Heating by 7kW Vaillant aroTHERM plus heat pump with Boxergy Hero system

The variation in living room temperature and relative humidity is shown in figure 4.5 for household B-01 for the period 1 Nov 21 to 15 Apr 22. The average temperature was 19.7˚C and ranged from 16.5 to 25.5˚C. The average living room temperature during the previous heating season using storage heaters and supplementary heating was only 17.48˚C and the temperature ranged from 12 to 28˚C. This shows a notable improvement in thermal comfort.

There was a daily variation of up to 4˚C in the living room temperature for the period 1 Nov 21 to 7 Mar 22 due to the settings on the thermostat. The heating system was turned off or set-back from 22:00 and this allowed the living room temperature to fall from about 21˚C to a minimum of about 17.5˚C. From about 06:00, the temperature started to rise again and reached 20˚C by 10:30, maintaining that temperature through most of the day, with an increase to 21˚C by 21:00. The lower temperatures occurred overnight and so did not have an impact on the thermal comfort of the residents, but meant the heat pump had to work harder from 06:00, potentially using more electricity.

From 8 Mar 22, the living room temperature ranged from 17.5˚C to 20.5˚C, with a daily variation of up to 3˚C. The average temperature was slightly lower at 19.02˚C over the full day, but was 19.31˚C from 17:00 to 21:00.

As an illustration of the improvement of the consistency of the temperature, for the heating season with storage heaters from 1 Nov 20 to 15 Apr 21, the standard deviation of the temperature in the living room was 2.44˚C. For the heating season the following year between 1 Nov 21 and 15 Apr 22 with the heat pump, the standard deviation in living room temperature was 1.05˚C. For the period after the change to the heating schedule between 8 Mar 22 and 15 Apr 22, the standard deviation in living room temperature was 0.58˚C.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Lounge 24 hours	19.71	25.5	16.5	1.05	51.63	71.5	37.0	5.9
Lounge 17:00 - 21:00	20.31	22.0	18.0		52.28	71.5	37.0	
Bedroom 24 hours	19.86	23.5	17.5	0.8	54.95	71.5	41.0	5.07
Bedroom 17:00 - 21:00	20.17	22.0	18.0		54.74	68.0	41.5	

Table 4.6 Household B-01 temperature and relative humidity between 1 Nov 21 and 15 Apr 22 Property with Boxergy Hero system with ASHP, but no electrical battery

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Lounge 24 hours	19.02	20.5	17.5	0.58	50.09	67.5	37.0	5.08
Lounge 17:00 - 21:00	19.31	20.5	18.5		50.76	67.5	37.0	
Bedroom 24 hours	18.99	20.0	17.5	0.48	53.11	69.5	41.5	4.57
Bedroom 17:00 - 21:00	19.02	20.0	18.0		52.75	67.0	41.5	

Table 4.7 Household B-01 temperature and relative humidity between 8 Mar 22 and 15 Apr 22 Property with Boxergy Hero system with ASHP, but no electrical battery

The graph showing bedroom temperature and humidity in figure 4.8 had similar characteristics to figure 4.5 for the living room, but the daily variation in temperature was lower.

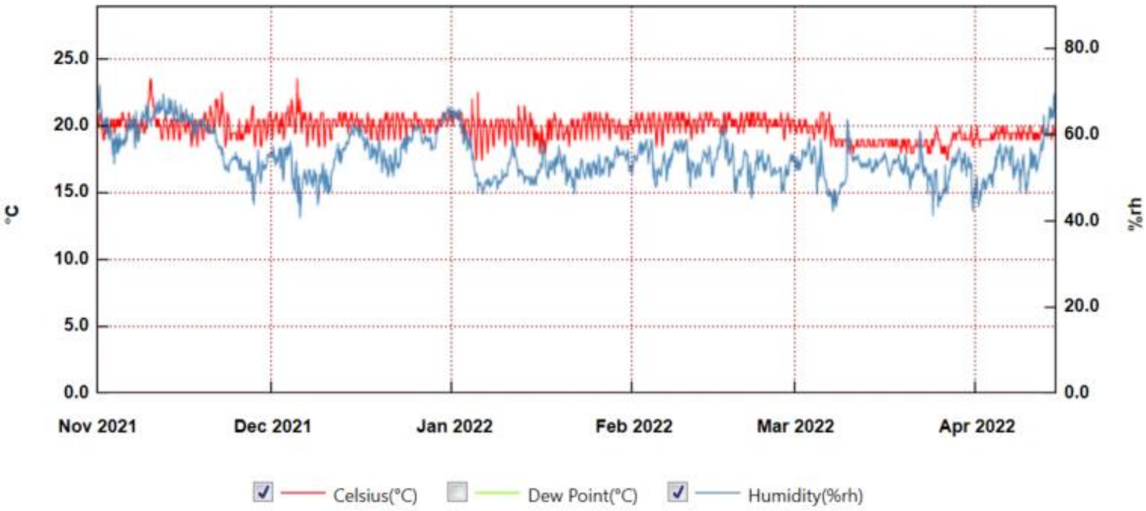


Figure 4.8 Graph of bedroom temperature and relative humidity for household B-01 Heating by 7kW Vaillant aroTHERM plus heat pump with Boxergy Hero system

The average bedroom temperature over the heating season with the heat pump was 19.86˚C and ranged from 17.5 to 23.5˚C. In comparison, the bedroom average temperature with the storage heaters over the equivalent period was 16.97˚C and ranged between 13 and 21˚C. As for the living room this shows a clear improvement of the thermal comfort in the bedroom during the heating season after the heat pump system was fitted.

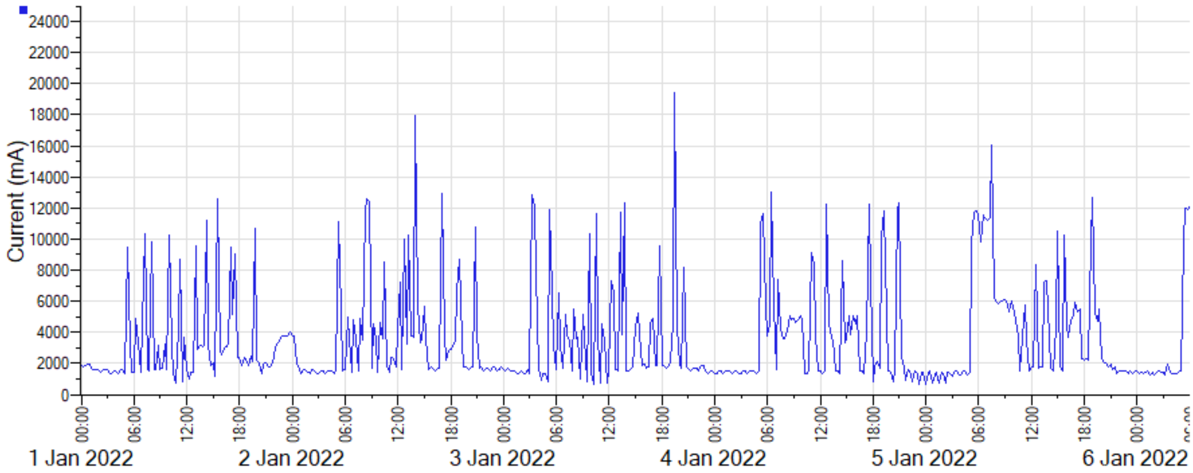


Figure 4.9 24-hour electricity circuit for household B-01 between 1 Jan 22 and 6 Jan 22 Property with Boxergy Hero system with ASHP, but no electrical battery

After the Boxergy Hero installation, none of the electricity consumption was on the off-peak heating circuit with all consumption now on the 24-hour circuit. All consumption during the off-peak hours whether on the 24-hour or off-peak heating circuit is charged at the off-peak rate for these installations.

Figure 4.9 shows the household electricity consumption from 1 Jan 22 to 6 Jan 22. The same period was analysed the year before with storage heaters. Peaks in electricity consumption started from about 05:00 and cut in and out during the day until about 21:00. The peaks were typically in the range 10 to 12,000mA, corresponding to a consumption of about 2.75kW. There was a baseload of about 1,500mA overnight. The rated maximum current for the 7kW aroTHERM plus air-source heat pump was 15A (or 3.45kW at 230V).

The Boxergy Hero system was commissioned with the Vaillant aroTHERM heat pump and Sunamp heat battery on 25 Jun 21. A 10.1kWh Alpha ESS electrical battery was fitted in November 2021 and failed after about 24 hours. Due to supply chain issues the replacement battery could only be fitted in July 2022. During the first year of operation, the household remained on their Economy 7 tariff as it was unclear when the replacement electrical battery would be available. A single rate tariff would have been better during this period as there was not particularly high overnight consumption until the battery was fitted.

Table 4.10 shows the electricity consumption of household B-01 recorded by a smart meter. From 1 Nov 21 to 30 Apr 22, the household consumed on average 20.5kWh per day with 26.9% of the consumption from off-peak electricity. During a similar length period in 2020/21, household B-01 used on average 27.72 kWh/day with 66.3% of the consumption using off-peak electricity (see table 4.4). This was with the storage heaters installed and it should be noted that the period was colder (more Heating Degree Days), but the total consumption in kWh/Degree Day was still lower with the heat pump.

The period from 1 Jul 21 to 1 Jul 22 covers a full year with the heat pump and heat battery operating. The total annual consumption during this period was 5,605 kWh or 15.36 kWh/day, with 24% of the consumption using off-peak electricity. The period from 1 Aug 22 to 1 Dec 22 had the Alpha ESS electrical battery also running with the heat pump. During this period, the total consumption was 13.95 kWh/day with 68.3% of the consumption using off-peak electricity. The greater off-peak consumption during this later period was due to the battery charging overnight and discharging during the day.

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
01-Nov-21	30-Apr-22	180	15.01	5.51	20.51	26.86%	2.38
01-Jul-21	01-Jul-22	365	11.68	3.68	15.36	23.96%	2.81
01-Aug-22	01-Dec-22	122	4.42	9.52	13.95	68.28%	4.45

Table 4.10 Electricity consumption for Household B-01 with Boxergy Hero system

Use of the heat pump was limited in August and September, and for some days the battery could fully power or nearly fully power the home during peak rate periods. Consumption from the heat pump made up a greater proportion of the electricity consumption in October and November. The electricity consumption per heating degree day is less meaningful outside the winter heating season, as the consumption has little temperature dependence.

Figure 4.11 shows a Power Diagram from the Alpha ESS battery portal for 22 Nov 22. The battery was charging from midnight and was fully charged by 04:00 (shown in green). From 07:00, the household load (shown in blue) was supplied by the battery rather than the grid. It is likely the heat pump was operating from 05:00 until about 10:00 with the heat pump starting up again at 15:30 and perhaps running until at least 19:30. The battery reached its maximum depth of discharge by 15:15 and electricity was subsequently supplied to the home from the grid (shown in brown).

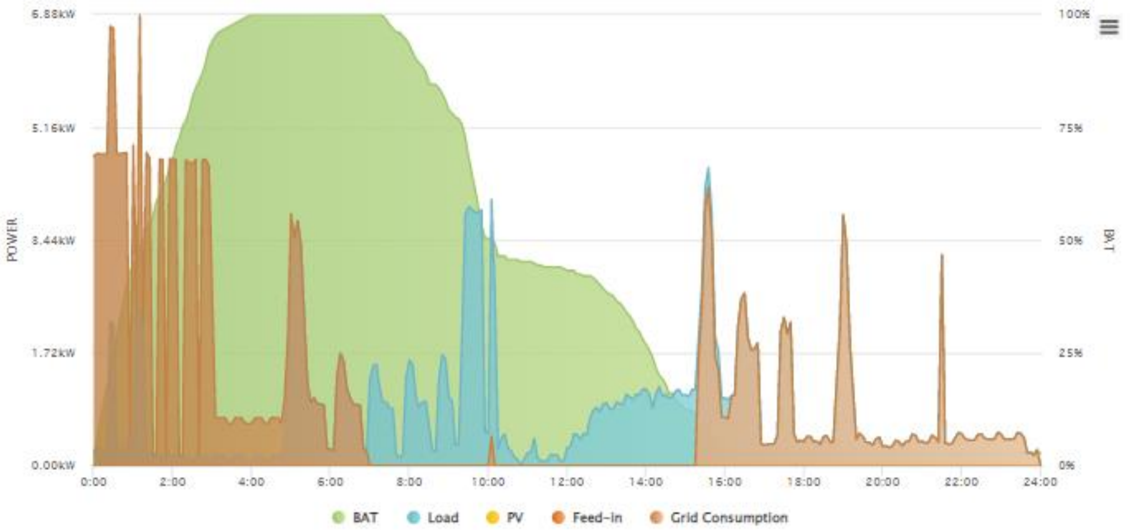


Figure 4.11 Power Diagram from the Alpha ESS battery portal for Household B-01 on 22 Nov 22 Property with Boxergy Hero system with ASHP and electrical battery operational

Month	Peak electricity consumption (kWh/day)	Off-peak electricity consumption (kWh/day)	Total electricity consumption (kWh/day)	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Heat Pump Coefficient of Performance (COP)	Percentage electricity consumed by heat pump (%)
Jul-21	7.59	1.37	8.95					
Aug-21	6.85	1.33	8.19					
Sep-21	7.77	1.33	9.09					
Oct-21	12.27	1.79	14.06					
Nov-21	15.44	4.19	19.63					
Dec-21	18.76	5.32	24.08	11.87	1.48	13.35		55.5%
Jan-22	19.09	6.11	25.20	14.63	1.40	16.03		63.6%
Feb-22	17.34	6.16	23.50	12.16	1.49	13.64		58.1%
Mar-22	10.23	5.86	16.08	8.19	1.13	9.32		58.0%
Apr-22	9.03	5.35	14.38	4.17	1.67	5.83	4.00	40.6%
May-22	8.25	3.24	11.49	0.74	1.68	2.42		21.1%
Jun-22	7.84	2.31	10.15	0.23	1.37	1.60	2.48	15.8%
Jul-22	2.55	9.78	12.33	0.23	1.10	1.32		10.7%
Aug-22	4.56	6.91	11.48	0.19	0.97	1.16		10.1%
Sep-22	4.53	6.77	11.30	0.63	1.03	1.67	3.08	14.8%
Oct-22	5.74	10.32	16.06	5.06	1.13	6.19	4.39	38.6%
Nov-22	3.11	14.16	17.27	7.57	0.93	8.50		49.2%

Table 4.12 Monthly consumption of electricity and heat pump for household B-01 Property with Boxergy Hero system installed

Details of the monthly electricity consumption for household B-01 are shown in table 4.12. For the period from July 2021 until June 2022, the system had just the 7kW Vaillant aroTHERM plus air-source heat pump and Sunamp heat battery operational. From July 2022, the Alpha ESS electrical battery also charged on the off-peak tariff. An estimate of the electricity consumed by the heat pump was obtained from the Vaillant sensoCOMFORT thermostat and Vaillant sensoAPP. Environmental Yield data from the thermostat allowed an estimate of the coefficient of performance (COP) for the heat pump to be made.

From July to September 2021, the total electricity consumption was about 9 kWh per day. There was not likely to be any space heating and the off-peak consumption of about 1.35 kWh/day may have been primarily due to water heating. The electricity consumption was higher during the heating season.

From the end of November 2021, data was available showing estimated consumption from the heat pump. In December 2021, the daily electricity consumption had risen to 24.1 kWh/day with about 55.5% of this consumption being from the heat pump. During the heating season the heat pump was estimated to use about 40.6 to 63.6% of the monthly electricity consumption. The estimates of the coefficient of performance of the heat pump were higher in April and October (4.0 and 4.39) when there was significant space heating, but lower in June and September (2.48 and 3.08) when most consumption was from water heating.

The percentage of off-peak electricity consumption was low when only the heat pump was operating. This ranged from 12.8% in October 2021 to 37% in April 2022. After the Alpha battery was operational in July 2022, the proportion of off-peak consumption rose considerably. It ranged between 59.9 and 82% for the months from July to November 2022.

The electricity consumption is shown in table 4.13 for 3 different periods and daily costs were modelled using 4 example tariffs. These costs ignore the daily standing charge which at the time of writing was about 52p/day.

Tariff 1 is for a single rate tariff at 34p/kWh, the typical unit rate for a single rate tariff under the Energy Price Guarantee at the time of writing. Tariff 2 was for an Economy 7 tariff with a day rate R1=24p/kWh and night rate R2=12p/kWh. This was available during the project and with a long fixed term contract, households might have been able to be on a similar tariff throughout the project.

Tariff 3 was an Economy 7 tariff for the standard variable rate available at the time of writing from one of the major energy suppliers. Here the day rate R1=42.9p/kWh and the night rate R2=14.6p/kWh. Finally Tariff 4 was another Economy 7 tariff which was available close to the time of writing for prepayment meter customers on the standard variable rate from another large energy supplier. The day rate R1=42.74p/kWh, but there was a particularly low night rate R2=9.32p/kWh, which was favourable for storage heaters. The tariffs apart from tariff 2 were high compared to previous years due to the energy crisis which began in Autumn 2021.

Start	End	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
30-Jul-20	01-Jun-21	21.88	59.60%	£7.44	£3.69	£5.70	£4.99
01-Jul-21	01-Jul-22	15.36	23.96%	£5.22	£3.24	£5.55	£5.33
01-Aug-22	01-Dec-22	13.95	68.28%	£4.74	£2.20	£3.29	£2.78

Table 4.13 Electricity consumption and costs for household B-01 using example electricity tariffs Before and after Boxergy Hero system was installed

During the consumption period from 30 Jul 20 to 1 Jun 21 in table 4.13, household B-01 was using storage heaters and supplementary heating. During the year from 1 Jul 21 to 1 Jul 22 heating was provided by the air-source heat pump. From 1 Aug 22 to 1 Dec 22, the Boxergy Hero system had both the heat pump and Alpha electrical battery operating.

Average daily consumption from 30 Jul 20 to 1 Jul 21 was 21.88 kWh/day. The average daily consumption and electricity costs were higher than for the other periods with the heat pump and the heat pump with the battery. It should be noted however that this was for a 10-month period rather than 1-year as with the analysis period for the heat pump.

The average daily electricity consumption for the year with the air-source heat pump was 15.36 kWh/day. The daily cost for tariff 1 (single rate) was slightly lower than for tariffs 3 and 4 (recent Economy 7 tariffs). This meant that household would have been better off on the single rate tariff had it been known that the battery would not be operational for a year and switching to and from time of use tariffs was straightforward.

For the period 1 Aug 22 to 1 Dec 22 with the battery, there was a lower daily electricity consumption (13.96 kWh/day) and a higher percentage of off-peak consumption (68.28%). The electricity costs were lowest for this period and costs with the Economy 7 tariffs were all cheaper than the single rate tariff. It should be noted that the 1 Aug 22 to 1 Dec 22 analysis period did not include the coldest periods of the winter where there is higher electricity consumption. The higher consumption of the heat pump during the winter period is likely to increase the percentage of consumption from the peak rate period.

Further analysis of the costs with monthly analysis periods is provided in Appendix 2.

4.3. Household B-02

At the start of monitoring for the project in October 2020, household B-01 had 5 storage heaters. There was a Dimplex Quantum QM150 in the living room, which was used on a daily basis in winter and the thermostat was set to 20˚C. There was a traditional storage heater in the second bedroom which again was used on a daily basis as the room tended to get colder and was prone to mould. The storage heaters in the main bedroom, hall and kitchen were not normally used due to the running cost. Supplementary heating was used in the living room 3-4 days a week in winter for an hour at a time in the afternoon/evenings due to the living room getting cold.

The Boxergy Hero system was commissioned on 25 Nov 21 with both the Vaillant aroTHERM plus air-source heat pump and Alpha ESS electrical battery operational from that date. This meant there was a year of monitoring data available with the storage heaters and a year with the Boxergy Hero installation.

It was not possible to obtain daily smart meter readings from this site, but monthly smart meter readings were available from electricity statements and regular manual meter readings were taken. Tinytag current clamp data loggers were fitted which recorded readings every 15 minutes. This allowed an assessment of electricity consumption profiles. Data was also available from the Alpha ESS monitoring portal and Vaillant sensoNET system from the date of the Boxergy Hero installation in November 2021.

4.3.1. Pre-installation period for household B-02

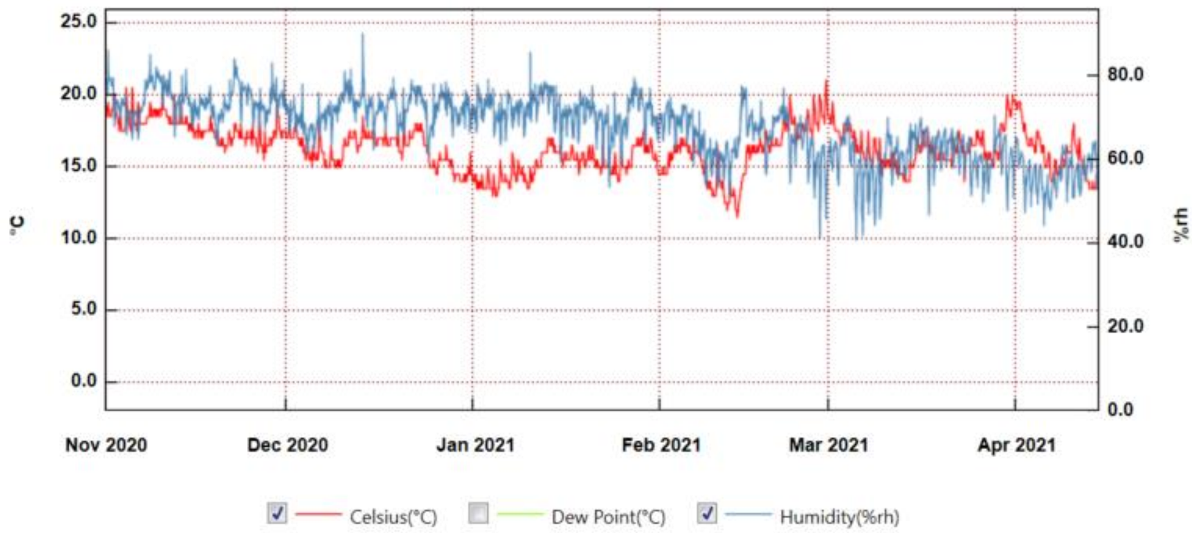


Figure 4.14 Graph of bedroom temperature and relative humidity for household B-02 Property with storage heaters before Boxergy Hero installation

A plot of the main bedroom temperature and relative humidity is shown in figure 4.14 for household B-02. The storage heater in the room was not used and so the residents normally relied on warmth coming from other parts of the house. There was little variation in temperature each day. However, the room temperature varied over longer periods as a result of the external temperature. There was a dip in the bedroom temperature during the second week of February 2021, dropping to 11.5˚C on the evening of 13 Feb 21. During this week, the daily Degree Days for the area ranged from 10.6 to 18.

Between 1 Nov 20 and 15 Apr 21, the average bedroom temperature was 16.27˚C and the temperature ranged from 11.5˚C to 21˚C during the analysis period. The average relative humidity was 67.59% and the humidity ranged from 41 to 90% during the analysis period.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	20.75	25.0	16.0	1.37	55.37	74.5	32.0	7.27
Living Room 17:00 - 21:00	21.62	23.5	17.0		56.22	74.5	36.5	
Bedroom 24 hours	16.27	21.0	11.5	1.53	67.59	90.0	41.0	7.17
Bedroom 17:00 - 21:00	16.33	20.0	11.5		67.24	90.0	45.5	

Table 4.15 Household B-02 temperature and relative humidity between 1 Nov 20 and 15 Apr 21 Property with storage heaters before Boxergy Hero installation

A graph showing the temperature and relative humidity in the living room between 1 Nov 20 and 15 Apr 21 is shown in figure 4.16. The average temperature of the living room during the analysis period across the whole day was 20.75˚C. For the period 17:00-21:00, the living room temperature was on average nearly 1˚C warmer at 21.62˚C. The storage heater in this room was a Dimplex Quantum high heat retention storage heater with a digital thermostat. This was able to maintain the room temperature better than traditional storage heaters.

The average temperature in the living room, where residents spent most of the day was nearly 4.5˚C warmer than the typically unheated main bedroom. The temperature in the living room was also in a more comfortable range, never dropping below 16˚C (or 17˚C in the period 17:00-21:00).

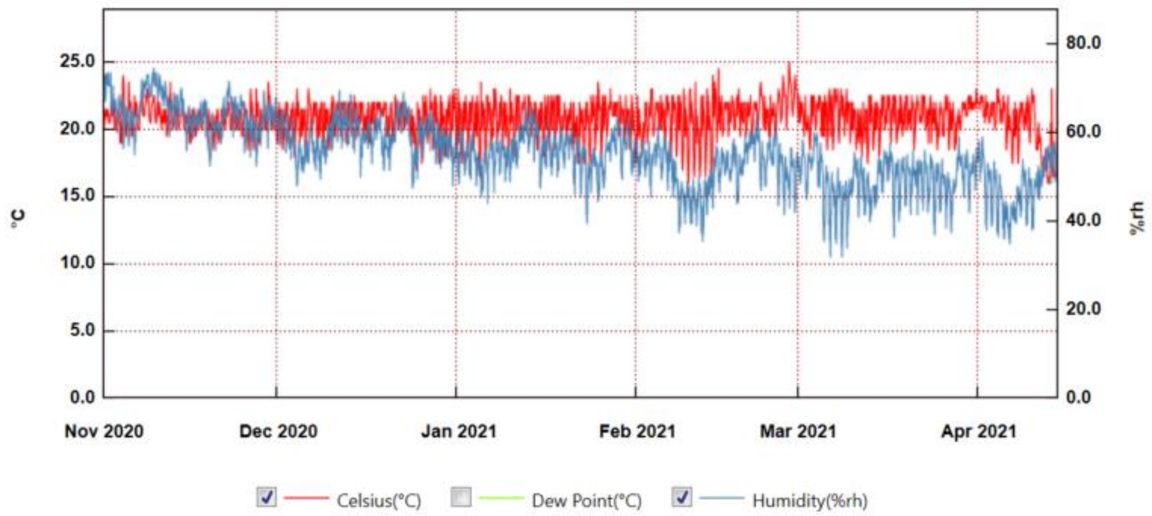


Figure 4.16 Graph of living room temperature and relative humidity for household B-02 Property with storage heaters before Boxergy Hero installation

While the average temperature in the living room was a comfortable 20.75˚C, there was a daily variation in the temperature of the living room over the course of the day. These variations ranged from 2˚C to as much as 8˚C during the cold period during mid-February 2021 (see Appendix 3).

The electricity consumption for the household was monitored using a Tinytag View 2 data logger with a current clamp. The wiring of the utility meter meant it recorded the total household consumption. In early January there was a base load of about 27,000mA between 00:00 and 07:00 due to charging of the storage heaters. This was equivalent to about 6.2kW and suggests the Dimplex Quantum in the living room and 2 smaller storage heaters were charging at this time.

In additional to this were occasional spikes in consumption taking the total consumption to about 40,000mA. This was due to the 3kW immersion heater in the hot water cylinder heating water overnight.

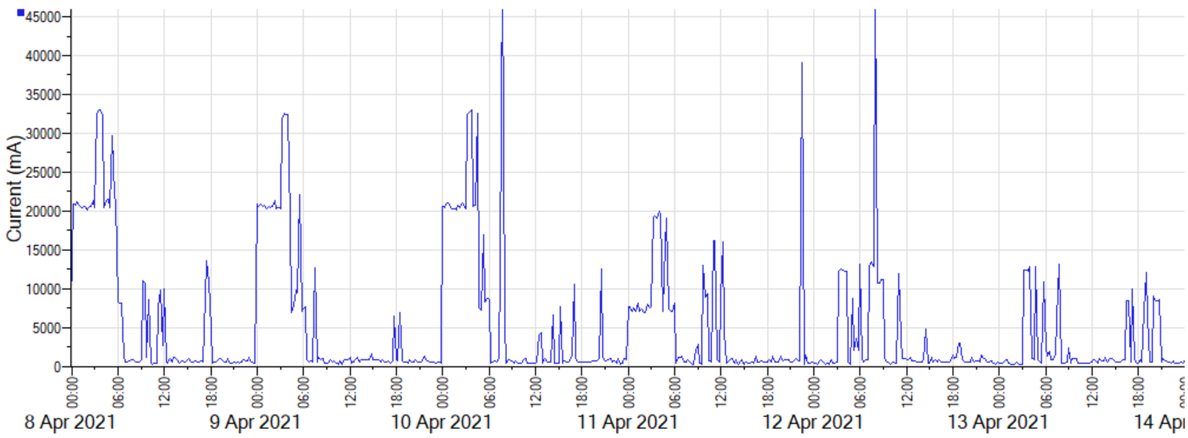


Figure 4.17 Electricity consumption for household B-02 between 8 Apr 21 and 14 Apr 21 Property with storage heaters before the Boxergy Hero installation

The baseload overnight consumption dropped from about 27,000mA to about 20,000mA on 10 Mar 21. This was likely to be due to reducing the number of storage heaters being used from 3 to 2 (in living room and second bedroom). Figure 4.17 shows the electricity consumption between 8 Apr 21 and 14 Apr 21. On 8, 9 and 10 Apr 21, the baseload overnight consumption was about 20,000mA due to the 2 storage heaters charging overnight. The baseload decreased to about 7,000mA (about 1.6kW) on 11 Apr 21 after the living room storage heater was turned off. All the storage heaters were turned off from 12 Apr 21, with the remaining overnight consumption due the immersion water heater. The graph shows some sharp peaks in consumption such as on 10 Apr 21 at 07:45 and 12 Apr 21 at 08:00 which were due to use of the electric shower.

Table 4.18 shows electricity consumption data for household B-02 over a 12-month period with storage heaters before the Boxergy Hero installation. The electricity consumption was high during the winter heating season, with an average consumption of 47.6kWh/day during the period 21 Nov 20 to 22 Feb 21. During this period the average off-peak consumption was 38.54kWh/day (81% of the total). It takes 23.1kWh to fully charge a Dimplex Quantum QM150 and 11.9kWh to charge the other Creda TSR12AW storage heater that was regularly used during this period. Note that a full charge was unlikely to be necessary most of the time.

During the summer, the peak rate consumption was in the range 6.2 to 8.6kWh/day, while in the winter it was 9 to 10.8kWh/day. The additional consumption in winter may be due to additional lighting and greater use of heating appliances such as supplementary heating and cookers. In summer there was about 5kWh of off-peak consumption per day which is likely to be primarily due to water heating.

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
29-Oct-20	21-Nov-20	23	10.83	19.91	30.74	64.78%	5.05
21-Nov-20	22-Feb-21	93	9.04	38.54	47.58	80.99%	4.41
22-Feb-21	22-Mar-21	28	6.67	35.02	41.69	84.00%	4.27
22-Mar-21	22-Apr-21	31	6.62	21.30	27.92	76.29%	3.08
22-Apr-21	22-May-21	30	8.64	5.37	14.01	38.34%	1.85
22-May-21	22-Jun-21	31	6.69	4.93	11.62	42.45%	3.88
22-Jun-21	22-Jul-21	30	6.23	4.87	11.10	43.89%	8.35
22-Jul-21	22-Oct-21	92	7.51	4.72	12.22	38.59%	6.19
29-Oct-20	22-Apr-21	175	8.47	32.47	40.94	79.32%	4.22
29-Oct-20	27-Oct-21	363	7.97	18.22	26.18	69.57%	4.20

Table 4.18 Electricity consumption for Household B-02 with storage heaters

Over the winter heating season period of 29 Oct 20 to 22 Apr 21, the average electricity consumption was 40.94kWh/day with 79.3% of the consumption off-peak. This compares to an average consumption of 27.72kWh/day for household B-01 with 66.25% of the consumption off-peak. Over this period, the consumption per degree day was 4.22 for household B-02 and 2.88 for household B-01.

Over nearly a year with the storage heaters, the average consumption was 26.18kWh/day (or 9,505kWh) with 69.6% of the consumption (6,613kWh) from off-peak electricity.

4.3.2. Post-installation period for household B-02

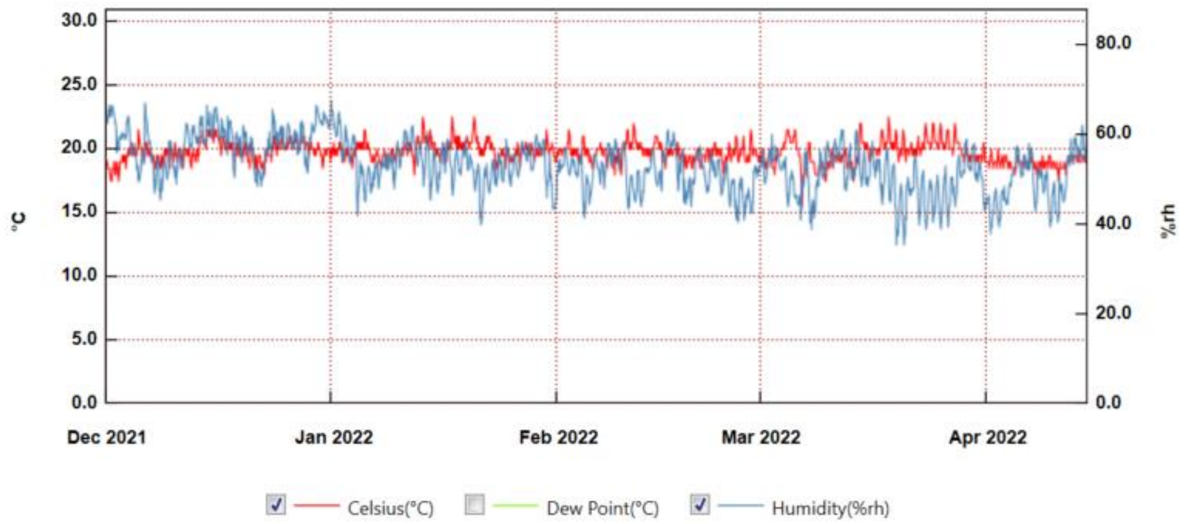


Figure 4.19 Graph of bedroom temperature and relative humidity for household B-02 Property after Boxergy Hero installation on 25 Nov 21

The Boxergy Hero installation with the Vaillant aroTHERM plus air-source heat pump, heat battery and electrical battery was commissioned on 25 Nov 21. The post-installation monitoring period for room temperature and relative humidity for household B-02 was between 1 Dec 21 and 15 Apr 22.

The average bedroom temperature for the full 24-hour period over the monitoring period was 19.74˚C and ranged from 15.5 to 22.5˚C. This was a significant improvement over the winter period the year before where the average bedroom temperature was nearly 3.5˚C cooler at 16.27˚C and fell to a minimum of 11.5˚C during a period of particularly cold weather. Prior to the Boxergy Hero installation, the household did not use the storage heater in the main bedroom due to the high running costs. They relied on heat coming from the rest of the house, which accounted for the low temperatures. After the Boxergy Hero installation, the residents felt able to use the heating in the bedroom and the temperature was maintained at a comfortable level throughout the winter heating season.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	21.3	25.0	17.5	0.97	55.09	71.5	32.5	6.05
Living Room 17:00 - 21:00	21.83	24.0	20.0		55.26	70.0	36.0	
Bedroom 24 hours	19.74	22.5	15.5	0.8	53.13	67.5	35.5	5.59
Bedroom 17:00 - 21:00	19.65	22.5	16.5		51.08	66.0	36.5	

Table 4.20 Household B-02 temperature and relative humidity between 1 Dec 21 and 15 Apr 22 Property after Boxergy Hero installation

The average relative humidity in the bedroom after the Boxergy Hero installation was 53.13%. The relative humidity ranged between 35.5 and 67.5%, spending most of the time in the optimum range for relative humidity of between 40 and 60%. The average relative humidity in the bedroom before the Boxergy installation was 67.6% and relative humidity was above 60% for the majority of the winter heating season.

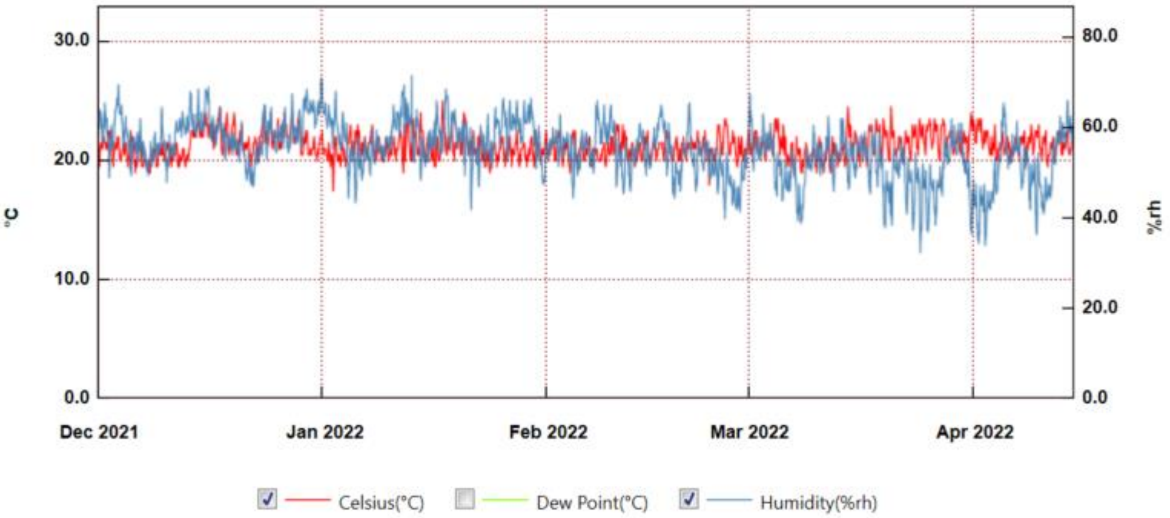


Figure 4.21 Graph of living room temperature and relative humidity for household B-02 Property after Boxergy Hero installation on 25 Nov 21

The average living room temperature after the Boxergy Hero installation was 21.3˚C over the winter heating season. This was 0.55˚C warmer than with the storage heaters and the minimum temperature was not as low at 17.5˚C instead of 16˚C. The temperature range tightened following a visit by the installers on 25 Jan 22. This may have included adjusting the Vaillant sensoCOMFORT smart thermostat for the heat pump.

During the time period 17:00 to 21:00 when residents typically want to be warm, the average living room temperature was 21.83˚C and the temperature never dropped below 20˚C. This was slightly warmer than the average with storage heaters of 21.62˚C. However, the minimum temperature dropped to 17˚C during this time window when the household had storage heaters.

The average living room relative humidity and values of maximum and minimum were comparable with the Boxergy Hero installation and the storage heaters. The average relative humidity was 55.37% with the Boxergy Hero system and 55.09% with the storage heaters.

Outside the heating season, the Alpha ESS battery will charge overnight and supply power for the household appliances during the day. The average peak rate consumption before the Boxergy Hero installation was below the 10kWh capacity of the Alpha battery for the months outside the heating season. This meant that the Alpha battery was able to supply most of and sometimes all the power required by the home during the summer months. Figure 4.22 shows a Power Diagram graph from the Alpha ESS portal for 21 Jun 22 where the battery fully powered the home during the peak rate period. The Alpha battery had discharged to 36.4% overnight and started charging at 03:00 on off-peak electricity. It reached 100% charge by 05:00. The Sunamp heat battery also charged from 03:00, leading to the sharper initial peak. From 07:00 the Alpha battery supplied power to the household. This was sufficient to fully power what might have been the kettle at 08:40, 11:30 and 20:20. The cooking at about 18:00 was also powered by the battery. By midnight, the battery charge had fallen to 30% and so did not need a full charge the following day.

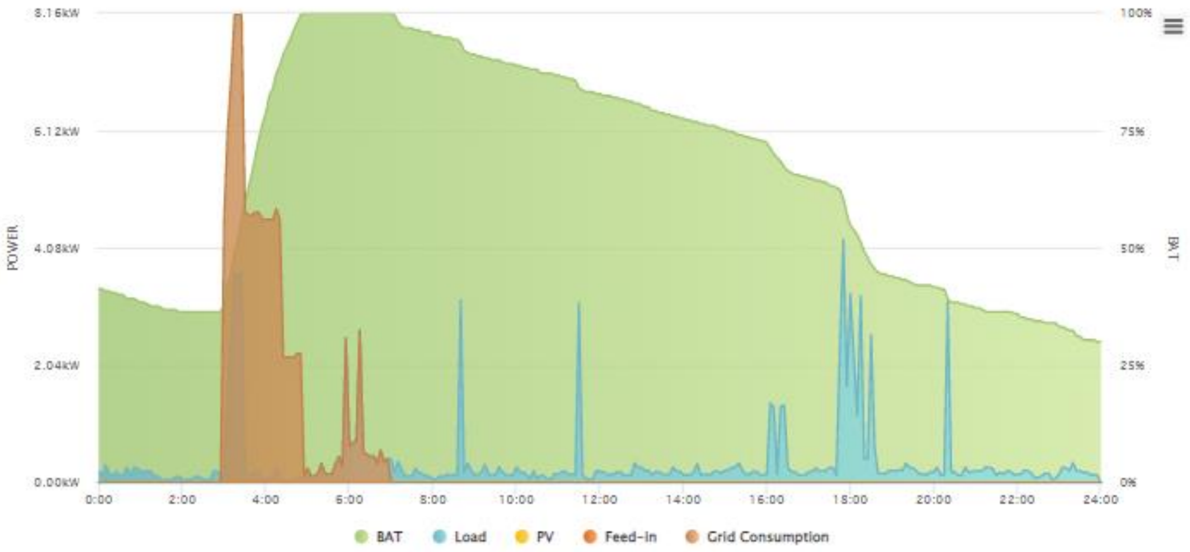


Figure 4.22 Power Diagram from the Alpha ESS battery portal for Household B-02 on 21 Jun 22 Property with Boxergy Hero system with ASHP and electrical battery operational

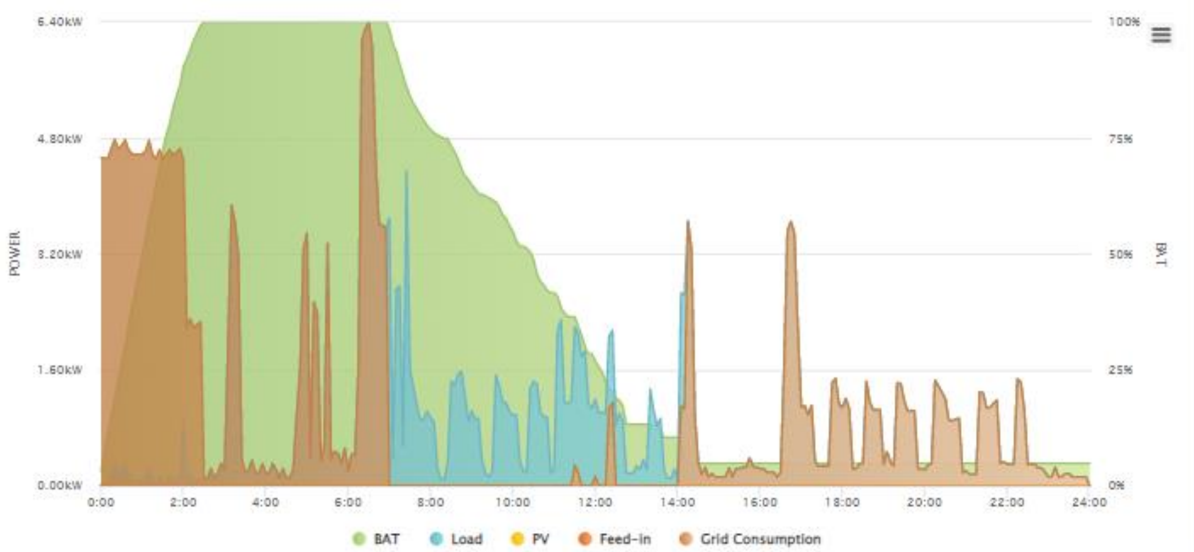


Figure 4.23 Power Diagram from the Alpha ESS battery portal for Household B-02 on 25 Nov 22 Property with Boxergy Hero system with ASHP and electrical battery operational

Figure 4.23 shows a Power Diagram from the Alpha ESS portal on 25 Nov 22 when the heat pump was used for much of the day. The battery had reached its maximum level of discharge the day before. From midnight the Alpha battery started charging and reached 100% charge level by 02:30. The peak in grid consumption at 03:00 was due to the heat pump charging the Sunamp heat battery. The battery started powering the heat pump and household appliances from 07:00 but was fully discharged by 14:15. From that time the heat pump and appliances were powered by peak rate electricity imported from the grid. During the evening, the heat pump cut in and out several times with a peak of up to 1.4kW. The heating system went into setback mode or was turned off from 22:30. During periods of colder weather the Alpha battery became fully discharged earlier in the day and more peak rate electricity was used.

The electricity consumption of household B-02 is shown in table 4.24 for the 12-month period after the Boxergy Hero system was operational. The data is based on smart meter readings from electricity statements but 2 readings were unavailable which accounts for the 2-month intervals.

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
25-Nov-21	22-Jan-22	58	16.99	18.87	35.85	52.62%	3.83
22-Jan-22	22-Feb-22	31	14.51	17.87	32.38	55.20%	3.45
22-Feb-22	22-Apr-22	59	6.60	16.74	23.34	71.72%	2.86
22-Apr-22	22-May-22	30	2.05	13.13	15.18	86.51%	3.23
22-May-22	22-Jun-22	31	1.12	11.81	12.93	91.37%	4.31
22-Jun-22	22-Jul-22	30	1.24	10.95	12.19	89.86%	8.73
22-Jul-22	22-Aug-22	31	1.15	11.09	12.24	90.64%	21.55
22-Aug-22	22-Sep-22	31	1.01	11.31	12.32	91.78%	8.64
22-Sep-22	22-Oct-22	30	4.37	11.60	15.97	72.64%	4.46
22-Oct-22	22-Nov-22	31	6.82	12.26	19.08	64.26%	3.98
25-Nov-21	22-Nov-22	362	6.54	14.22	20.76	68.50%	3.94

Table 4.24 Electricity consumption for Household B-02 with Boxergy Hero system operational

Over the 12-month period, the average electricity consumption after the Boxergy Hero system was operational was 20.76kWh/day (or 7,514kWh) with 68.5% of this consumption being off-peak electricity. This compares to an average of 26.18kWh/day with 69.57% being off-peak for the year with storage heaters. This indicates that the electricity consumption with the Boxergy Hero system was lower than with the storage heaters despite providing better thermal comfort.

The 12-month period with storage heaters was colder than the period with the Boxergy Hero system. There were 2,264.8 Degree Days in the year with storage heaters compared to 1,909.2 with the Boxergy Hero system. When external temperature is also taken into account, the consumption with the Boxergy Hero system was also lower at 3.94kWh/DD compared to 4.2kWh/DD with the storage heaters.

The consumption was however higher than for Household B-01, which was a similar sized property, but with fewer occupants. Here the consumption was 21.88kWh/day (or 2.96kWh/DD) with storage heaters and 15.36kWh/day (or 2.81kWh/DD) with the air-source heat pump alone.

The total electricity consumption with the Boxergy Hero system was lower during the winter than with the storage heaters, but the proportion of off-peak electricity used was not as high. For example between 21 Nov 20 and 22 Feb 21 the average consumption per day with storage heaters was 47.58kWh/day with 81% of the consumption off-peak. This compares to 35.85kWh/day with 52.62% off-peak with the Boxergy Hero system over the period 25 Nov 21 to 22 Jan 22. The peak rate consumption was higher with the Boxergy Hero system at 17kWh/day compared to 9.04/day with the storage heaters, but the off-peak consumption was considerably lower at 18.87kWh/day instead of 38.54kWh/day.

In the summer months, the consumption with the Boxergy Hero system is slightly higher, but there was a significant shift in this consumption to lower cost off-peak electricity. Taking the period 22 Jun 22 to 22 Jul 22, the average electricity consumption of household B-02 with the Boxergy Hero system installed was 12.19kWh/day with 89.9% of the consumption off-peak. During the equivalent period the year before with the storage heater system and no battery, the electricity consumption was 11.1kWh/day with 43.89% of the consumption off-peak. Losses in the inverter and battery are likely to be at least part of the reason for the average daily consumption in summer being slightly higher after the Boxergy Hero system was fitted. However, the electricity costs would have been much lower due to the reduction in peak rate consumption. For the period discussed this was 6.23kWh/day with storage heaters and 1.24kWh/day with the Boxergy Hero system.

Start	End	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
29-Oct-20	27-Oct-21	26.18	69.57%	£8.90	£4.10	£6.08	£5.10
25-Nov-21	22-Nov-22	20.76	68.50%	£7.06	£3.28	£4.88	£4.12

Table 4.25 Electricity consumption and costs for household B-02 using example electricity tariffs Before and after Boxergy Hero system was installed

Table 4.25 shows electricity costs with different tariff rates for the 12-month period with storage heaters (29 Oct 20 to 27 Oct 21) and the 12-month period after with the Boxergy Hero system. Tariff 1 is a typical single rate tariff under the electricity price guarantee in Winter 22/23. Tariff 2 was an example Economy 7 tariff available during the project and tariffs 3 and 4 were Economy 7 tariffs available in Autumn 2022.

There was a reduction in electricity cost for household B-02 after switching from storage heaters to the Boxergy Hero system for all 4 the example tariffs. The saving was £1.20/day for a typical Economy 7 tariff (tariff 3). The Economy 7 tariffs were cheaper than the single rate tariff over the year for both the storage heaters and the Boxergy Hero system. In contrast, for household B-01 during the year using just the air-source heat pump, the single rate tariff was £0.33/day cheaper than Economy 7 tariff 3 due to the Alpha battery not being operational.

A table with costs with the different tariffs for the monitoring period with intervals of 1 to 3 months is shown in Appendix 3. During the coldest period of the winter, electricity costs could be cheaper with storage heaters on tariff 4 than with the Boxergy Hero system due to the particularly low off-peak cost. In Spring and Summer, the Boxergy Hero system was always cheaper than the storage heaters on the Economy 7 tariffs. It was slightly more expensive than storage heaters on the single rate tariff in the middle of summer due to the slightly higher consumption in the summer.

Smart electricity meters are able to show the amount of electricity that has been exported to the grid since they were installed. This is normally observed when a home has a solar PV system fitted.

During this project it was noticed that a number of the households with Boxergy Hero systems were showing electricity exported to the grid. This might usually occur when there was a mismatch of a few tens of watts between the power consumption within the home and the output of the battery.

It was noted for household B-02 that the export was 402kWh on 18 Nov 22. The battery for the Boxergy Hero system had been operating for almost a year, the longest among the installations. This meant the export was over 1kWh/day and was likely to be due to more than a slight mismatch between the power consumption within the home and the output of the battery. The battery appears not to have been correctly setup on the Alpha ESS monitoring portal until 12 Feb 22, perhaps due to CT clamps not being fitted correctly. The portal was not showing the full household load and there was also a rapid discharge of the battery each day. It is likely that the higher levels of export occurred during this period.

Figure 4.26 shows an example plot from the Alpha ESS portal for 30 Dec 21 before the monitoring portal was correctly setup. The charging of the battery was not recorded as grid consumption. The battery was at 100% charge at 07:00 but was fully discharged by 09:40. The rapid discharge might have been due to high consumption from the air-source heat pump during the cold weather period. However, during a period of particularly cold weather in December 2022, the battery was not fully discharged until around 12:00. This suggests excess electricity was exported to the grid during these discharge cycles.

Assuming a cost of 14.6p/kWh for off-peak electricity as for tariff 3, the export had a value of £58.69. The issue of electricity export was discussed with Boxergy in November 2022 and the batteries were set by Alpha not to export. About a month later on 19 Dec 22, the export recorded had only risen a further 3kWh to 405kWh.

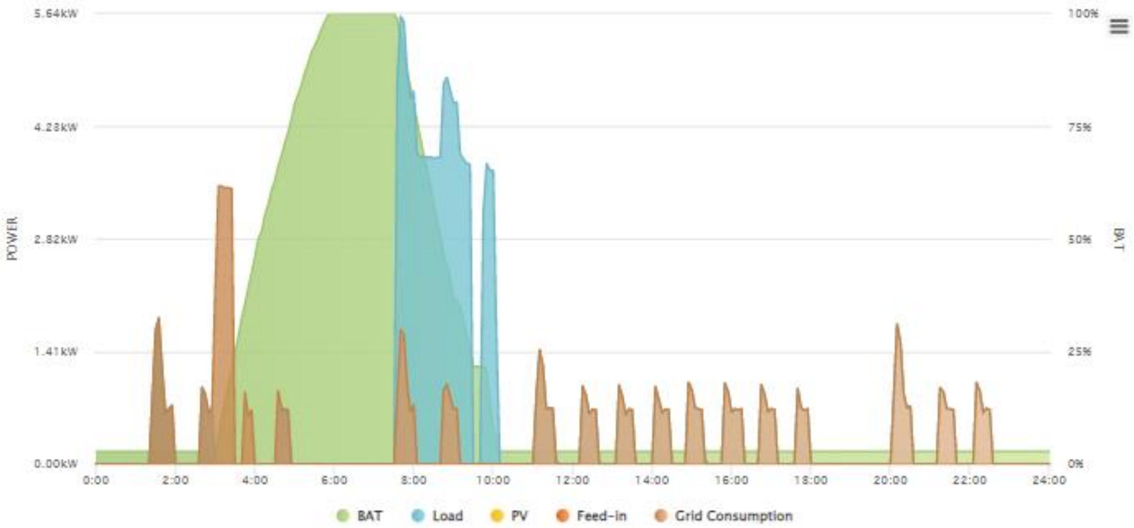


Figure 4.26 Power Diagram from the Alpha ESS battery portal for Household B-02 on 30 Dec 21 Property with Boxergy Hero system running but the Alpha portal not correctly setup

4.4. Household B-03

Household B-03 live in a mid-terraced house with a floor area of about 100m^2. This was the largest home to have a Boxergy Hero system fitted. It also had the largest family, with between 4 and 6 residents over the period of the project.

The property was on an Economy 7 tariff and there were high electricity bills and this had led to a debt on the prepayment meter. The residents felt the bills did not correspond to their usage. However, based on an EPC with the original storage heaters, the space heating demand was 13,064kWh/year and the water heating demand was 2,237kWh/year, which was of a similar magnitude the household electricity consumption.

At the start of the project, the heating in the living room was provided by an electric fire running on peak rate electricity. The only storage heater used in the house was on the upstairs landing. The bedrooms had electric panel heaters which were not normally used due to the expense. There was a storage heater in a downstairs bedroom but this was not used. There was an electric fan heater in the kitchen which was occasionally used for 5-10 minutes in the morning. The high use of peak rate electricity led to higher bills.

The household felt the heating was not fit for purpose, not cost effective and you couldn't control when you had heat. They were very dissatisfied with the cost and level of control of the heating system and how warm their home got when it was cold outside.

There were a number of challenges with the monitoring for this household over the project. Monitoring began at the end of October 2020. During the pre-installation phase, the temperature and humidity logger in the bedroom stopped prematurely on 5 Feb 21, probably due a battery with insufficient charge. The temperature and humidity logger that was used in the living room during the post installation phase failed after a day, which meant it was not possible to assess any improvement in temperature in this room apart from through the questionnaires.

Meter readings were recorded from the prepayment meter during visits. Further readings were obtained from the electricity supplier. There were issues with some of these readings as meter readings for the same period, but obtained from the supplier at different times did not always match up. Errors might have occurred during a manual process of copying over meter readings. A Wibeee Box electricity data logger was fitted, but data was only available for the period 19 May 22 to 28 Oct 22 due to issues caused by the household switching broadband supplier on 2 occasions.

The heat pump and electrical battery system need to be online to provide monitoring and to allow control of the system to make changes to improve performance. It is also a requirement of the warranty of the battery that it is kept online. This system went through several extended periods with the system offline. This might be due to some technical issues or because the family unplugged the connection for the Boxergy Hero system to the broadband router due to fears it might be slowing down their broadband connection. This meant there were gaps in the data from the Alpha ESS portal (with half of the data from May and all of the data from June missing). Readings from the Vaillant sensoAPP may also be less reliable due to periods with missing data.

4.4.1. Pre-installation period for household B-03

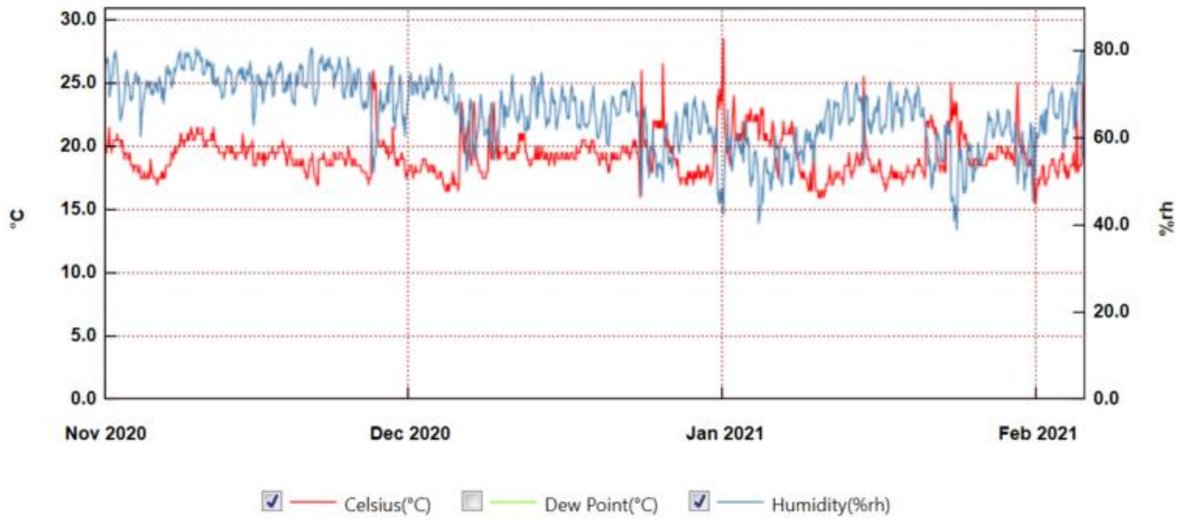


Figure 4.27 Graph of bedroom temperature and relative humidity for household B-03 from 1 Nov 20 to 5 Feb 21, while the property had storage heaters before the Boxergy Hero installation

The heating in the main bedroom during the period before the Boxergy Hero system was installed was likely to have been provided mainly from the storage heater at the top of the stairs. The average bedroom temperature between 1 Nov 20 and 1 Feb 21 was 19.29˚C, with a temperature range over that period of 15.5 to 28.5˚C. There was typically limited variation in temperature in the room over a day and the room temperature was likely to have been colder during periods of colder weather.

There were however occasional spikes in temperature, which were likely to be when a panel heater or other form of supplementary heating was used in the room.

The bedroom temperature was warmer than usual on 31 Dec 20, reaching 24˚C by 12:00. There was a further rise as New Year approached and the temperature reached 28.5˚C at 02:00 on 1 Jan 21. Another example of a temperature spike was on 27 Nov 20. The bedroom temperature was 17.5˚C at 07:00 and increased to 26˚C by 13:00.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	17.81	25.5	11.5	2.36	64.71	82	47.0	6.38
Living Room 17:00 - 21:00	19.39	25.5	14.5		63.79	81.5	48.5	
Bedroom 24 hours	19.29	28.5	15.5	1.57	65.58	80.5	39.0	7.81
Bedroom 17:00 - 21:00	19.05	25.0	15.5		63.16	77.0	41	

Table 4.28 Household B-03 temperature and relative humidity between 1 Nov 20 and 1 Feb 21 Property with storage heaters before Boxergy Hero installation

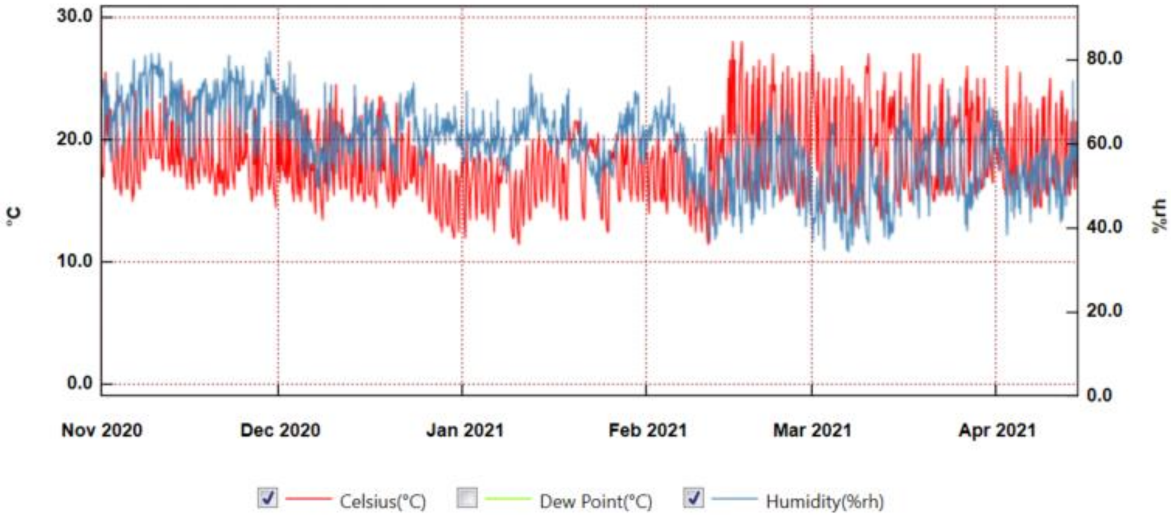


Figure 4.29 Graph of living room temperature and relative humidity for household B-03 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

The average relative humidity in the bedroom was 65.58% in the period 1 Nov 20 to 1 Feb 21. During the monitoring period, the humidity was in the range 39% to 80.5%. However, for the majority of the time, the humidity was above the optimal 40 to 60% range. This is likely to be a factor in why the room was prone to mould.

A graph of the temperature and relative humidity in the living room for household B-03 is shown in figure 4.29. There was change in the temperature profile on 14 Feb 21 which may have occurred when the household fitted a new electric fire in the living room. Between 1 Nov 20 and 1 Feb 20, the average living room temperature over the full day was 17.81˚C and the temperature ranged from 11.5 to 25.5˚C. In the early evening the average temperature was warmer at 19.39˚C.

Table 4.30 shows temperature and relative humidity data for the living room for the period 15 Feb 21 to 15 Apr 21. The average temperature of the living room over the full day increased from 17.81˚C to 19.29˚C. However, there was a wide temperature range from 13 to 28˚C. This increase in temperature range is apparent in figure 4.29 and in the higher temperature standard deviation for the later period. In the early evening, from 17:00 to 21:00, the average temperature was 21.41˚C and the temperature ranged from 16 to 26.5˚C. The average humidity decreased from 64.71% to 53.18% in the later time period. Appendix 4 shows a graph of the temperature and relative humidity for the period 24 Jan 21 to 8 Mar 21 and discusses the change in behaviour from 14 Feb 21 in more detail.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	19.29	28.0	13	3.25	53.18	75	34.5	7.38
Living Room 17:00 - 21:00	21.41	26.5	16.0		51.19	75.0	35.0	

Table 4.30 Household B-03 temperature and relative humidity between 15 Feb 21 and 15 Apr 21 Property with storage heaters before Boxergy Hero installation

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
25-Oct-17	02-Nov-18	373	26.85	20.12	46.98	42.84%	7.55
02-Nov-18	21-Oct-19	353	25.22	13.68	38.91	35.17%	6.81
21-Oct-19	29-Oct-20	374	24.12	12.79	36.91	34.65%	6.22
29-Oct-20	31-Oct-21	367	24.75	13.16	37.90	34.71%	6.33

Table 4.31 Annual electricity consumption of household B-03 from Oct 17 to Oct 21, before the Boxergy Hero installation

Table 4.31 shows the annual electricity consumption for household B-03 in the years before the Boxergy Hero system was installed. There was a high electricity consumption with a relatively low percentage of off-peak electricity consumption. For the 3 later years, the average total consumption was 37.9kWh/day, which is equivalent to 13,834kWh/year. An EPC lodged in 2020 with the original heating system suggested the space heating demand was 13,064kWh/year and the water heating demand was 2,237kWh/year. The RdSAP software assumes a standard heating pattern for the home and heating up to 21˚C in the living area and 18˚C elsewhere. The heating would run for up to 16 hours per day at the weekend and 9 hours per day during the week[20].

Based on the EPC, the space and water heating demand for the house was 15,301kWh with all this to be provided by electric heating. While the actual electricity consumption of the home was high, it still was not adequately heated, with many parts of the house having limited heating. The living room was the main heated room and while over-heated at times, it also fell to low temperatures. The percentage off-peak consumption was low for a household on Economy 7 and depending on the tariff rates may be close to the point where a single rate tariff could be cheaper. This was due to limited use of the storage heaters and using a peak rate electric heater in the living room. Other factors raising the electricity consumption include an electric shower and typically using the washing machine and tumble drier twice a day.

The electricity consumption per degree day over the year was typically in the range 6.2 to 6.8kWh per degree day. This was more than double the value for household B-01 and about 50% higher than the value for household B-02. These were however bungalows which had nearly half the floor area.

Electricity consumption over approximately monthly periods from 4 Aug 20 to 10 Jul 21 is shown in table 4.32. The average off-peak consumption was 34.4% over this period and was close to or above 40% in October, November and December. It is likely the storage heater on the landing was turned on during October. It was a Creda TSR12MW with a storage capacity of 11.9kWh. About 5kWh of the off-peak consumption was likely to be due to the electric immersion water heater. Additional storage heaters were not used, so the consumption above about 17 – 19 kWh/day in December and January was likely to be due to peak rate heaters used during the Economy 7 period of 00:00 to 07:00.

[20] RdSAP Manual Methodology (2016), Stroma, p.9 https://files.stroma.com/certification/rdsap-manual.pdf (Accessed 30 Dec 22)

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
04-Aug-20	04-Sep-20	31	13.84	7.65	21.48	35.59%	20.18
04-Sep-20	03-Oct-20	29	15.62	7.52	23.14	32.49%	7.65
03-Oct-20	02-Nov-20	30	19.93	14.33	34.27	41.83%	6.09
02-Nov-20	01-Dec-20	29	25.59	19.76	45.34	43.57%	6.24
01-Dec-20	03-Jan-21	33	35.73	23.03	58.76	39.20%	5.67
03-Jan-21	02-Feb-21	30	46.77	26.37	73.13	36.05%	6.29
02-Feb-21	06-Mar-21	32	38.16	17.69	55.84	31.67%	5.16
06-Mar-21	04-Apr-21	29	42.24	18.76	61.00	30.75%	6.98
04-Apr-21	06-May-21	32	30.41	12.34	42.75	28.87%	4.52
06-May-21	06-Jun-21	31	20.74	9.35	30.10	31.08%	5.49
06-Jun-21	10-Jul-21	34	15.50	3.65	19.15	19.05%	10.57
04-Aug-20	10-Jul-21	340	27.63	14.49	42.12	34.41%	6.16

Table 4.32 Approximately monthly electricity consumption for household B-03, during the period 4 Aug 20 to 10 Jul 21 before the Boxergy Hero installation

The total electricity consumption was in the range 55 to 75kWh/day between the beginning of December and the beginning of April. This consumption was high and costly as 60 to 70% of this consumption was during the peak rate period. Most of this was likely to be due to peak rate electricity heaters.

Table 4.33 shows the electricity costs for the same period with the example tariffs used throughout the report. At the time when this consumption occurred, the tariff rate paid by the household was cheaper than for Tariff 2. The other more expensive tariffs are more typical of the time of writing. Tariff 4 was always cheaper than the single rate Tariff 1 and Tariff 3, the other Economy 7 tariff. The electricity cost with tariff 3 is cheaper than the single rate tariff when the percentage of off-peak consumption was greater than 31.45%. For household B-03, the percentage off-peak consumption was lower than 31.45% in March, April, May and June. This meant that the single rate tariff was slightly cheaper during these periods. However, over the full period between 4 Aug 20 and 10 Jul 21, tariff 3 would still have been cheaper for the household than a single rate tariff.

Start	End	Total electricity consumption (kWh/day)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
04-Aug-20	04-Sep-20	21.48	£7.30	£4.24	£7.05	£6.63
04-Sep-20	03-Oct-20	23.14	£7.87	£4.65	£7.80	£7.38
03-Oct-20	02-Nov-20	34.27	£11.65	£6.50	£10.64	£9.86
02-Nov-20	01-Dec-20	45.34	£15.42	£8.51	£13.86	£12.78
01-Dec-20	03-Jan-21	58.76	£19.98	£11.34	£18.69	£17.42
03-Jan-21	02-Feb-21	73.13	£24.87	£14.39	£23.91	£22.45
02-Feb-21	06-Mar-21	55.84	£18.99	£11.28	£18.95	£17.96
06-Mar-21	04-Apr-21	61.00	£20.74	£12.39	£20.86	£19.80
04-Apr-21	06-May-21	42.75	£14.54	£8.78	£14.85	£14.15
06-May-21	06-Jun-21	30.10	£10.23	£6.10	£10.26	£9.74
06-Jun-21	10-Jul-21	19.15	£6.51	£4.16	£7.18	£6.96
04-Aug-20	10-Jul-21	42.12	£14.32	£8.37	£13.97	£13.16

Table 4.33 Electricity consumption and costs for household B-03 using example electricity tariffs, during the period 4 Aug 20 to 10 Jul 21 before the Boxergy Hero system was installed

Over the analysis period 4 Aug 20 to 10 Jul 21, the difference in the average cost per day between Tariffs 1, 3 and 4 was small. The values were in the range £13.16 to £14.32/day. The small difference was because the average off-peak percentage consumption was close to the boundary where there is a switch between the single rate and Economy 7 tariffs becoming cheaper.

The electricity costs were particularly high between the beginning of December and the beginning of April. The average costs per day were between £18 and £25 on Tariff 1 (single rate) and Tariff 3 (Economy 7) during these months. Even during the summer, the household would have paid more than £6.50/day.

4.4.2. Post-installation period for household B-03

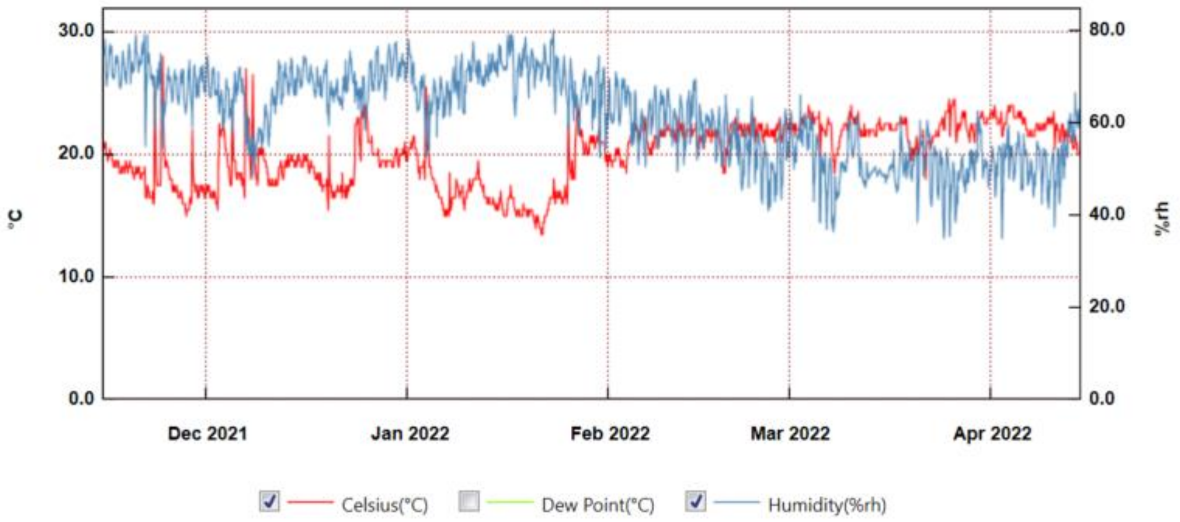


Figure 4.34 Graph of bedroom temperature and relative humidity for household B-03 From 15 Nov 21 to 15 Apr 22. The property used storage heaters and supplementary heating before the Boxergy Hero system operational on 28 Jan 22.

Unfortunately, the temperature and humidity logger in the living room for household B-03 failed after a day. This means it was not possible to assess any changes to the temperature and humidity in that room. However, the logger in the bedroom collected data for a full winter heating season. The Boxergy Hero installation was commissioned on 28 Jan 22. The old storage heaters were removed and the wet central heating system fitted during January. A pre-installation period of 15 Nov 21 to 1 Jan 22 was used for the analysis (table 4.35). Although the old heating system was in place for part of January prior to the household becoming reliant on supplementary heating, the exact date appliances were removed was not known. The Boxergy Hero system was operating after 28 Jan 22 and the post-installation period used for the analysis was 1 Feb 22 to 15 Apr 22.

Over the period 15 Nov 21 to 1 Jan 22, it was apparent from figure 4.34 that there were occasional temperature spikes due to supplementary heating as during the monitoring period in the previous heating season (figure 4.27). The average temperature was 18.92˚C, which was slightly colder than the 19.29˚C average over the previous heating season. The temperature range was wide, as for the previous heating season, going from a minimum of 15˚C up to a maximum of 28.0˚C. The average relative humidity was 68.17% which was comparable to the value of 65.58% over the previous heating season.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
15 Nov 21 to 1 Jan 22								
Bedroom 24 hours	18.92	28.0	15.0	1.88	68.17	79.0	48.5	5.10
Bedroom 17:00 - 21:00	18.38	23.5	15.5		66.24	74.0	53.0	
1 Feb 22 to 15 Apr 22								
Bedroom 24 hours	21.90	24.5	18.0	1.04	54.08	71.0	35.0	6.57
Bedroom 17:00 - 21:00	21.75	24.0	18.0		51.74	67.0	35.0	

Table 4.35 Bedroom temperature and relative humidity for household B-03 for a period with storage heaters and a later period with the Boxergy Hero installation

Figure 4.34 shows a clear change in temperature and relative humidity of the bedroom after the Boxergy Hero system was installed on 28 Jan 22. The bedroom temperature was warmer and varied less and there was a decrease in humidity in the room.

For the monitoring period 1 Feb 22 to 15 Apr 22, the average temperature in the bedroom increased by nearly 2˚C to 21.9˚C. The temperature range was lower as reflected by the reduced standard deviation in the temperature and the range from 18.0 to 24.5˚C.

There was a significant decrease in the average humidity from 68.17% to 54.08%. The humidity in the room gradually decreased during the first month after the Boxergy Hero system was installed. After a couple weeks, the humidity was mainly in the optimum range of 40 to 60%. This room had been prone to mould. The more consistent temperature and lower relative humidity after the Boxergy Hero installation is likely to have reduced the risk of further mould developing.

Although there was no post-installation temperature and relative humidity data available for the living room for this household, several points are clear from the data from the bedroom and the questionnaire. The household strongly agreed that their thermal comfort had improved after the Boxergy Hero installation and that they had whole house heating rather than room heating. They also strongly agreed that the new heating system was better than the old heating system and they felt warmer, and it benefited their physical and mental health. The data for the bedroom shows a transition from room heating to whole house heating with a more consistent and comfortable room temperature.

Electricity consumption of the household during the period after the Boxergy Hero installation is shown in table 4.36. The heat pump and battery of the system are likely to have been operational throughout this period, but there were gaps in the monitoring data due to a loss of the internet connection.

Over the analysis period with the Boxergy Hero system running from 3 Feb 22 to 19 Dec 22, the average total household consumption was 31.74kWh/day, with 45.95% of this from off-peak electricity. With the old heating system, in previous years, the average total consumption was typically 36.9 to 38.9kWh/day, with 34.6 to 35.2% of consumption off-peak. In 2017/18 the total consumption averaged at 47kWh/day and for the period 4 Aug 20 to 10 Jul 21 it was 42.1kWh/day. It is not possible to assess savings over a full year with the

Boxergy Hero system as the post installation monitoring period did not include a full winter heating season. Some comparisons can be made by comparing similar periods.

Looking at colder weather periods, the consumption of household B-03 between 2 Feb 21 and 6 Mar 21 was 55.8kWh/day, with 31.67% off-peak with the old heating system compared to 39.38kWh with 41.1% off-peak between 3 Feb 22 and 1 Mar 22 with the Boxergy Hero system. Taking into account the external temperature, with the old heating system the consumption was 5.16kWh/degree day while with the Boxergy Hero system it was 4.36kWh/degree day.

Similarly for the period 6 Mar 21 to 4 Apr 21 with the old heating system, the consumption was 61kWh/day (6.98kWh/DD) compared to 44.35kWh/day (5.37kWh/DD) with the Boxergy Hero system for the period 1 Mar 22 to 1 Apr 22.

In the summer, the electricity consumption of household B-03 still tended to be high. For the period 6 Jun 21 to 10 Jul 21, the average consumption was 19.15kWh/day with 19.1% off-peak. For another pre-installation summer period from 4 Aug 20 to 4 Sep 20, the consumption was 21.5kWh/day with 35.6% off-peak.

During the summer after the Boxergy Hero installation, there was little change in the average daily consumption, but more of the consumption was shifted to off-peak periods, reducing bills. For example, between 19 May 22 and 29 Jul 22, the average consumption was 21.9kWh/day with 59.4% of the consumption off-peak. Likewise for the period 29 Jul 22 to 1 Sep 22 the average consumption was 19.76kWh/day with 42.86% off-peak.

The Alpha ESS electrical battery installed at household B-03 had a total capacity of 11.4kWh and a usable capacity of 11kWh. Even in summer the average daily consumption for household B-03 was considerably more than the battery capacity, which limited the amount of consumption that could be shifted to off-peak times. For comparison, household B-02 had a typical consumption of 12 to 13kWh/day in summer, which allowed about 90% of the consumption to be shifted to the Economy 7 off-peak tariff.

During colder periods of the heating season, the electricity consumption for household B-03 was still sufficiently large with the Boxergy Hero system that the total consumption could reach 40 to 60kWh/day. Even with the heating system getting to temperature during the off-peak period, the percentage off-peak consumption was often between 34 and 43%.

Start Date	End Date	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Total consumption per Degree Day (kWh/DD)
03-Feb-22	01-Mar-22	26	23.19	16.19	39.38	41.11%	4.36
01-Mar-22	01-Apr-22	31	19.74	24.61	44.35	55.49%	5.37
01-Apr-22	19-May-22	48	14.90	16.46	31.35	52.49%	5.20
19-May-22	29-Jul-22	71	8.90	13.00	21.90	59.36%	10.20
29-Jul-22	01-Sep-22	34	11.29	8.47	19.76	42.86%	38.84
01-Sep-22	28-Sep-22	27	17.96	9.48	27.44	34.55%	12.86
28-Sep-22	28-Oct-22	30	17.50	9.33	26.83	34.78%	7.94
28-Oct-22	27-Nov-22	30	21.57	15.43	37.00	41.71%	6.50
27-Nov-22	19-Dec-22	22	39.55	21.27	60.82	34.98%	4.50
03-Feb-22	19-Dec-22	319	17.16	14.58	31.74	45.95%	6.42

Table 4.36 Electricity consumption for household B-03 during the period 3 Feb 22 to 19 Dec 22 after the Boxergy Hero installation

The level of electricity demand for household B-03 requires either a bigger battery (not cost effective), a solar PV system (to charge the battery, which would be particularly beneficial from March to October) or to be on a time of use tariff with a longer off-peak period.

Economy 10 would be ideal having 3 off-peak periods in a day, typically from 00:00 to 05:00, 13:00 to 16:00 and 20:00 to 22:00. This would allow the battery to charge during the middle of the day, considerably increasing the consumption during off-peak times. Unfortunately, this household at the time of writing was unable to switch to a more advanced time of use tariff as they had a prepayment meter and had problems obtaining a smart meter.

Household B-03 were concerned that their prepayment electricity meter had not been accurately recording their consumption for several years. A Wibeee Box electricity logger was fitted during the project and monitored the household electricity consumption over the period 19 May 22 to 28 Oct 22. The consumption from the meter readings closely matched the consumption derived from the electricity logger which indicated the meter was accurately recording consumption. Further details of the comparison are in Appendix 4.

Figure 4.37 shows a Power Diagram from the Alpha ESS battery portal for Household B-03 on 26 Oct 22. The battery charged on the off-peak tariff from 00:00 to 03:00. After 07:00, the Alpha battery provided power to the home during the peak rate period until it was fully discharged at 18:00. After this time, all power to the home came from the grid.

The heat pump was regularly cutting in and out overnight and during the day in a cycle that lasted about 25 minutes. For example, at 05:30, the household consumption rose from a baseload of about 270W to about 1.3kW, decreasing to around 0.9kW after a few minutes. At 05:55, the heat pump cut out and the cycle was repeated again between 06:22 and 06:47.

One of the residents used the electric shower at 09:00. This could only be partially powered by the Alpha battery with the remaining power coming from the grid. Figure 4.38 shows a plot for the same day from the Wibeee electricity logger. Circuit 1 in yellow shows the household consumption, circuit 2 in blue the consumption by the downstairs sockets and circuit 3 in red shows the consumption by the electric shower.

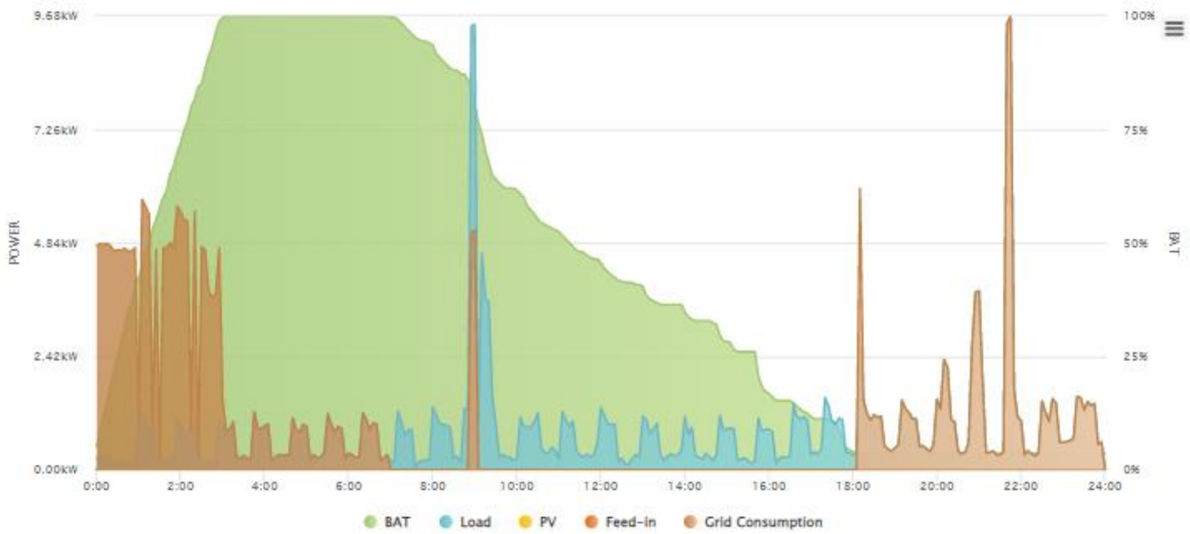


Figure 4.37 Power Diagram from the Alpha ESS battery portal for Household B-03 on 26 Oct 22 Property with Boxergy Hero system with ASHP and electrical battery operational

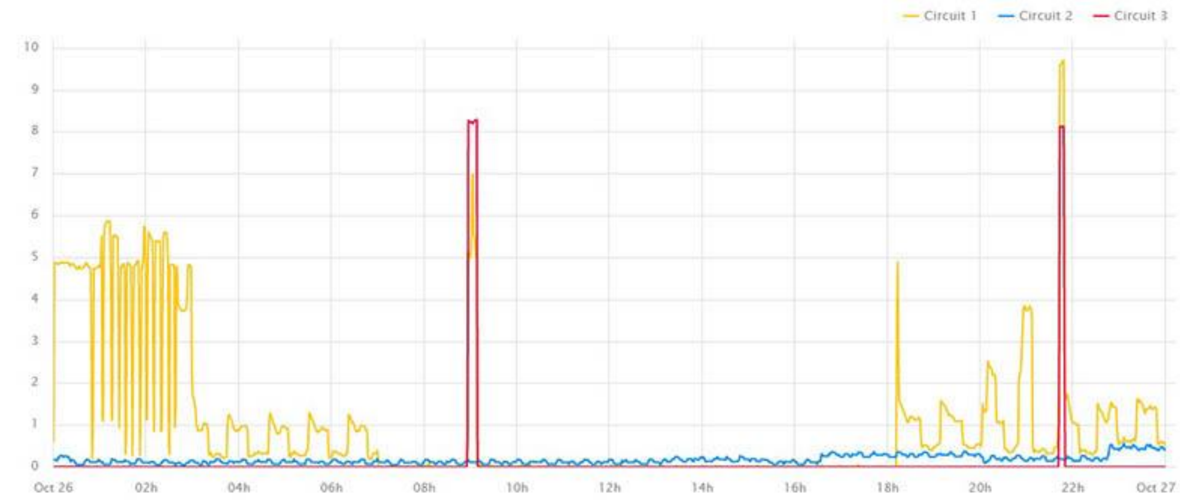


Figure 4.38 Plot of electricity consumption (kW) against time for household B-03 on 26 Oct 22 after the installation of the Boxergy Hero system. Circuit 1 = household consumption, Circuit 2 = downstairs sockets, Circuit 3 = electric shower

On 26 Oct 22, the total electricity consumption of household B-03 was 23.96kWh, with 4.03kWh consumed by the downstairs sockets (including the fridge, TV and games console) and 2.45kWh by the electric shower. The Wibeee electricity logger was fitted before the Boxergy Hero installation and the electric shower was monitored as there was a concern this might be making a significant contribution to the total electricity consumption. It is hoped in the future the Wibeee logger can be reset and the current clamp moved to monitor the consumption of the heat pump.

Figure 4.39 shows a Power Diagram from the Alpha ESS battery portal for household B-03 during colder weather on 3 Mar 22, with the grid consumption estimated to be 48kWh. The battery was able to power the home until it was discharged at 14:25. On a day such as this, the household would have benefited from being on an Economy 10 type tariff.

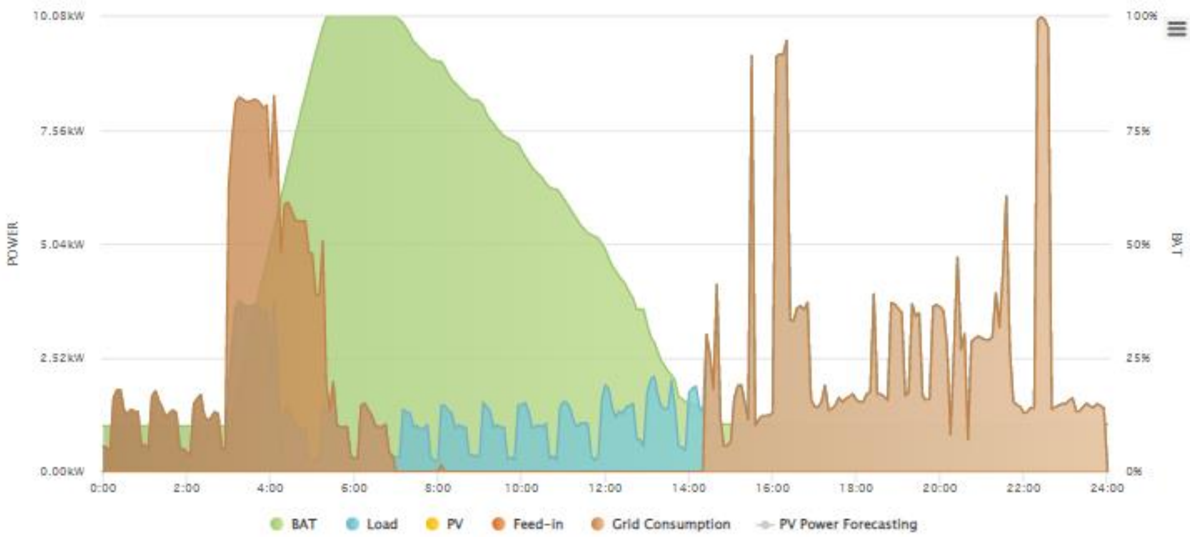


Figure 4.39 Power Diagram from the Alpha ESS battery portal for Household B-03 on 3 Mar 22 Property with Boxergy Hero system with ASHP and electrical battery operational

When the Boxergy Hero system was installed, there was no heating provided in the outhouse which has the washing machine, tumble drier and another room. There was an external door between the main building and the outhouse which is traditionally unheated. The residents sometimes use an oil-filled electric radiator in the additional room in the outhouse to keep it warm with it running for an hour or two a day. The soffits for the outhouse were removed during the Boxergy Hero installation to allow pipes and wiring to be fed into the house. These soffits had not been replaced and so would have led to additional heat loss from the outhouse. North Devon Homes have been informed about this and they will be replaced in 2023.

Table 4.40 shows the electricity costs after the Boxergy Hero installation using the 4 model tariffs. The Economy 7 tariffs were cheaper than the single rate tariff for all the periods shown, however the difference in cost between Tariff 1 and Tariff 3 was often limited.

Looking at the performance during the coldest period after the Boxergy Hero system was installed, between 27 Nov 22 and 19 Dec 22, the average total electricity consumption was 60.82kWh/day during a period when there was on average 13.5 Degree Days each day. During another cold spell between 3 Jan 21 and 2 Feb 21, with the old heating system, household B-03 was using 73.1kWh/day during a period which was on average less cold with 11.6 Degree Days per day.

Comparing the electricity costs during the 2 cold weather periods, between 3 Jan 21 and 2 Feb 21 with the old heating system, the average electricity cost was £24.87/day on Tariff 1 with a single rate and £23.91/day with Tariff 3 on Economy 7. For the period 27 Nov 22 to 19 Dec 22 with the Boxergy Hero system, the cost was lower at £20.68/day on the single rate and £20.07/day on Tariff 3. This indicates that the electricity cost for household B-03 is cheaper in cold weather with the Boxergy Hero system than with their old heating system. The daily costs in winter were still high at over £20/day. There was also limited benefit from being on Tariff 3 compared to the single rate tariff. This is the period when an Economy 10 tariff would be most beneficial, allowing more of the consumption to be shifted to the lower cost off-peak period.

Start	End	Total electricity consumption (kWh/day)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
03-Feb-22	01-Mar-22	39.38	£13.39	£7.51	£12.31	£11.42
01-Mar-22	01-Apr-22	44.35	£15.08	£7.69	£12.06	£10.73
01-Apr-22	19-May-22	31.35	£10.66	£5.55	£8.79	£7.90
19-May-22	29-Jul-22	21.90	£7.45	£3.70	£5.72	£5.02
29-Jul-22	01-Sep-22	19.76	£6.72	£3.73	£6.08	£5.62
01-Sep-22	28-Sep-22	27.44	£9.33	£5.45	£9.09	£8.56
28-Sep-22	28-Oct-22	26.83	£9.12	£5.32	£8.87	£8.35
28-Oct-22	27-Nov-22	37.00	£12.58	£7.03	£11.51	£10.66
27-Nov-22	19-Dec-22	60.82	£20.68	£12.04	£20.07	£18.88
03-Feb-22	19-Dec-22	31.74	£10.79	£5.87	£9.49	£8.69

Table 4.40 Electricity consumption and costs for household B-03 using example electricity tariffs, during the period 3 Feb 23 to 19 Dec 22 after the Boxergy Hero system was installed

4.5. Household B-04

Household B-04 lived in a 2-bedroom semi-detached bungalow. There were originally 6 traditional storage heaters in the property. Only the storage heater in the hallway, a 2.55kW Dimplex XL18N (which stored up to 17.85kWh) and the small storage heater in the bathroom (a Dimplex XL6N, storing up to 5.95kWh) were normally used in winter. In the living room, the residents used a peak rate electric fire instead of the storage heater. The residents noted there were draughts from the back door and windows.

The storage heaters were removed and the wet central heating system was installed during December 2021 and the first week in January 2022. The Boxergy Hero system was commissioned on 28 Jan 22. This meant that during most of January, the household relied on supplementary electric heating. Although the heat pump and heat battery were operational from the end of January, there were issues with the electrical battery installation which meant it was not fully operational until the end of August 2022.

4.5.1. Pre-installation period for household B-04

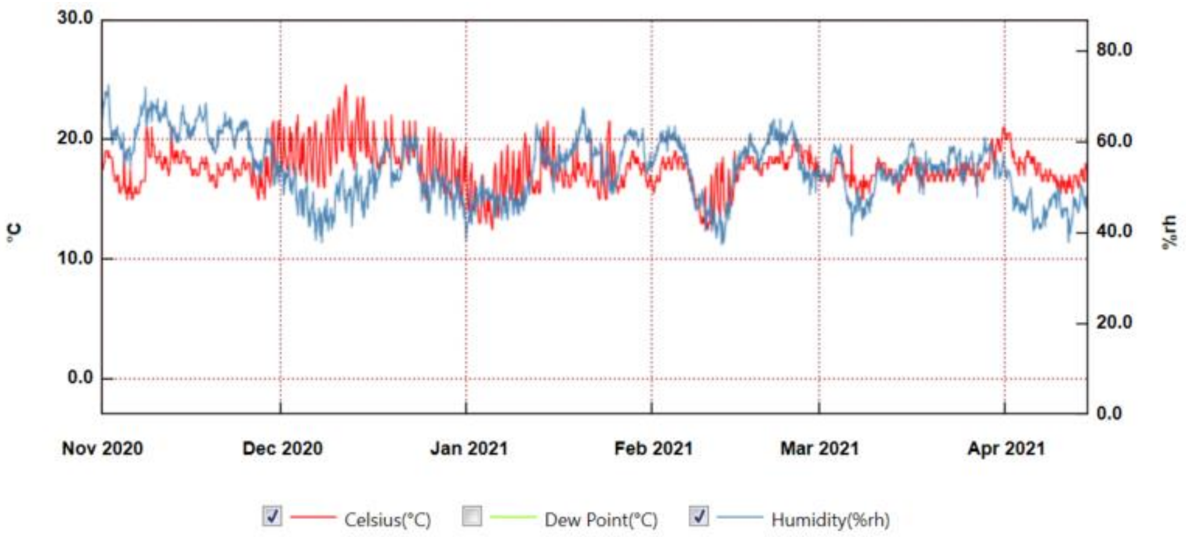


Figure 4.41 Graph of living room temperature and relative humidity for household B-04 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

A graph of living room temperature and relative humidity is shown for household B-04 for the pre-installation heating season. The graph shows longer term variation in the living room temperature as a result of periods of cold weather. From 3 to 5 Nov 20 the daily Degree Days exceeded 10. For the period 27 Dec 20 to 10 Jan 21, there were between 10- and 17-Degree Days each day. A period with particularly cold weather occurred from 5 to 14 Feb 21 where there were between 10- and 18-Degree Days each day. These periods of cold weather corresponded to the significant dips in living room temperature on the graph.

The daily temperature range was higher between late November and mid-January. This was likely to correspond to increased use of the electric fire in the living room during the coldest weather.

The average living room temperature over the period was 17.54˚C. The lowest temperature recorded was 12.5˚C at 07:30 on 5 Jan 21, during one of the cold weather spells. The average living room temperature was slightly higher during the early evening (17:00 to 21:00) at 18.25˚C. Since the residents were older and had health conditions, the heating did not maintain the living room at a suitable temperature.

The living room reached a maximum temperature of 24.5˚C on 11 Dec 20 at 21:00. The average relative humidity was 54.03% and the humidity ranged from 37.5% to 72.5% over the analysis period.

The bedroom temperature and humidity showed similar characteristics to the living room. A graph with the same analysis period is shown in Appendix 5. The average bedroom temperature was slightly colder at 17.18˚C. The bedroom also experienced a wide temperature range during the analysis period, going from a particularly cold 11.5˚C on 9 Feb 21 at 14:30 to a maximum of 22.5˚C at 16:30 on 11 Dec 20. The average bedroom relative humidity of 56.65% was comparable to the living room average of 54.03%.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	17.54	24.5	12.5	1.63	54.03	72.5	37.5	6.81
Living Room 17:00 - 21:00	18.25	24.5	13.0		54.08	71.0	38.0	
Bedroom 24 hours	17.18	22.5	11.5	1.53	56.65	77.5	34.5	7.31
Bedroom 17:00 - 21:00	17.53	22.5	11.5		56.05	75.0	38.5	

Table 4.42 Household B-04 temperature and relative humidity between 1 Nov 20 and 15 Apr 21 Property with storage heaters before Boxergy Hero installation

During the year before the Boxergy Hero installation, from 1 Dec 20 to 30 Nov 21, household B-04 used a total of 12,354 kWh of electricity, with 32.5% coming from the off-peak tariff. Table 4.43 shows the average monthly peak and off-peak consumption.

An Energy Performance Certificate (EPC) lodged when the property had the storage heaters estimated the space heating demand to be 7,506kWh and the water heating demand to be 1,651kWh, making a total of 9,157kWh. The earlier discussion on room temperatures showed that there was an inadequate level of thermal comfort in the home. This was despite the electricity consumption being considerably higher than the heating demand for the property.

The average electricity consumption was in the range 31 to 53kWh/day during the heating season from November to May. From June to September the consumption was a more moderate 13 to 21 kWh/day. In summer, the off-peak consumption was typically 5 to 7kWh/day, which was likely to be due to use of the immersion water heater and the baseload electricity consumption from appliances like the fridge-freezer and freezer. The washing machine was typically used twice a week and the tumble drier twice a week in winter. The electric shower was typically used twice daily. An 8kW shower used for 15 minutes a day could use about 2kWh of electricity. Monitoring of the shower for household B-03 with a Wibeee electricity logger showed the shower using 2.45kWh on 26 Oct 22.

In January 2021, the average off-peak consumption was 12.4kWh/day and the peak rate consumption was 36.87kWh/day. There was limited use of the storage heaters, which accounted for the low off-peak consumption. Figure 4.44 shows a plot of electricity consumption (in milliamps) between 5 Jan 21 and 10 Jan 21. The majority of the consumption was during peak rate times, with a wide peak of 10 to 11.7A on several days.

On 5 Jan 21, the consumption was at least 11.6A between 12:15 and 21:45, with the consumption going as high as 47.6A when the electric shower was used. It is possible that a 2.5kW peak rate electric heater was used that day for about 9.5 hours. This might have consumed about 23.75kWh, close to half the average daily consumption in January. There were other periods of extended use of peak rate heaters during the other days shown in figure 4.44. The peaks above 47.6A confirm the regular use of the electric shower.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Dec-20	31	39.67	13.37	53.03	25.20%	312.4	5.26
Jan-21	31	36.87	12.40	49.27	25.17%	366.2	4.17
Feb-21	28	36.07	16.44	52.51	31.31%	301.0	4.88
Mar-21	31	32.30	16.72	49.02	34.10%	284.1	5.35
Apr-21	30	29.05	16.02	45.08	35.55%	284.5	4.75
May-21	31	20.80	12.25	33.05	37.05%	203.9	5.02
Jun-21	30	13.60	7.46	21.06	35.43%	58.6	10.78
Jul-21	31	9.71	5.98	15.69	38.13%	30.4	16.00
Aug-21	31	7.89	5.43	13.32	40.77%	46.7	8.84
Sep-21	30	11.23	6.04	17.26	34.96%	52.0	9.96
Oct-21	31	16.89	9.73	26.63	36.56%	121.0	6.82
Nov-21	30	20.77	10.61	31.38	33.81%	246.0	3.83
Year	365	22.843	11.004	33.847	32.51%	2306.8	5.36

Table 4.43 Monthly electricity consumption from Dec 2020 to Nov 2021 for household B-04, before the Boxergy Hero installation

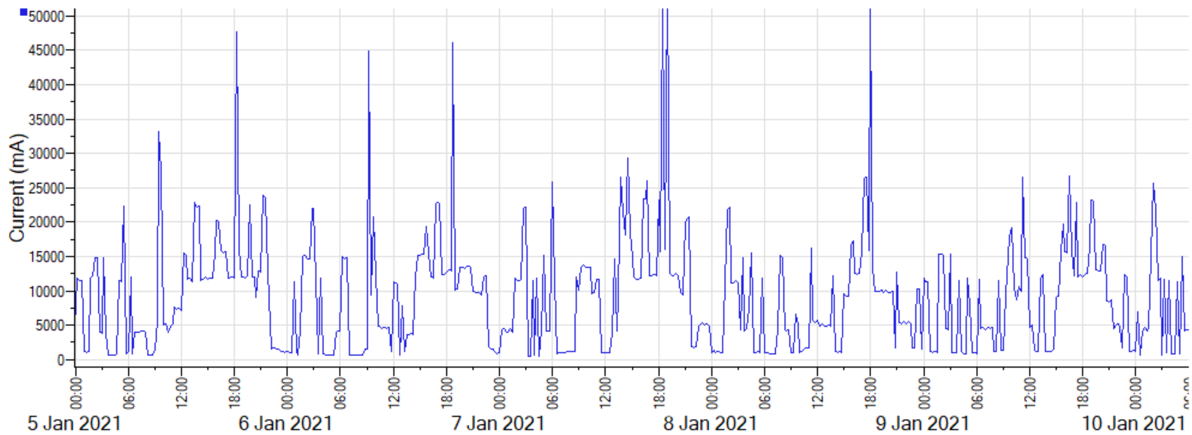


Figure 4.44 Electricity consumption for household B-04 between 5 Jan 21 and 10 Jan 21 Property with storage heaters before the Boxergy Hero installation

The electricity consumption of Household B-04 before the Boxergy Hero system was installed was higher than for the similar sized bunglows for households B-01 and B-02. At times, the pre-installation consumption was close to that for household B-03, where the property was a house of nearly double the floor area. For example the average total consumption between 1 Dec 20 and 3 Jan 21 for household B-03 was 58.76kWh/day compared to 53.03kWh/day in December for household B-04. Household B-04 used the heating for a greater proportion of the year than for some of the other households due to needing to keep warmer because of health conditions.

Table 4.45 shows the electricity costs for household B-04 using the model electricity tariffs. During this period before the Boxergy Hero system was installed, the household was on an Economy 7 tariff which was comparable to Tariff 2, which meant the costs at the time were considerably lower than those modelled with Tariffs 1, 3 and 4. The other tariffs were examples available during the period of the Energy Price Guarantee between 1 Oct 22 and 31 Mar 23 after high rises in energy prices.

During Dec 20 and Jan 21, the average daily cost on the single rate Tariff 1 was cheaper than Economy 7 tariffs 3 and 4. This was because of the high electricity consumption during the peak rate times though use of peak rate electric heaters. In February the single rate tariff was still £0.02/day cheaper than Tariff 3 as the percentage of off-peak consumption was just below the threshold for that Economy 7 tariff to be more economic. Between Mar 21 and Nov 21, tariffs 3 and 4 were cheaper than the single rate tariff 1. This was because the peak rate consumption had decreased with reduced or no use of peak rate electric heating, while there was still off-peak consumption due to the immersion water heater.

Looking at the year as a whole, the average cost per day was only slightly cheaper on Tariffs 3 and 4 compared to the single rate tariff. Household B-04 would have saved £0.10/day by being on Tariff 3 and £0.72/day being on tariff 4 compared to the single rate tariff. This was a relatively low saving on an average cost of over £10/day. In order to make greater savings on the time of use tariff, the percentage off-peak consumption needed to be higher, with less use of electric heating during peak rate times.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Dec-20	53.03	25.20%	£18.03	£11.12	£18.97	£18.20
Jan-21	49.27	25.17%	£16.75	£10.34	£17.63	£16.91
Feb-21	52.51	31.31%	£17.85	£10.63	£17.87	£16.95
Mar-21	49.02	34.10%	£16.67	£9.76	£16.30	£15.36
Apr-21	45.08	35.55%	£15.33	£8.90	£14.80	£13.91
May-21	33.05	37.05%	£11.24	£6.46	£10.71	£10.03
Jun-21	21.06	35.43%	£7.16	£4.16	£6.92	£6.51
Jul-21	15.69	38.13%	£5.34	£3.05	£5.04	£4.71
Aug-21	13.32	40.77%	£4.53	£2.55	£4.18	£3.88
Sep-21	17.26	34.96%	£5.87	£3.42	£5.70	£5.36
Oct-21	26.63	36.56%	£9.05	£5.22	£8.67	£8.13
Nov-21	31.38	33.81%	£10.67	£6.26	£10.46	£9.87
Year	33.85	32.51%	£11.51	£6.80	£11.41	£10.79

Table 4.45 Electricity consumption and costs for household B-04 using example electricity tariffs, between 1 Dec 20 and 30 Nov 21, before the Boxergy Hero system was installed

4.5.2. Post-installation period for household B-04

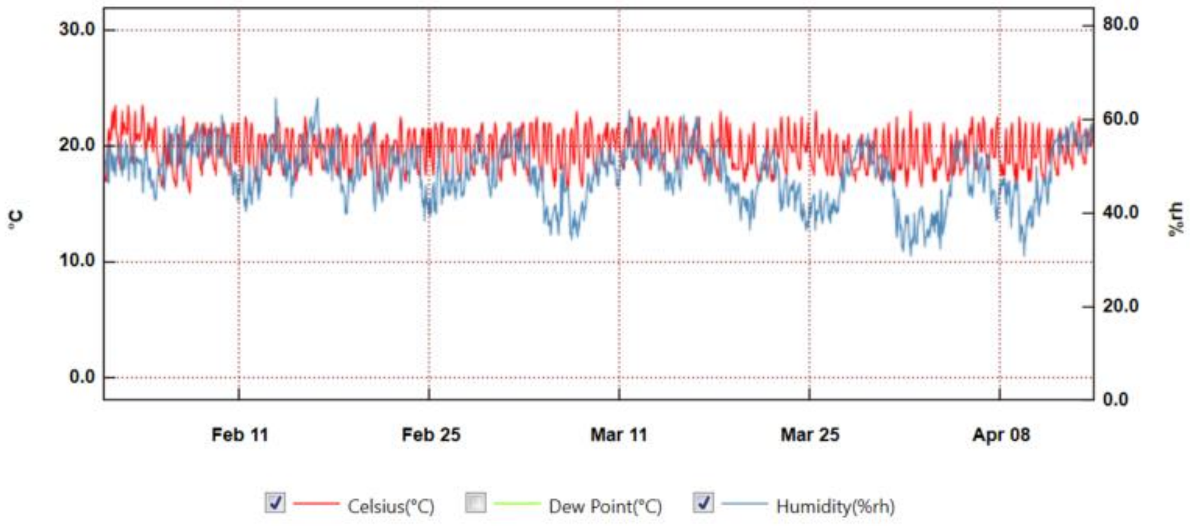


Figure 4.46 Graph of living room temperature and relative humidity for household B-04 from 1 Feb 22 to 15 Apr 22, after the Boxergy Hero installation

The Boxergy Hero system was commissioned on 28 Jan 22, however the Alpha ESS battery system was not operating correctly until the end of August. This meant that during the Spring of 2022, the system was operating with just the Vaillant aroTHERM plus heat pump and the Sunamp heat battery.

Figure 4.46 shows that there was a consistent pattern of temperature between the beginning of February and middle of April 2022 after the Boxergy Hero system was installed. There was a daily rise and fall in temperature, with the living room temperature decreasing overnight. The living room temperature was no longer strongly affected by the external temperature, with the room temperature colder during periods of colder weather. As an illustration of the daily rise and fall in temperature, on 25 Feb 22, the temperature fell to 17.5˚C by 08:00, but increased back to 19.5˚C by 09:00. The temperature remained in the range 19.0 to 22.0˚C for the rest of the day.

The average living room temperature increased by more than 2˚C, from 17.54˚C during the 2020/21 heating season to 19.68˚C after the heat pump was operational. During the period 17:00 to 21:00 it was a warmer 20.35˚C. The new heating system also ensured the room temperature fell to a minimum of only 16.0˚C instead of a much colder 12.5˚C the year before with the old heating system.

The average relative humidity of the living room was 48.62% after the Boxergy Hero system was operational compared to 54.03% with the old heating system. There was also a fall in the maximum humidity from 72.5% with the old heating system to 64.5% with the heat pump. The relative humidity was in the optimum 40 to 60% range for the majority of the time, but there were times when conditions were too dry where the humidity was below 40%.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	19.68	23.5	16.0	1.56	48.62	64.5	31.0	5.95
Living Room 17:00 - 21:00	20.35	23.5	17.5		48.83	64.5	31.0	
Bedroom 24 hours	19.59	23.0	16.0	1.15	49.61	61.0	34.0	4.99
Bedroom 17:00 - 21:00	19.63	22.5	17.0		49.44	61.0	36.0	

Table 4.47 Household B-04 temperature and relative humidity between 1 Feb 22 and 15 Apr 22 Property with storage heaters before Boxergy Hero installation

A graph of the bedroom temperature and relative humidity is provided in Appendix 5. This showed strong similarities to the graph for the living room. The values of temperature and relative humidity in table 4.47 are similar, providing further evidence of whole house heating.

The average bedroom temperature was 19.59˚C after the new heating system was running, a temperature increase of 2.4˚C compared to the previous heating season with the old heating system. The average relative humidity was 49.6% compared to 56.65% during the previous heating season.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Feb-22	28	22.80	5.99	28.79	20.81%	249.7	3.23
Mar-22	31	19.20	6.05	25.24	23.96%	256.0	3.06
Apr-22	30	14.88	6.41	21.30	30.10%	220.6	2.90
May-22	31	11.62	4.73	16.35	28.94%	120.1	4.22
Jun-22	30	9.90	4.04	13.94	29.01%	73.4	5.70
Jul-22	31	8.94	9.83	18.76	52.38%	29.4	19.78
Aug-22	31	10.37	5.70	16.07	35.48%	15.9	31.33
Sep-22	30	6.96	7.67	14.63	52.43%	73.9	5.94
Oct-22	31	9.01	9.16	18.17	50.40%	93.7	6.01
Nov-22	30	7.54	14.07	21.61	65.09%	198.6	3.26
Full period	303	12.05	7.37	19.42	37.96%	1331.3	4.42

Table 4.48 Monthly electricity consumption from 1 Feb 2022 to 30 Nov 2022 for household B-04, after the Boxergy Hero installation

The average electricity consumption of household B-04 after the Boxergy Hero system was fitted was 19.42kWh/day over the period 1 Feb 22 to 30 Nov 22. During the equivalent period the year before, the average electricity consumption was 30.3kWh/day with the old heating system. This amounted to a 36% reduction in electricity consumption after the Boxergy Hero system was installed. However, the analysis period in 2021 was colder with 1628.2 Degree Days compared to 1331.3 Degree Days between 1 Feb 22 and 30 Nov 22. Taking external temperature into account, the consumption fell from 5.64kWh/degree day with the old heating system to 4.42kWh/degree day with the new heating system, a reduction of 21.65%.

Comparing the average total electricity consumption per month (kWh/day) before and after the Boxergy Hero installation, the consumption was lower after the installation for each month apart from July and August. The heat pump and heat battery were operational from 28 Jan 22, but there were issues with the electrical battery. The battery was able to charge and discharge following a service visit in July, however the current clamp for the battery was unable to measure the full household load due to the arrangement of the wiring between the electricity meter and the consumer units. This led the battery to charge and then rapidly discharge, exporting electricity to the grid. After the issue was discovered, part way through August, the battery was stopped from discharging to avoid exporting electricity. It was only after the 24 hour and heating circuit consumer units were replaced by a single consumer at the end of August 2022 and the battery current clamp was able to measure the full household consumption that the battery was able to operate correctly.

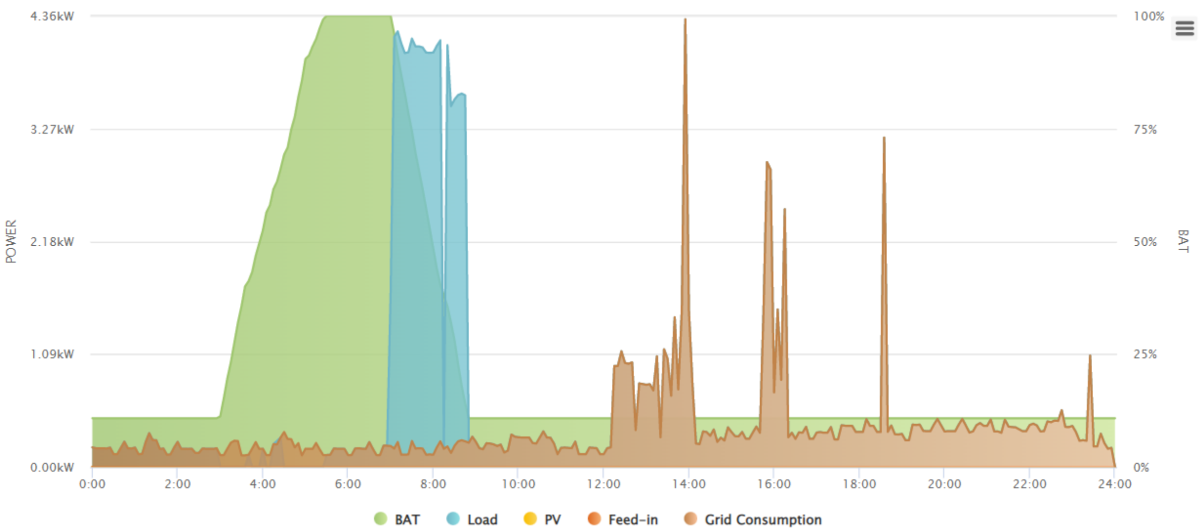


Figure 4.49 Power Diagram from the Alpha ESS battery portal for Household B-04 on 20 Jul 22, where the full household load was not measured and the battery rapidly discharged

Figure 4.49 for household B-04 shows the Power Diagram for the Alpha ESS battery on 20 Jul 22 during the period when the battery current clamp was unable to measure the full household load. The graph does not show the grid consumption due to the battery charging between 03:00 and 05:30. After 07:00, the battery was able to discharge, reaching the minimum of 10.8% before 09:00. Similar behaviour occurred on a daily basis until the battery was maintained at a charge level in mid-August.

On 18 Nov 22, a reading for electricity exported to the grid was obtained from the household smart meter. Since the system was installed, the electricity exported to the grid had been 249.0kWh. It is likely that most of this export occurred in July and August 2022. This would account for the higher average consumption in these months compared to June and September. Assuming a cost for off-peak electricity of 14.6p/kWh, the value of the electricity exported was £36.35.

A Power Diagram for the battery on 15 Nov 22 is shown in figure 4.50 with the battery operating correctly. The battery started charging at midnight and was fully charged by 02:50. The grid consumption (shown in brown) was about 4.7kW during this period.

The smart thermostat for the heat pump was set to 20˚C, with a heating time between 05:00 and 11:00 in the morning and between 16:00 and 20:00 in the afternoon/evening. The heat pump had a series of cycles where it operated for about 25 minutes, taking the electricity consumption above 1kW. These began from 05:15 with the last morning cycle completed by 10:55. Further cycles began in the afternoon from 16:05, with higher consumption during the first cycle. This might be due to the heat pump working harder to bring the house up to temperature or due to also needing to provide heat for the heat battery. The electrical battery was fully discharged by 18:45, but there were periods where additional electricity was required from the grid before that.

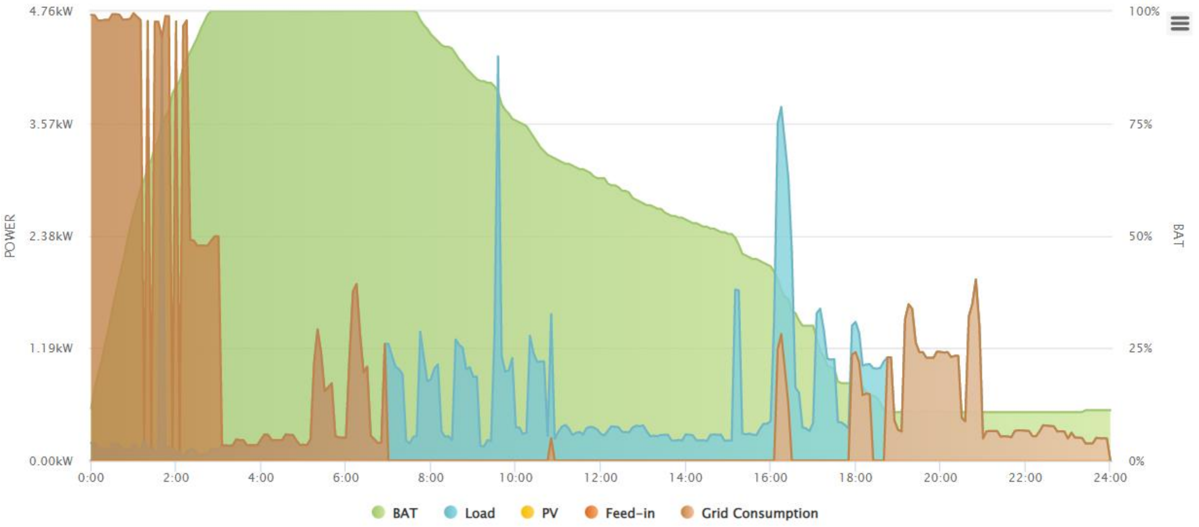


Figure 4.50 Power Diagram from the Alpha ESS battery portal for Household B-04 on 15 Nov 22 Property with Boxergy Hero system with ASHP and electrical battery operational

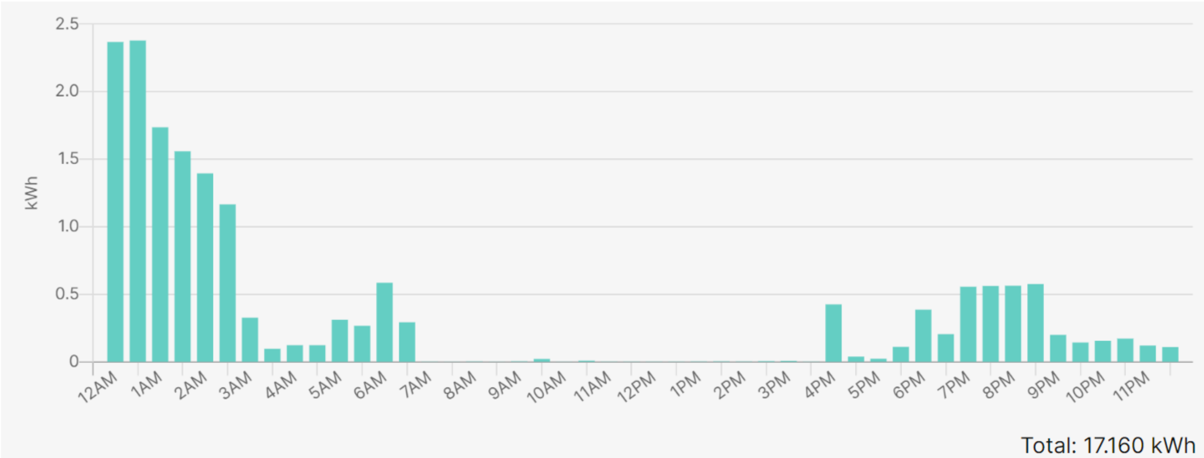


Figure 4.51 Half-hourly electricity consumption from Carbon Coop PowerShaper monitor portal for household B-04 on 15 Nov 22 after the Boxergy Hero installation

Figure 4.51 shows a plot of half-hourly electricity consumption on 15 Nov 22 from smart meter data for comparison. The maximum half-hourly consumption recorded by the smart meter that day was 2.378kWh for the half hour after 00:30. From 07:00 until 16:00, grid consumption was very low due to power being supplied by the battery. The half-hourly consumption was between 0.002 and 0.009 kWh for these periods apart from the half hour after 09:30 when it was 0.021kWh due to a short spike in grid consumption.

The electricity cost per month after the Boxergy Hero installation is shown in table 4.52 for the 4 model electricity tariffs. Between 1 Feb 22 and 5 Jul 22, the electrical battery was not charging and discharging. As a result, during this period, the system was effectively operating as an air-source heat pump without an electrical battery. This led the percentage off-peak consumption to be low at 20.81 to 30.1%. Most households with air-source heat pumps will be on a single rate tariff and the single rate Tariff 1 was cheaper than the Economy 7 Tariff 3 for the months February to June. This was because the percentage off-peak consumption for Tariff 3 to become cheaper was 31.45%. Economy 7 Tariff 4 was more expensive than single rate Tariff 1 in February and March, but was cheaper in all other months.

In July, the percentage off-peak consumption was high at 52.38% due to the battery charging daily, with some of the discharge going to the grid. This meant the Economy 7 tariffs were all cheaper than the single rate. In August once the issue with the battery was discovered, the battery was stopped from charging and discharging and this led the percentage off-peak consumption to drop. The level was high enough however for the Economy 7 tariffs to all be cheaper than the single rate tariff.

From September, once the Alpha ESS battery was operating correctly, the percentage off-peak consumption was above 50%. This led to larger differences in cost between the single rate tariff and Economy 7 tariffs. For example in November, the daily average cost on single rate Tariff 1 was £7.35/day compared to £6.24 on Econony 7 Tariff 3. Over the full period analysed since the Boxergy Hero system was installed, Economy 7 tariff 3 came out cheaper than single rate Tariff 1 (£6.24/day compared to £6.60/day) despite the battery only running correctly since September.

The costs were cheaper that the equivalent period the year before with the old heating system. For Economy 7 Tariff 3, the cost from February to November was £10.00/day with the old heating system and £6.24/day with the new heating system. It should be noted however that the weather was colder for the period with the old heating system, with 1628.2 Degree Days between 1 Feb 21 and 30 Nov 21 compared to 1331.3 Degree Days between 1 Feb 22 and 30 Nov 22.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Feb-22	28.79	20.81%	£9.79	£6.19	£10.66	£10.30
Mar-22	25.24	23.96%	£8.58	£5.33	£9.12	£8.77
Apr-22	21.30	30.10%	£7.24	£4.34	£7.32	£6.96
May-22	16.35	28.94%	£5.56	£3.36	£5.68	£5.41
Jun-22	13.94	29.01%	£4.74	£2.86	£4.84	£4.61
Jul-22	18.76	52.38%	£6.38	£3.32	£5.27	£4.74
Aug-22	16.07	35.48%	£5.46	£3.17	£5.28	£4.96
Sep-22	14.63	52.43%	£4.98	£2.59	£4.11	£3.69
Oct-22	18.17	50.40%	£6.18	£3.26	£5.20	£4.71
Nov-22	21.61	65.09%	£7.35	£3.50	£5.29	£4.54
Full period	19.42	37.96%	£6.60	£3.78	£6.24	£5.84

Table 4.52 Electricity consumption and costs for household B-04 using example electricity tariffs, between 1 Feb 22 and 30 Nov 22, after the Boxergy Hero system was installed

4.6. Household B-05

Household B-05 lived in a 2-bedroom semi-detached bungalow, which was connected to the bungalow where household B-04 lived. At the start of the project, the property had storage heaters in the living room, hall and 2 bedrooms. There were also panel heaters in the kitchen and outhouse.

The storage heater in the living room was a Dimplex CXL24N traditional storage heater with manual input charge control which was used daily in winter. This had an input rating of 3.4kW and a maximum storage capacity of 23.8kWh. It also had a built-in convector heater which was thermostatically controlled with an output of 2kW and could be turned on with a boost/on-off switch. The resident mainly used the living room and used the convector heater or other supplementary heating in the evening after the storage heater had gone cold.

The storage heater in the hallway was used daily in winter and this provided heat to the rest of the house. It was a Dimplex XLN18N traditional storage heater which had an input of 2.55kW. If this charged for the full 7 hours on Economy 7, it would use up to 17.85kWh of electricity. The bedroom was unheated and the immersion heater for the hot water cylinder was not used every day.

Installation of the new heating system began during the first week of January 2022, when the old storage heaters were removed and the new wet central heating system was installed. The resident used supplementary electric heating until the Boxergy Hero system was installed in late January, with the system commissioned on 28 Jan 22.

During Storm Eunice on 18 Feb 22, the outhouse roof of the bungalow blew off. The consumer unit for the bungalow was in the outhouse and the resident had to move out until the roof could be replaced. He returned home on 27 Feb 22 and used supplementary electric heating until a service visit for the Boxergy Hero unit on 8 Mar 22. A mixer shower was also fitted at the property at this time. This should save the resident money as the electricity cost of heating water by the heat pump at off-peak times is lower than from using an electric shower during the peak rate period.

The Alpha ESS battery was not operational until 5 Jul 22. Prior to this, the Alpha ESS portal was not showing grid consumption and the battery was not charging or discharging. There may have been an issue with the current clamps for the battery and/or settings on the battery. This means that during the period February to June, the system was operating just as an air-source heat pump, but after 5 Jul 22, the household was able to benefit from the battery charging using low-cost off-peak electricity and supplying this to the home during the period of expensive peak rate electricity.

There was a multifuel stove with a back boiler in the living room of household B-05 until 2001. In order to provide ventilation for the stove, an air vent had been fitted, but it was no longer required after the stove was removed. The vent caused draughts and was blocked up in December 2022. There was a similar vent in the bungalow for household B-04, but this was blocked in Spring 2022.

4.6.1. Pre-installation period for household B-05

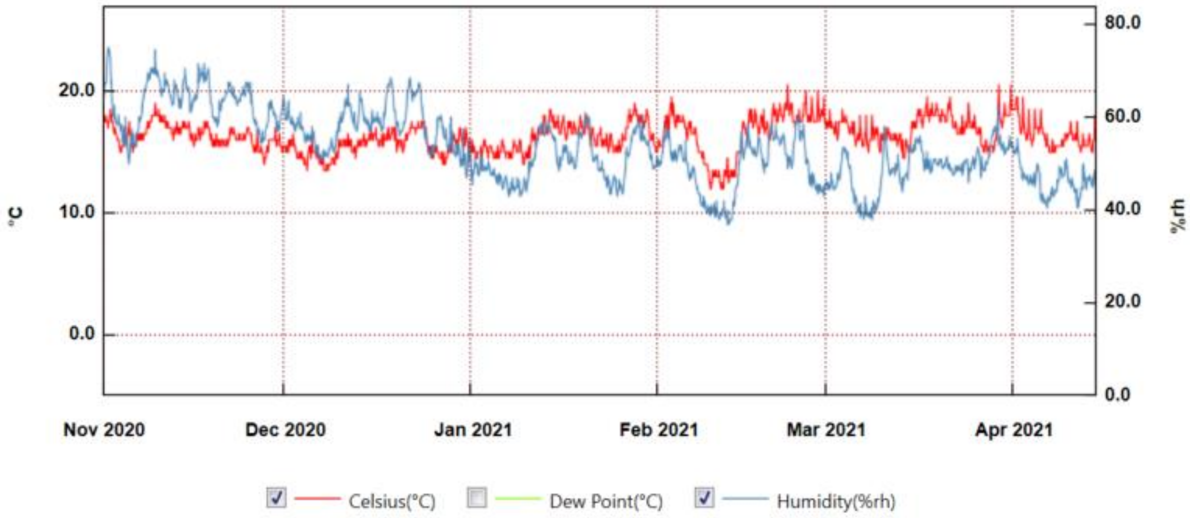


Figure 4.53 Graph of bedroom temperature and relative humidity for household B-05 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

The bedroom in the property at the start of the project was unheated and relied on heat from the rest of bungalow. There was little variation in the room temperature during a day. However, the room temperature was affected by the external temperature and dipped to as low as 12.0˚C at 20:30 on 9 Feb 21 during a period of particularly cold weather. The average bedroom temperature was 16.33˚C and the maximum temperature during the analysis period was 20.5˚C on 22 Feb 21. The average relative humidity was 53.24% and the humidity in the bedroom ranged from 37.0 to 75.0%.

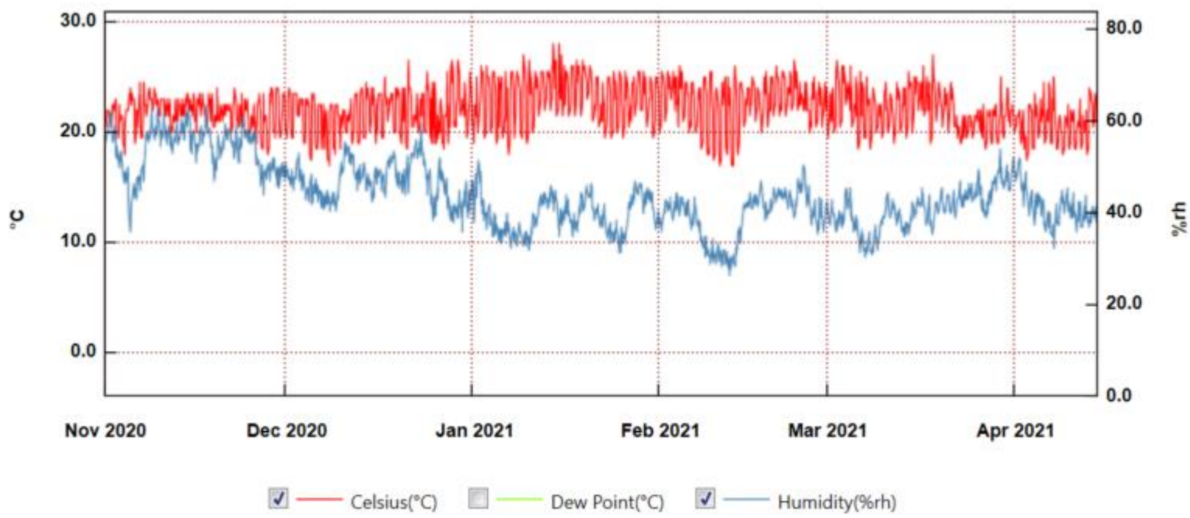


Figure 4.54 Graph of living room temperature and relative humidity for household B-05 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

The average temperature of the living room was 5.81˚C warmer than the bedroom at 22.14˚C. During the early evening, between 17:00 and 21:00, the average living room temperature was over a degree warmer at 23.33˚C. The temperature ranged between 17.0 and 28.0˚C over the monitoring period. There was a wide daily temperature range as the room was heated and cooled down, with the temperature range largest during cold weather periods, such as mid-February, with lower minimum temperatures.

The average relative humidity in the living room was 43.97%, nearly 10% lower than for the bedroom. While the average is within the optimum range for humidity of 40 to 60%, during the monitoring period the humidity went as low as 26.5%. When the air becomes too dry there can be health impacts affecting the eyes, skin and respiratory tract[21].

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	22.14	28.0	17.0	1.97	43.97	63.5	26.5	6.97
Living Room 17:00 - 21:00	23.33	27.0	19.0		44.49	62.5	26.5	
Bedroom 24 hours	16.33	20.5	12.0	1.29	53.24	75.0	37.0	7.55
Bedroom 17:00 - 21:00	16.32	20.5	12.0		53.28	74.5	37.0	

Table 4.55 Household B-05 temperature and relative humidity between 1 Nov 20 and 15 Apr 21 Property with storage heaters before Boxergy Hero installation

Over the 12 month period 1 Jul 20 to 30 Jun 21, household B-05 used 12,896kWh or an average of 35.33kWh/day (see table 4.56). This period had 2359.9 Degree Days and the average consumption per Degree Day was 5.46kWh/DD. For comparison, household B-04 used 12,354kWh over a 12 month period with 2306.8 Degree Days, with an average consumption of 5.36kWh/DD.

Both households B-04 and B-05 had older reasidents with health conditions who felt the cold more and required greater heating. While the total consumption between the 2 households was similar, the percentage off-peak consumption for household B-05 was higher at 57.35% compared to 32.51% for household B-04 in the pre-installation period. This was due to greater use of the storage heaters by household B-05.

The coldest month during this pre-installation monitoring was January 2021 and household B-05 used on average 64.97kWh/day, with 56.24% of the consumption on the off-peak rate. The monthly average peak rate consumption in the period 1 Nov 20 to 31 Mar 21 was in the range 19.38 to 28.43kWh/day. This higher level of peak rate consumption during the colder months were an indication of supplementary electric heating. During the summer when no heating was required, the peak rate consumption was in the range 3.75 to 6.48kWh/day.

Figures 4.57 (a) and (b) show the heating circuit and 24 hour circuit electricity consumption of household B-05 between 1 Jan 21 and 6 Jan 21 measured using Tinytag View 2 data

[21] A.V Arundel, E.M. Sterling, J.H. Biggin and T.D. Sterling, (1986) 'Indirect Health Effects of Relative Humidity in Indoor Environments', Environmental Health Perspectives, Vol. 65, 351-361 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/pdf/envhper00436-0331.pdf (Accessed 5 Jan 23)

loggers with current clamps. There was daily use of the storage heaters with a consistent consumption of about 21,000mA (about 5.0kW) for around 4.5 hours overnight with a further consumption of about 10,000mA (about 2.4kW) for about another hour.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Jul-20	31	5.20	3.88	9.08	42.75%	44.1	6.38
Aug-20	31	3.75	3.89	7.64	50.89%	32.1	7.38
Sep-20	30	6.00	7.96	13.96	56.99%	81.6	5.13
Oct-20	31	12.89	20.95	33.84	61.91%	178.1	5.89
Nov-20	30	19.38	23.81	43.19	55.13%	213.3	6.07
Dec-20	31	26.39	26.00	52.39	49.63%	312.4	5.20
Jan-21	31	28.43	36.54	64.97	56.24%	366.2	5.50
Feb-21	28	25.86	36.19	62.05	58.32%	301.0	5.77
Mar-21	31	19.56	31.66	51.22	61.81%	284.1	5.59
Apr-21	30	15.62	23.23	38.86	59.79%	284.5	4.10
May-21	31	11.90	22.73	34.63	65.63%	203.9	5.27
Jun-21	30	6.48	7.23	13.71	52.75%	58.6	7.02
Year	365	15.07	20.26	35.33	57.35%	2359.9	5.46

Table 4.56 Monthly electricity consumption from Jul 2020 to Jun 2021 for household B-05, before the Boxergy Hero installation

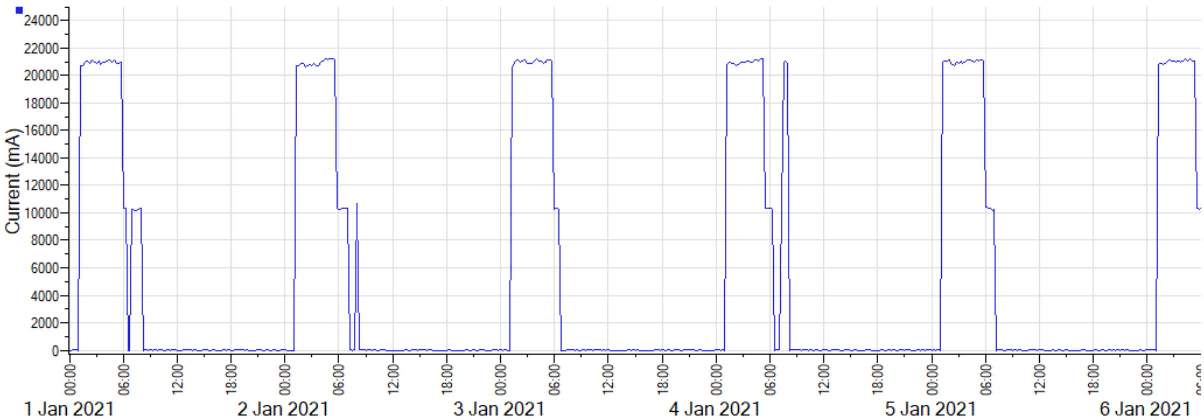


Figure 4.57 (a) Heating circuit consumption for household B-05 between 1 Jan 21 and 6 Jan 21 Property with storage heaters before the Boxergy Hero installation

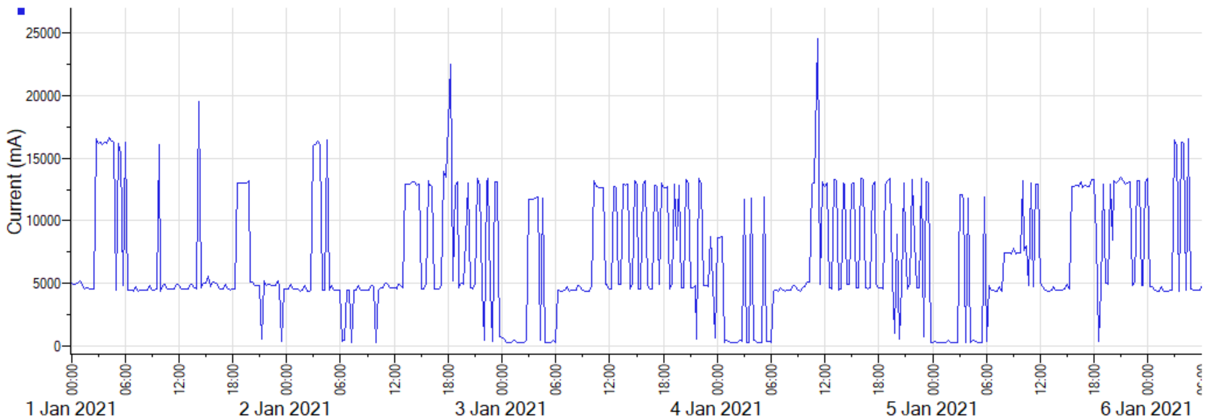


Figure 4.57 (b) 24-hour electricity circuit consumption for household B-05 between 1 Jan 21 and 6 Jan 21. Property with storage heaters before the Boxergy Hero installation

There was a consistent consumption of at least 4,600mA on the 24-hour electricity circuit (figure 4.57 (b)) for most of the period 1 Jan 21 to 6 Jan 21. This was likely to be due to a 1kW electric heater with no thermostatic control. There were regular additional peaks in consumption on 2, 3 and 4 Jan 21. These took the total peak rate consumption to about 13,000mA are were likely to be due to a 2kW electric heater were thermostatic control. This may have been the panel heater with the Dimplex CXL24N.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Jul-20	9.08	42.75%	£3.09	£1.71	£2.80	£2.58
Aug-20	7.64	50.89%	£2.60	£1.37	£2.18	£1.97
Sep-20	13.96	56.99%	£4.75	£2.40	£3.74	£3.31
Oct-20	33.84	61.91%	£11.51	£5.61	£8.59	£7.46
Nov-20	43.19	55.13%	£14.68	£7.51	£11.79	£10.50
Dec-20	52.39	49.63%	£17.81	£9.45	£15.12	£13.70
Jan-21	64.97	56.24%	£22.09	£11.21	£17.53	£15.56
Feb-21	62.05	58.32%	£21.10	£10.55	£16.38	£14.43
Mar-21	51.22	61.81%	£17.41	£8.49	£13.01	£11.31
Apr-21	38.86	59.79%	£13.21	£6.54	£10.09	£8.84
May-21	34.63	65.63%	£11.78	£5.58	£8.43	£7.21
Jun-21	13.71	52.75%	£4.66	£2.42	£3.84	£3.44
Year	35.33	57.35%	£12.01	£6.05	£9.42	£8.33

Table 4.58 Electricity consumption and costs for household B-05 using example electricity tariffs, between 1 Jul 20 and 30 Jun 21, before the Boxergy Hero system was installed

Table 4.58 shows the electricity costs for household B-05 before the Boxergy Hero system was installed. During the heating season most of these costs were due to the use of the storage heaters and peak rate heaters. The average total electricity consumption over the year was 35.33kWh/day compared to 33.85kWh/day for household B-04 over a 12 month period with a comparable number of Degree Days.

The average cost over the year for household B-05 on the single rate tariff 1 was £12.01/day. This was higher than for household B-04 (£11.51/day) due to the higher average total consumption.

Household B-05 was cheaper on all the Economy 7 tariffs than on the single rate for each monthly period. The average annual cost on the Economy 7 tariffs was lower for household B-05 than for household B-04. For example on Tariff 3, the cost for household B-05 was £9.42/day compared to £11.41/day for household B-04.

Looking at the coldest period of the heating season, January 2021, the cost on Tariff 3 was £17.53/day for household B-05 compared to £17.63/day for household B-04. Despite paying more for the electricity on tariff 3, household B-04 was using less electricity (49.27kWh/day compared to 64.97kWh/day). This was because household B-04 used only 25.17% off-peak electricity (with a lower unit rate) while household B-05 used 56.24%. Household B-05 was able to achieve a higher level of thermal comfort in January 2021 than household B-04 at a slightly lower cost due to greater use of the storage heaters.

4.6.2. Post-installation period for household B-05

The Boxergy Hero heating system was running from 28 Jan 22. However during Storm Eunice on 18 Feb 22, the roof blew off the outhouse for the bungalow. The resident had to move out for 9 days and the property was left unheated. After returning, the resident used supplementary heating until 8 Mar 22 when the Boxergy Hero unit was serviced.

During the installation, the heating engineers used the wrong specification of glycol in the heating system. Boxergy had used compression joints with rubber and the glycol caused these to fail. As a result of leaks, the pressure in the system could fall and once it reduced by 50%, the system could cut out. The system could be repressurised, but it was necessary to turn the external AC isolators off and on to reset the system. The resident had mobility issues and since the AC isolators were not close to the door of the bungalow, it was not easy for the resident to reset the system.

Figure 4.59 AC isolators and pipework for Boxergy Hero system

During a service visit, Boxergy replaced the seals for the pipework and addressed the issue with the leaks. Although the Alpha ESS electrical battery was fitted on 28 Jan 22, it was not fully operational until 5 Jul 22. This meant that just the air-source heat pump and heat battery were running until the July service

The level of export recorded on the household smart meter was 11.1kWh on 18 Nov 22 and 12.3kWh on 19 Dec 22. This is much lower than the 249kWh of export recorded by household B-04 on 18 Nov 22, which had the issue with the battery current clamp not recording the full household electricity consumption for several weeks.

As a result of the disruption due to Storm Eunice in late February/early March, there was not an extended period where room temperatures could be analysed in the cold weather with the Boxergy Hero system operational. In the period between 8 Mar 22 and 30 Apr 22, the average temperature of the living room was 22.36˚C, which was 0.22˚C warmer than during the winter heating season with the old heating system. The temperature range was narrower, falling to only 20.5˚C instead of 17.0˚C in the analysis period the year before.

The resident noted the new heating system provided a steady heat over the day, getting heat when he wanted it. In contrast the old heating system meant it was too hot during the day and ran out of heat in the evening, requiring use of the boost or convector heaters.

The average living room relative humidity was 42.73% with the Boxergy Hero system between 8 Mar 22 and 30 Apr 22. This was little different than for the previous heating season. However, maximum humidity was nearly 10% lower with the new heating system at

54.0%. These values indicate that the conditions in the room continued to be dry with periods where the humidity was lower than the 40-60% optimum range.

A graph of the bedroom temperature and relative humidity is shown in figure 4.61 for the period 8 Mar 22 to 30 Apr 22. The average bedroom temperature for this period after the Boxergy Hero installation was 20.07˚C. With the old heating system, the resident relied on heat from the rest of the bungalow to heat the bedroom. During the winter heating season from 1 Nov 20 to 15 Apr 21, the average bedroom temperature was 16.33˚C. Using a pre-installation analysis period of 8 Mar 21 to 30 Apr 21, which was more comparable with the post-installation analysis period, the average bedroom temperature was still only 17.1˚C.

The average relative humidity in the bedroom was 43.46% during the post-installation monitoring period and was comparable to the living room. Previously when the bedroom was unheated, the relative humidty was higher than for the bedroom.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	22.36	26.5	20.5	1.02	42.73	54.0	28.5	4.83
Living Room 17:00 - 21:00	22.41	25.5	21.0		44.56	53.5	32.5	
Bedroom 24 hours	20.07	23.0	16.0	1.21	43.46	54.0	30.0	4.56
Bedroom 17:00 - 21:00	20.40	23.0	16.0		43.41	54.0	30.0	

Table 4.60 Household B-05 temperature and relative humidity between 8 Mar 22 and 30 Apr 22 Property after the Boxergy Hero installation

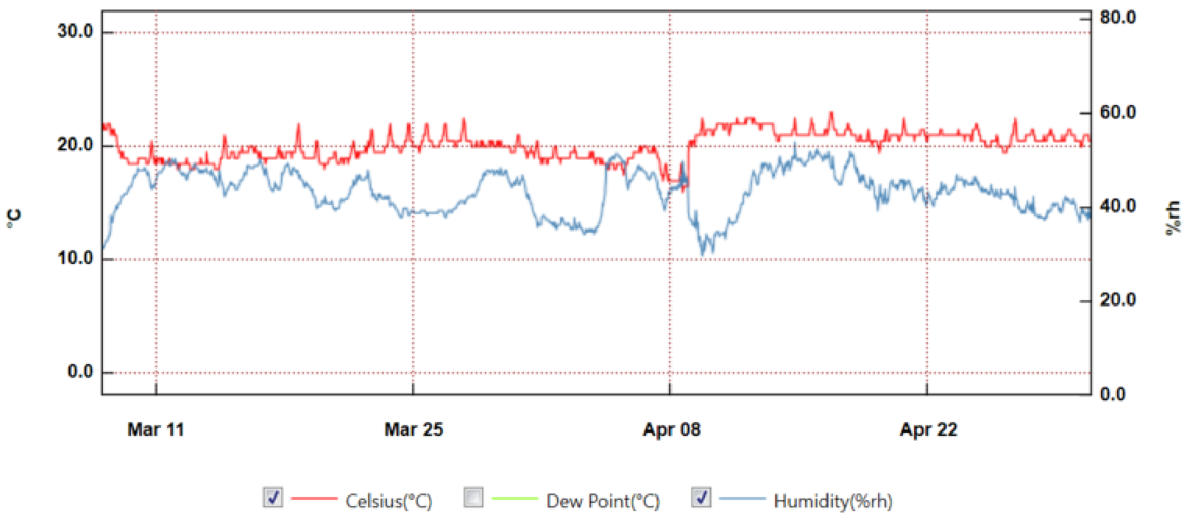


Figure 4.61 Graph of bedroom temperature and relative humidity for household B-05 from 8 Mar 22 to 30 Apr 22, with the Boxergy Hero installation

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Mar-22	11.87	2.39	14.26	16.7%	1.44
Apr-22	8.67	2.30	10.97	21.0%	1.18
May-22	4.56	1.29	5.85	22.0%	1.18
Jun-22	2.09	1.47	3.56	41.3%	0.85
Jul-22	0.71	1.13	1.84	61.4%	0.75
Aug-22	0.35	1.16	1.52	76.6%	0.69
Sep-22	1.40	1.17	2.57	45.5%	0.57
Oct-22	4.06	1.35	5.42	25.0%	1.34
Nov-22	8.90	0.97	9.87	9.8%	1.34
Dec-22	22.03	1.61	23.65	6.8%	1.92
Total	4.25	1.32	5.57	23.7%	0.90

Table 4.62 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-05. Data derived from the Vaillant sensoAPP.

Estimates of the electricity used by the Vaillant aroTHERM plus heat pump are shown in table 4.62 for household B-05. This was obtained from the Vaillant sensoAPP and the measuring error in this data might be up to 20%. The total consumption of the heat pump was high in the colder months of March, April, November and December. It was particularly high in December, using an average of 23.65kWh/day due to it being a cold month with 356.2 Degree Days. Over 40% of the electricity consumed by the heat pump for the months of June to September was due to heating domestic hot water.

The Vaillant sensoCOMFORT smart thermostat was run in manual mode with the set point temperature 21.5˚C over the full day. This installation may have been more efficient than some, with the heat pump not having to work hard raising the room temperature after a period with a set-back or turned off during the day. Data from the Vaillant sensoCOMFORT thermostat including the environmental yield was used to estimate the Coefficient of Performance (COP) for the heat pump for several months. In April 2022 it was 3.32, rising to 3.69 in September and 3.87 in October 2022.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Apr-22	30	15.38	7.93	23.31	34.03%	220.6	3.17
May-22	31	9.17	4.57	13.74	33.27%	120.1	3.55
Jun-22	30	7.14	3.55	10.69	33.21%	73.4	4.37
Jul-22	31	1.15	8.87	10.02	88.48%	29.4	10.57
Aug-22	31	4.70	4.51	9.21	48.96%	15.9	17.95
Sep-22	30	5.28	8.00	13.28	60.26%	73.9	5.39
Oct-22	31	5.22	10.68	15.90	67.16%	93.7	5.26
Nov-22	30	4.53	17.73	22.26	79.66%	198.6	3.36
Full period	244	6.55	8.21	14.76	55.65%	825.6	4.36

Table 4.63 Monthly electricity consumption from Apr 22 to Nov 2022 for household B-05, after the Boxergy Hero installation

Table 4.63 shows monthly electricity consumption for household B-05 using smart meter data. The Vaillant sensoAPP indicated an average of about 14.26kWh/day was used by the heat pump in April, out of a total electricity consumption of 23.31kWh/day. This suggests that 61.1% of the electricity consumption was from the heat pump.

The data from the sensoAPP suggested the heat pump was using about 1.5 to 3.5kWh/day in summer, primarily due to water heating. This was out of a total electricity consumption of about 9 to 13kWh/day.

During the colder period in November 2022, there was greater space heating from the heat pump and the heat pump consumption was about 9.9kWh/day out of a total of 22.26kWh/day or 44.3% of the total consumption.

There was a reduction in total electricity consumption of household B-05 after the Boxergy Hero system was installed. In April 2021, the resident used 38.86kWh/day compared to 23.31kWh/day the following year. April was a colder month in 2021 compared to 2022. Correcting for external temperature with Degree Days, the consumption with the old heating system was 4.1kWh/DD compared to 3.17kWh/DD with the Boxergy Hero system.

Comparing consumption in November, the total average electricity consumption for household B-05 in November 2020 was 43.19kWh/day with the old heating system and 22.26kWh/day with the Boxergy Hero system in November 2022. Again using Degree Days to correct for external temperature, the consumption was 6.07kWh/DD with the storage heaters and 3.36kWh/DD with the Boxergy Hero system.

The Alpha ESS electrical battery was not charging and discharging overnight until 6 Jul 22. As a result, during April, May and June, the Boxergy Hero system was running like a standard air-source heat pump, with the majority of the consumption during the day, at peak rate times. If the electricity consumption was the same throughout the day, $\frac{7}{24}$ of the electricity consumption would be off-peak, or 29.1%. For household B-05, the percentage off-peak consumption was slightly more than this at 33 – 34%, perhaps due to the heat battery charging overnight.

The consumption of household B-05 was significantly lower in summer, with average total consumption in the range 7 to 14kWh/day during the summer months of 2020. The Alpha ESS battery for household B-05 had a usable capacity of 11kWh. As a result, on most summer days, after charging overnight, the battery could power most or all of the household electricity consumption during the peak rate period. This explains the significant increase in percentage off-peak consumption in July 2022 to 88.48%.

Figure 4.64 shows a Power Diagram from the Alpha ESS battery portal for household B-05 on 20 Jul 22. The battery charged overnight and even after powering appliances throughout the day only fell to a charge level of 40.8%.

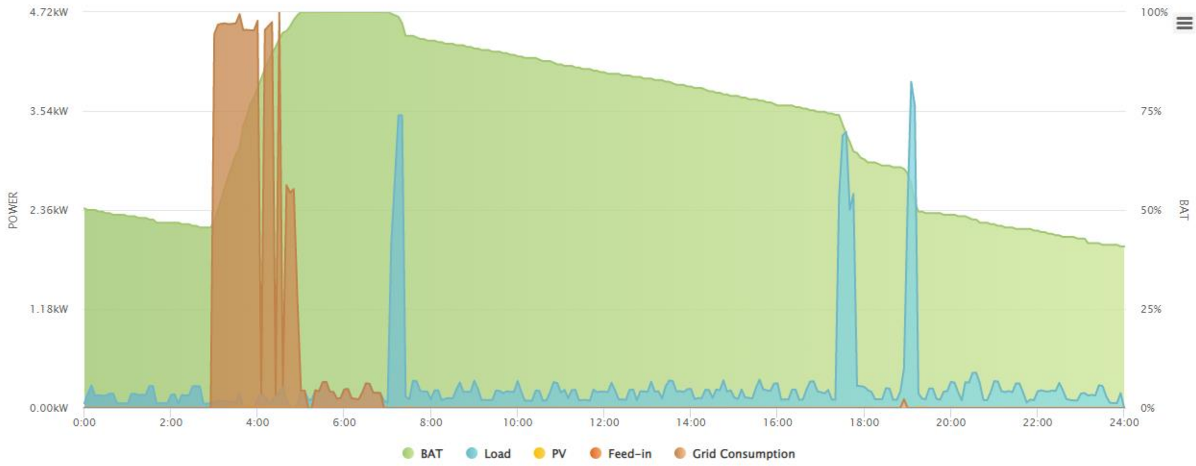


Figure 4.64 Power Diagram from the Alpha ESS battery portal for Household B-05 on 20 Jul 22 Property with Boxergy Hero system with ASHP and electrical battery operational

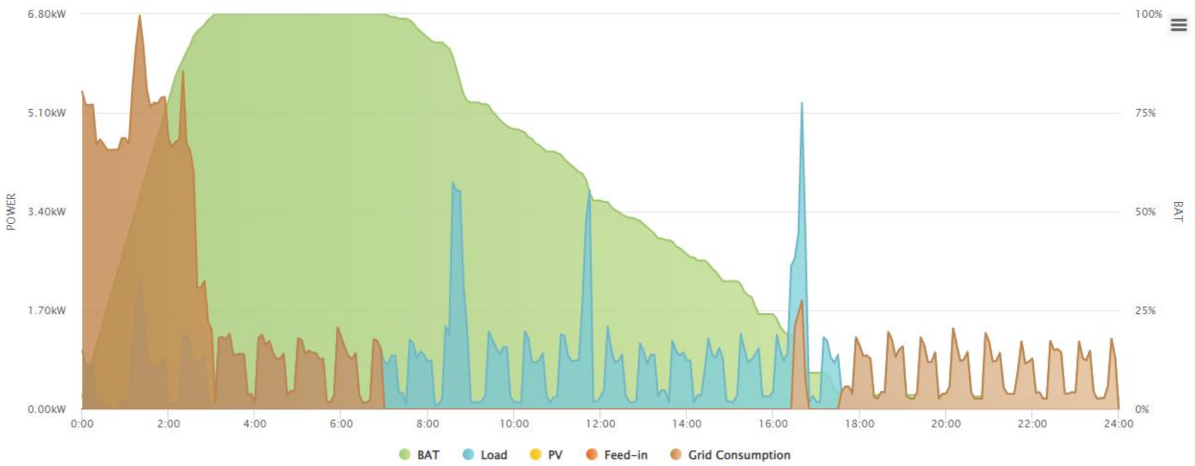


Figure 4.65 Power Diagram from the Alpha ESS battery portal for Household B-05 on 26 Nov 22 Property with Boxergy Hero system with ASHP and electrical battery operational

Another Power Diagram is shown in figure 4.65 for household B-05 on 26 Nov 22. The battery was initially fully discharged and charged from midnight (instead of 03:00 on 20 Jul 22). It was fully charged by 03:05 and provided power to the house from 07:00 once the peak rate period began. Throughout the day and night, the heat pump was operating in approximately 25-minute cycles, taking the consumption typically up to about 1.24kW. The battery was discharged by 17:35 and after that further electricity was imported from the grid.

Table 4.66 shows monthly electricity costs using 4 model tariffs for household B-05 after the installation of the Boxergy Hero system. Despite the battery not being operational between April and June and the system effectively operating only as an air-source heat pump, the electricity costs on the Economy 7 tariffs were cheaper than on the single rate tariff. This was because the percentage of off-peak consumption at 33 – 34% was just above the threshold that the model Economy 7 tariffs became cheaper than the single rate tariff.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Apr-22	23.31	34.03%	£7.93	£4.64	£7.76	£7.31
May-22	13.74	33.27%	£4.67	£2.75	£4.60	£4.34
Jun-22	10.69	33.21%	£3.63	£2.14	£3.58	£3.38
Jul-22	10.02	88.48%	£3.41	£1.34	£1.79	£1.32
Aug-22	9.21	48.96%	£3.13	£1.67	£2.67	£2.43
Sep-22	13.28	60.26%	£4.52	£2.23	£3.43	£3.00
Oct-22	15.90	67.16%	£5.41	£2.53	£3.80	£3.23
Nov-22	22.26	79.66%	£7.57	£3.21	£4.53	£3.59
Full period	14.76	55.65%	£5.02	£2.56	£4.01	£3.56

Table 4.66 Electricity consumption and costs for household B-05 using example electricity tariffs, between 1 Apr 22 and 30 Nov 22, after the Boxergy Hero system was installed

After the battery was charging overnight and discharging during the day, the benefits of the Economy 7 tariffs became greater. In November, when 79.7% of the consumption was off-peak, the cost on the single rate Tariff 1 was £7.57/day compared to £4.53/day on Tariff 3 on Economy 7.

Looking at data from the full period since the Boxergy Hero installation, the average cost on the single rate Tariff 1 was £5.02/day compared to £4.01/day on the most expensive of the Economy 7 tariffs.

Comparing the costs before and after the Boxergy Hero installation, in November 2020, the electricity cost on Economy 7 tariff 3 would have been £11.79/day with the old heating system and £4.53/day with the Boxergy Hero system in November 2022. There were also savings in the summer after the Boxergy Hero installation. In July 2020 the cost with Economy 7 tariff 3 was £2.80/day which reduced to £1.79/day in July 2022.

4.7. Household B-06

Household B-06 lived next door to household B-01 in a 2-bedroom semi-detached bungalow. Before the new heating system was installed, the household noted in an interview that they had been using the large storage heater in the living room and the storage heater in the hall on a daily basis in winter. They also used an electric fire in the living room on cold winter evenings.

The new wet central heating system was fitted in late January/early February 2022 and the Boxergy Hero system was commissioned on 10 Feb 22. There was a power cut due to Strom Eunice on 18 Feb 22 and the system cut out as a result of this. There were periods subsequently with the fan for the outdoor unit being noisy and the unit regularly going into restart mode. There was a service visit by Boxergy and Vaillant on 6 Mar 22 which resolved these issues.

Due to supply chain problems, it was not possible to initially install a Vaillant sensoNET unit which allows remote monitoring and control of the system. This could not be fitted until 18 May 22. There were issues with the monitoring of the Alpha ESS battery, with the battery portal only showing household load and grid consumption from early July 2022.

4.7.1. Pre-installation period for household B-06

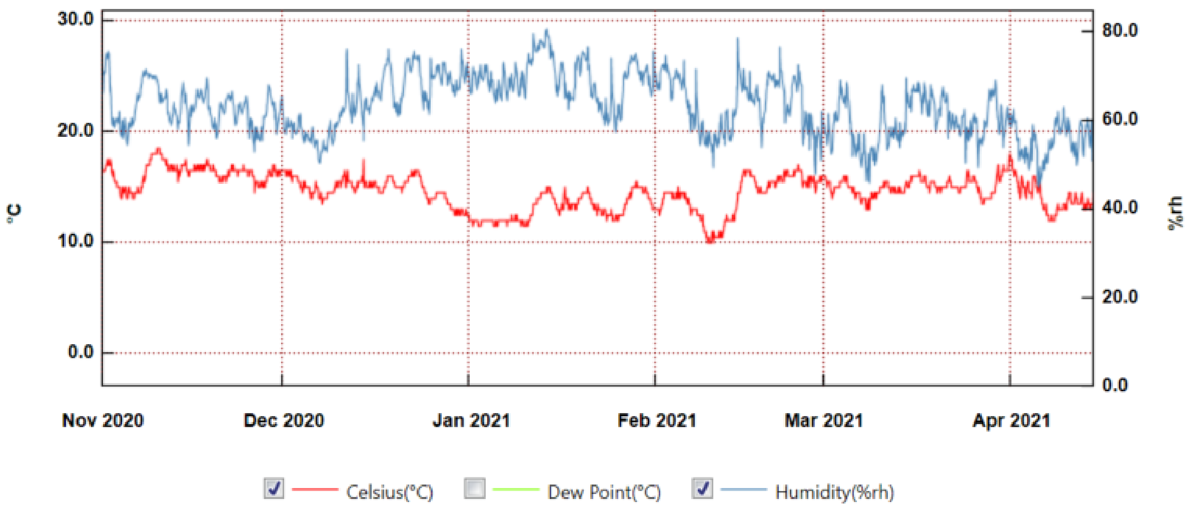


Figure 4.67 Graph of living room temperature and relative humidity for household B-06 from 1 Nov 20 to 15 Apr 21, before the Boxergy Hero installation

Figure 4.67 shows a graph of the living room temperature and humidity for household B-06. There was little heating and cooling within the day. The living room temperature was strongly affected by the external temperature, with extended periods of colder temperatures during periods when the external temperature was colder (a higher number of Degree Days). This includes the periods in early November, early January and mid-February. Such a profile is typical of a largely unheated room. However, the residents regularly left external doors open, even in colder weather. This might have meant the heating system had little impact on warming the room.

A graph of temperature and relative humidity is shown in figure 4.68 for the bedroom for household B-06 for the period 1 Nov 20 to 15 Apr 21. Again, there were typically low temperatures apart from a period with much higher temperatures in mid-February. During this period, the temperature was normally above 20˚C and even reached 30.5˚C at 08:30 on 15 Feb 21. This might have been due to supplementary heating during a period of colder external temperatures.

The living room and bedroom temperature and humidity was analysed between 8 Mar 21 and 30 Apr 21. This avoided the anomalous period in mid-February for the bedroom temperature. It also allowed the same dates to be used the following year to analyse the data for when the heat pump for the Boxergy Hero system was operating as expected.

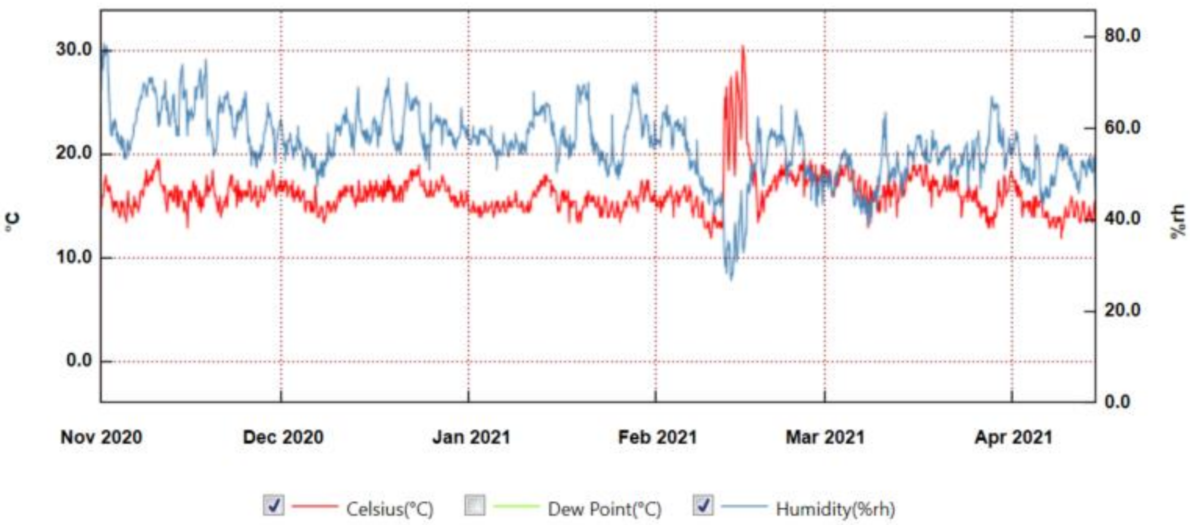


Figure 4.68 Graph of bedroom temperature and relative humidity for household B-06 from 1 Nov 20 to 15 Apr 21, before the Boxergy Hero installation

Table 4.x shows the temperature and relative humidity for the living and bedrooms for the analysis period 8 Mar 21 to 30 Apr 21. The average living room temperature was 15.03˚C while the average for the bedroom was slightly higher at 15.82˚C. During this period, the bedroom temperature ranged from 12.0 to 19.0˚C. Low temperatures in the home increase the risk of health issues, with increased likelihood of respiratory problems, heart attacks and strokes, exacerbating existing medical conditions and increasing the likelihood of falls.[22]

The average relative humidity in the living room at 55.55% was slightly higher than the value of 51.02% for the bedroom during the 8 Mar 21 to 30 Apr 21 analysis period. Figure 4.67 for the living room shows that the relative humidity in the room was above 60% for much of the time between 15 Dec 20 and 1 Feb 21. The average relative humidity that period was 69.11% with the range between a minimum of 57.5% and a maximum of 80.5%.

The living room wall on the gable end of the house suffered from penetrating damp and this may partially account for the higher levels of humidity during the winter months. Moisture due to rain penetration into the masonry was coming through the cavity wall. Remedial work

[22] Fuel Poverty, Cold Homes and Health Inequalities in the UK, Institute for Health Equity (2022), p.18, https://www.instituteofhealthequity.org/resources-reports/fuel-poverty-cold-homes-and-health-inequalities-in-the-uk/read-the-report.pdf (Accessed 6 Jan 23)

carried out during the project found the insulation within the cavity had slumped and was wet. These issues could have led to greater heat loss and higher humidity in the room.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	15.03	18.0	12.0	1.24	55.55	69.5	36.0	6.41
Living Room 17:00 - 21:00	15.09	17.5	12.0		55.89	69.5	37	
Bedroom 24 hours	15.82	19.0	12.0	1.42	51.02	67.0	33.0	5.06
Bedroom 17:00 - 21:00	16.09	19.0	13.0		50.87	66.0	33.0	

Table 4.69 Household B-06 temperature and relative humidity between 8 Mar 21 and 30 Apr 21 Property with storage heaters before Boxergy Hero installation

Table 4.70 shows the monthly electricity consumption between 1 Dec 20 and 30 Nov 21 for household B-06, while using the original heating system. The total electricity consumption over the year was 7,796 kWh or an average of 21.36kWh/day, with 69% of the consumption on the off-peak tariff.

This compares with the neighbouring property, household B-01 using 21.9kWh/day over a 10-month period. Correcting for external temperature with Degree Days, Household B-01 used 2.96kWh/DD with the old heating system compared to household B-06 using 3.38kWh/DD. The poorer level of thermal comfort for household B-06 despite using more electricity could be due to excess ventilation with open external doors and poorer wall insulation. Households B-02, B-04 and B-05 had similar sized bungalows and their consumption with the old heating system was higher than for households B-01 and B-02, ranging from 4.2 to 5.46kWh/DD.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Dec-20	31	6.77	25.00	31.76	78.70%	312.4	3.15
Jan-21	31	6.79	25.62	32.41	79.04%	366.2	2.74
Feb-21	28	6.90	33.41	40.31	82.89%	301.0	3.75
Mar-21	31	6.55	25.66	32.21	79.65%	284.1	3.51
Apr-21	30	6.44	14.34	20.78	68.99%	284.5	2.19
May-21	31	6.81	13.60	20.41	66.64%	203.9	3.10
Jun-21	30	6.56	4.65	11.22	41.48%	58.6	5.74
Jul-21	31	6.02	4.48	10.51	42.68%	30.4	10.72
Aug-21	31	6.34	4.75	11.09	42.81%	46.7	7.36
Sep-21	30	6.83	4.66	11.49	40.55%	52.0	6.63
Oct-21	31	6.79	5.38	12.17	44.18%	121.0	3.12
Nov-21	30	6.74	16.41	23.15	70.89%	246.0	2.82
Year	365	6.63	14.73	21.36	68.97%	2306.8	3.38

Table 4.70 Monthly electricity consumption from Dec 2020 to Nov 2021 for household B-06, before the Boxergy Hero installation

There was very little variation in the peak rate consumption, with the average monthly consumption in the range 6.0 to 6.9kWh/day throughout the year. This suggested that there was little or no supplementary electric heating used during peak rate times. The off-peak consumption dropped to 4.5 to 4.7kWh/day in summer, with most of this due to water heating by the Economy 7 immersion heater. The average off-peak consumption increased to 33.41kWh/day in February 2021 when there was greater use of the storage heaters. The percentage of off-peak consumption was high at 69.0%, with only household B-02 higher during the analysis period with the old heating system.

Table 4.71 shows electricity costs for household B-06 using 4 example electricity tariffs. A typical tariff used by households for the period analysed between 1 Dec 20 and 30 Nov 21 was Economy 7 Tariff 2. The average cost of the electricity over the year was £3.36/day (or £1225.76 over the year). Tariffs 1, 3 and 4 were available during the period of the Government's Electricity Price Guarantee between 1 Oct 22 and 31 Mar 23. The cost over the year on Economy 7 Tariff 3 would have been £4.99/day or £1822.77 over the year. The high percentage off-peak consumption meant that the single rate Tariff 1 was more expensive at £7.26/day or an annual bill of £2650.48.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Dec-20	31.76	78.70%	£10.80	£4.62	£6.55	£5.22
Jan-21	32.41	79.04%	£11.02	£4.70	£6.65	£5.29
Feb-21	40.31	82.89%	£13.70	£5.66	£7.84	£6.06
Mar-21	32.21	79.65%	£10.95	£4.65	£6.56	£5.19
Apr-21	20.78	68.99%	£7.07	£3.27	£4.86	£4.09
May-21	20.41	66.64%	£6.94	£3.27	£4.91	£4.18
Jun-21	11.22	41.48%	£3.81	£2.13	£3.50	£3.24
Jul-21	10.51	42.68%	£3.57	£1.98	£3.24	£2.99
Aug-21	11.09	42.81%	£3.77	£2.09	£3.41	£3.15
Sep-21	11.49	40.55%	£3.91	£2.20	£3.61	£3.35
Oct-21	12.17	44.18%	£4.14	£2.28	£3.70	£3.40
Nov-21	23.15	70.89%	£7.87	£3.59	£5.29	£4.41
Year	21.36	68.97%	£7.26	£3.36	£4.99	£4.21

Table 4.71 Electricity consumption and costs for household B-06 using example electricity tariffs, between 1 Dec 20 and 30 Nov 21, before the Boxergy Hero system was installed

4.7.2. Post-installation period for household B-06

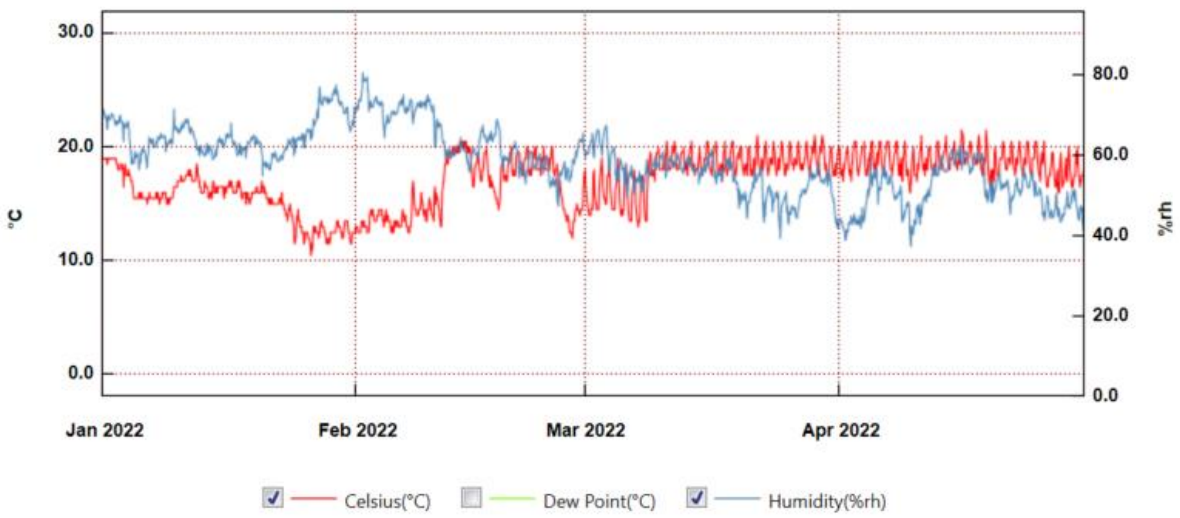


Figure 4.72 Graph of bedroom temperature and relative humidity for household B-06 from 1 Jan 22 to 30 Apr 22, before and after the Boxergy Hero installation

A graph of the bedroom temperature and relative humidity is shown in figure 4.72 for the period 1 Jan 22 to 30 Apr 22 for household B-06. Between late January and early February, the storage heaters were taken out and the new wet cental heating system was fitted. This might account for the lower temperatures. The temperature of the bedroom increased from when the Boxergy Hero system was commissioned on 10 Feb 22. The temperature dipped to 14.5˚C on 18 Feb 22 as a result of power cuts during Storm Eunice. It dropped again to 12.5˚C due to issues with the heat pump in late February. The heat pump was operating correctly from 8 Mar 22 following a service by Boxergy and Vaillant. The temperature in the bedroom was more consistent from this time, with an average of 18.69˚C between 8 Mar 22 and 30 Apr 22. Table 4.74 shows that the temperature ranged from a minumum of 13.5˚C while the home was still warming up following the service, to a maximum of 21.5˚C during the analysis period. The average relative humidity was 52.15% in the bedroom.

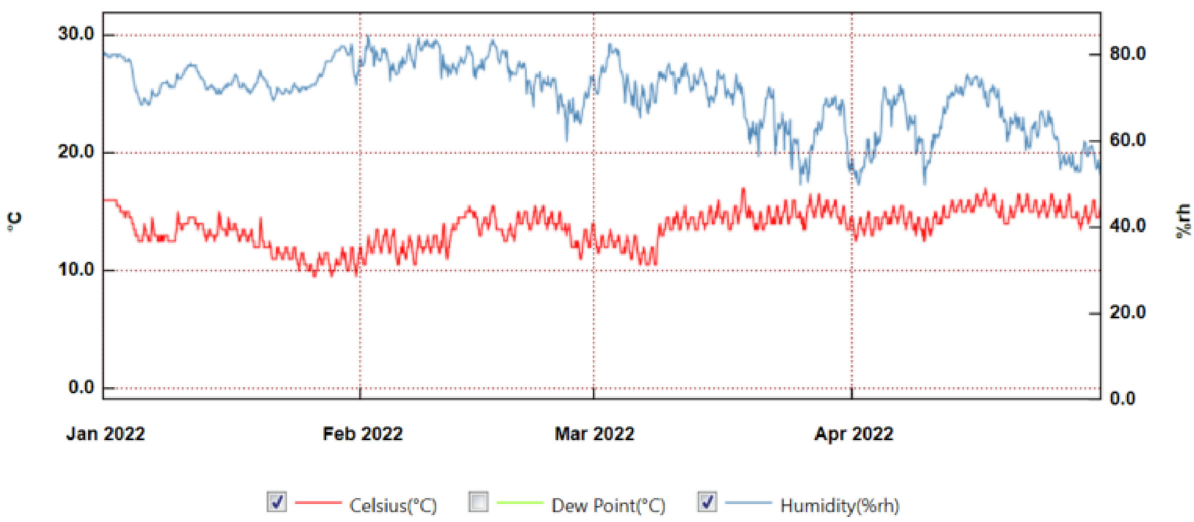


Figure 4.73 Graph of living room temperature and relative humidity for household B-06 from 1 Jan 22 to 30 Apr 22, before and after the Boxergy Hero installation

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	14.68	17.0	10.5	0.92	65.18	78.0	50.0	7.04
Living Room 17:00 - 21:00	14.82	16.5	12.5		64.7	77.5	50.0	
Bedroom 24 hours	18.69	21.5	13.5	1.08	52.15	62.5	37.5	5.19
Bedroom 17:00 - 21:00	19.01	21.0	16.0		51.38	62.5	37.5	

Table 4.74 Household B-06 temperature and relative humidity between 8 Mar 22 and 30 Apr 22 Property after the Boxergy Hero installation

There was a 3.04˚C increase in average bedroom temperature between the analysis period 8 Mar 21 to 30 Apr 21 and the same dates in 2022. While there was an increase in the bedroom temperature, after the Boxergy Hero installation, there was also a small decrease in the living room average temperature. This decreased from 15.03˚C to 14.68˚C for the analysis periods before and after the Boxergy Hero installation. The cause for this is unclear. The living room may have become colder than the bedroom due to greater ventilation from open external doors and poorer wall insulation. The average relative humidy of the living room was 65.18% and the maximum humidity reached 78%. The humidity was quite high over this period and may have been affected by the damp from the gable end wall before it dried out and the room was redecorated.

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Jun-22	3.63	1.53	5.17	29.7%	1.49
Jul-22	1.03	1.35	2.39	56.8%	1.09
Aug-22	0.81	2.06	2.87	71.9%	1.57
Sep-22	4.10	2.03	6.13	33.2%	1.66
Oct-22	5.35	2.10	7.45	28.1%	1.77
Nov-22	12.30	1.83	14.13	13.0%	1.86
Dec-22	25.45	1.97	27.42	7.2%	2.22
Total	7.54	1.84	9.38	19.6%	1.92

Table 4.75 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-06. Data derived from the Vaillant sensoAPP.

Estimates of the electricity consumed by the Vaillant aroTHERM plus heat pump for household B-06 are shown in table 4.75. The Vaillant sensoNET unit which allowed online monitoring and control was fitted on 18 May 22 and so data is shown from June onwards.

The Vaillant sensoCOMFORT smart thermostat was using the manual setting with the set point at 20.5˚C. This meant the heating system was trying to maintain a room temperature of 20.5˚C throughout the day. Household B-05 also had the thermostat running in manual mode, but the set point at 21.5˚C throughout the day.

There were similarities in the electricity consumed by the heat pumps during the last quarter of 2022 for households B-06 and B-05. This might be expected given the properties were the same size and with similar thermostat settings. In December the electricity consumed by the heat pump for household B-06 was an average of 27.42kWh/day compared to 28.13kWh/day for household B-05. In October 2022, 7.45kWh/day was used by the heat pump for household B-06 compared to 7.58kWh/day for the heat pump for household B-05.

The heat pump for household B-06 appeared to use 10kWh of electricity heating water on 1 Aug 22 and this led to the average consumption while heating water for household B-06 to be double that for household B-05 in August 2022.

Using data from the Vaillant sensoCOMFORT thermostat it was possible to estimate monthly values of the coefficient of performance (CoP) of the heat pump. In June the CoP was 3.43, falling to 3.10 in September and rising again to 3.35 in October.

The monthly electricity consumption for household B-06 after the Boxergy Hero installation is shown in table 4.76 for the period between 1 Mar 22 and 31 Dec 22. In July 2022, the percentage off-peak consumption was 89.34%, but this fell to 51 to 56% during the months of August, September and October.

The fall in off-peak consumption was due to changing the time when the battery started to charge to midnight. The times for off-peak electricity for the supplier for household B-05 were from 00:00 to 07:00 on Greenwich Mean Time (GMT) throughout the year. This meant that off-peak electricity was from 01:00 to 08:00 while on British Summer Time (BST). The change in off-peak times happens with some suppliers and meters, but not all. The off-peak times were 00:00 to 07:00 for household B-05 throughout the year.

As a result of the battery charging from midnight, about 4.5 to 5.0kWh of the battery charge was on the peak rate, not providing any benefit to the household. In fact there were losses due to the inefficiencies in the battery.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Mar-22	31	13.22	12.25	25.47	48.09%	256.0	3.08
Apr-22	30	8.82	14.06	22.88	61.46%	220.6	3.11
May-22	31	6.34	15.04	21.38	70.34%	120.1	5.52
Jun-22	30	4.26	15.65	19.90	78.62%	73.4	8.14
Jul-22	31	1.56	13.04	14.59	89.34%	29.4	15.39
Aug-22	31	6.63	8.47	15.10	56.12%	15.9	29.44
Sep-22	30	9.12	9.54	18.66	51.13%	73.9	7.57
Oct-22	31	9.05	10.54	19.59	53.79%	93.7	6.48
Nov-22	30	9.48	17.19	26.67	64.45%	198.6	4.03
Dec-22	31	18.92	21.93	40.84	53.68%	356.2	3.55
Full period	306	8.75	13.77	22.52	61.14%	1437.8	4.79

Table 4.76 Monthly electricity consumption from Mar 22 to Dec 2022 for household B-06, after the Boxergy Hero installation

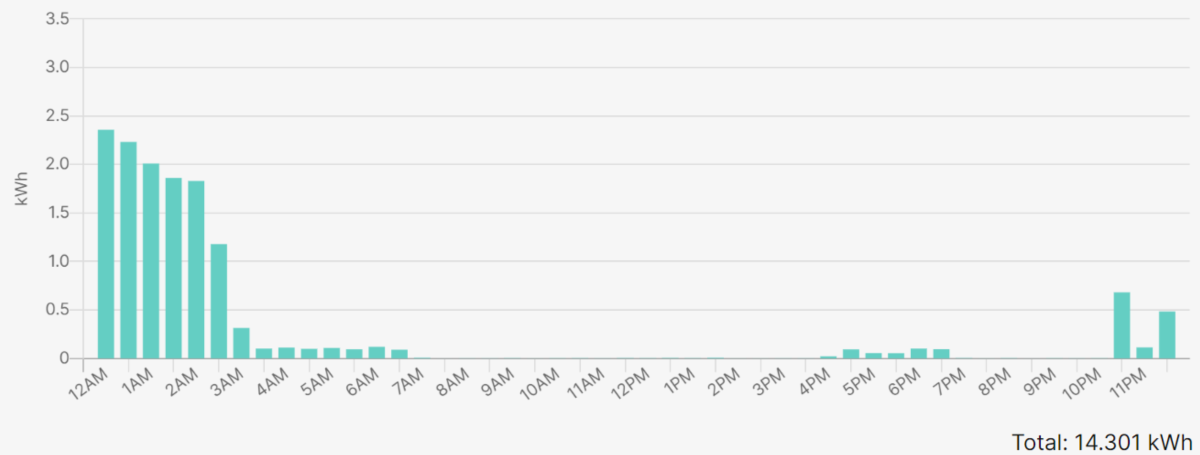


Figure 4.77 Half-hourly electricity consumption from Carbon Coop PowerShaper monitor portal for household B-06 on 4 Aug 22 after the Boxergy Hero installation

Figure 4.77 shows the half-hourly electricity consumption on 4 Aug 22 for household B-06. With the off-peak period starting at 01:00, the periods with high consumption at 00:00 and 00:30 due to the battery charging were during the peak rate period.

There were other issues with the battery as well. Household smart meters can record the amount of electricity that has been exported to the grid since the smart meter was fitted. On 28 Oct 22 the smart meter for B-06 had an export reading of 299kWh and this increased to 302kWh by 18 Nov 22. Most of the export may have occurred during a period when the current clamps for the battery were not accurately recording the grid consumption.

Prior to July 2022, the Alpha ESS battery portal was only registering the battery charge and household load, but not the grid consumption. It is possible that much of the export may have occurred during the period before July.

The electricity consumption of household B-06 was in the range 10.5 to 12.2kWh/day for the months June to October 2021 before the Boxergy Hero system was installed. For the same months in 2022 after the Boxergy Hero system was running, the consumption was 15.1 to 19.9kWh/day.

The difference between the total electricity consumption and the electricity consumed by the heat pump was in the range 12.1 to 14.7kWh/day for household B-06 during the months June to December 2022. The difference was only 6.2 to 8.5kWh/day for household B-05 during the months of April to November 2022.

Figure 4.78 shows a Power Diagram from the Alpha ESS battery portal on 24 Nov 22 for household B-06. This has some similarities to the Power Diagram for household B-05 on 26 Nov 22 in figure 4.65. The battery charged from midnight and reached 100% charge at 03:15. The battery stayed fully charged until 07:00 when it began to provide power to the home during the peak rate period. The heat pump typically ran in cycles of 25-30 minutes, initially taking the consumption to about 1.2kW before dropping to 0.9kW for 15-minutes and then back to the baseload of about 0.14kW for about 20 minutes. These cycles took place throughout the day. By 17:30, the battery had fully discharged. There were peaks with high levels of grid consumption (in brown) after 17:30 when the battery was fully discharged. The peaks were not normal, having the grid consumption higher than the recorded household load, which normally only occurs when the battery is charging.

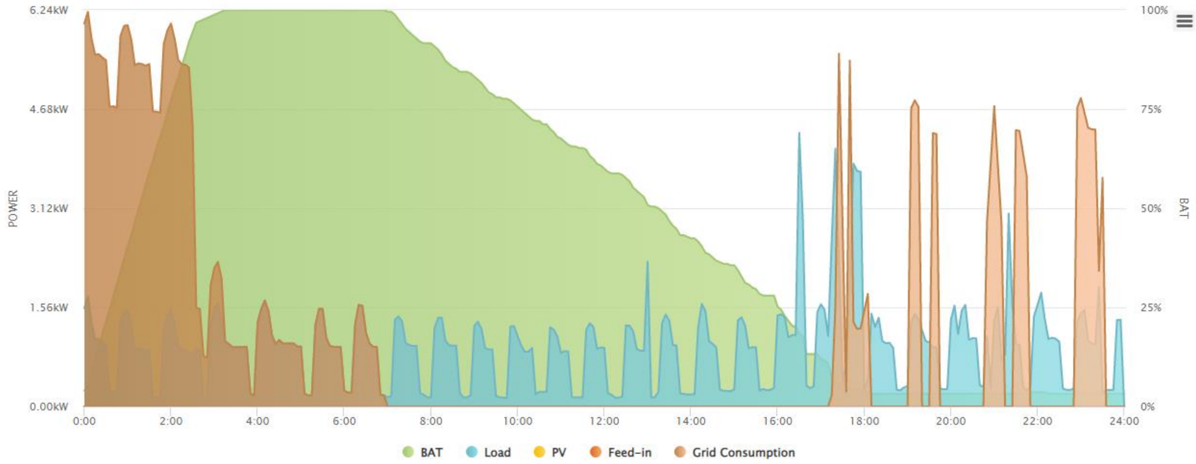


Figure 4.78 Power Diagram from the Alpha ESS battery portal for Household B-06 on 24 Nov 22 Property with Boxergy Hero system with ASHP and electrical battery operational

On 24 Nov 22, the Alpha portal recorded that 16.1kWh electricity was used charging the battery. On 14 Dec 22, a day with many more high grid consumption peaks, the amount of battery charge recorded by the Alpha portal was 26.1kWh. Since the Alpha battery installed with the Boxergy Hero system had a capacity of 11.4kWh, you would expect the amount of battery charge to be of that order and not more than double that value unless there had been more more than one charge/discharge cycle. Unless there is another explanation for the high electricity consumption, issues with the battery system are likely to have caused increased levels of electricity consumption for household B-06.

Table 4.79 shows the monthly average cost of the electricity for household B-06 after the Boxergy Hero installation using the 4 model tariffs. Over the period from March to the end of December 2022, the average cost on the single rate Tariff 1 was £7.66/day. It was cheaper on all the Economy 7 tariffs over the full period and for each month. With Tariff 3, the most expensive of the Economy 7 tariffs, the average electricity cost over the full period was £5.76/day.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Mar-22	25.47	48.09%	£8.66	£4.64	£7.46	£6.79
Apr-22	22.88	61.46%	£7.78	£3.80	£5.84	£5.08
May-22	21.38	70.34%	£7.27	£3.33	£4.92	£4.11
Jun-22	19.90	78.62%	£6.77	£2.90	£4.11	£3.28
Jul-22	14.59	89.34%	£4.96	£1.94	£2.57	£1.88
Aug-22	15.10	56.12%	£5.13	£2.61	£4.08	£3.62
Sep-22	18.66	51.13%	£6.34	£3.33	£5.30	£4.79
Oct-22	19.59	53.79%	£6.66	£3.44	£5.42	£4.85
Nov-22	26.67	64.45%	£9.07	£4.34	£6.58	£5.66
Dec-22	40.84	53.68%	£13.89	£7.17	£11.32	£10.13
Full period	22.52	61.14%	£7.66	£3.75	£5.76	£5.02

Table 4.79 Electricity consumption and costs for household B-06 using example electricity tariffs, between 1 Mar 22 and 30 Dec 22, after the Boxergy Hero system was installed

There was a small increase in average electricity consumption between July and August 2022. This led cost the on single rate Tariff 1 to increase by £0.17/day between the months. However on Economy 7 Tariff 3, the increase was £1.51/day. This was because the time when the battery started charging was shifted to midnight, while the lower cost Economy 7 off-peak period started from 01:00 while on British Summer Time (BST).

There was an increase in the electricity consumption during the warmer weather period after the Boxergy Hero installation. Between June and September 2021, the average monthly consumption was in the range 10.5-11.5kWh/day but for the same period the following year after the Boxergy Hero installation it was 14.6-19.9kWh/day. This may have been due to issues with the Alpha battery, although there might have been some increase in general household electricity use.

There were impacts on the electricity costs as a result of this. In July 2022, despite using 14.59kWh/day instead of 10.51kWh/day in July 2021, the costs were lower on Economy 7 due to 89.34% of the consumption being off-peak. The cost on Tariff 3 was £2.57/day in July 2022 compared to £3.24/day in July 21.

In September 2022 the household used 18.66kWh/day costing £5.30/day on tariff 3 compared to 11.49kWh/day with a cost of £3.61/day in September 2021. The higher consumption was a major factor in the increased cost. More of the consumption would have been during the off-peak time had the battery charging started from the beginning of the off-peak period at 01:00. As a result the difference in costs between the two periods would have been lower.

The consumption during the cold weather period was also higher. In November 2022, the household used 26.67kWh/day compared to 23.15kWh/day in November 2021 despite the period the year before having colder weather. The cost on Economy 7 tariff 3 was £5.29/day in November 2021 and increased to £6.58/day in November 2022. It should be noted that there was also an improvement in thermal comfort with the Boxergy Hero installation despite the higher cost.

For comparison, the electricity cost on Tarff 3 for household B-05 was £4.53/day in November 2022. The heat pump consumption was similar – 13.67kWh/day for household B-05 compared to 14.13kWh/day for household B-06. The off-peak consumption was also comparable with 17.7kWh/day for B-05 compared to 17.2kWh/day for B-06. The difference was in the peak rate consumption, with a household B-06 using a higher 9.48kWh/day instead of 4.53kWh/day by household B-05. This extra consumption could have been at least in part due to the spikes in grid consumption later in the day associated with battery charging which were seen in figure 4.78 on days like 24 Nov 22.

4.8. Household B-07

Household B-07 lived in a 2-bedroom mid-terraced house with a floor area of about 87m^2. At the start of the project, there was a Dimplex Quantum QM150 high heat retention storage heater in the living room which had a heat output of 1.5kW and a storage capacity of up to 23.1kWh (3.3kW input for 7 hours). The resident stopped using this heater after one of her children was burnt after touching the case. She was not aware that storage heater guards were available.

There were Dimplex XL18N storage heaters in the kitchen and at the top of the stairs. These had manual charge controls and had an input rating of 2.55kW, storing up to 17.85kWh of heat. There were also panel heaters in the bedrooms.

When the family first moved in, they used the storage heaters, but they tended to get cold by late afternoon. The resident later used a bottled gas heater in the living room and 3 oil filled electric radiators in the kitchen and bedrooms. The property had an electric shower, but the bath was regularly used for the children.

An Energy Performance Certificate (EPC) which was lodged at the start of the project with the old heating system showed the energy rating for the property was Band E. The annual space heating demand was 11,372kWh and the water heating demand was 2,177kWh.

A smart meter was fitted at the beginning of December 2020. The household was put on a single rate tariff despite having storage heaters and off-peak water heating. The meter fitted was however capable of running on Economy 7, with the smart meter having 5 tails. Installation of the new wet central heating system started in mid-January 2022, but was not finished until early February due to issues with COVID-19. The Boxergy Hero system was commissioned on 11 Feb 22.

The household started trying to get their electricity supplier to switch them back onto an Economy 7 tariff in Spring 2022 to benefit from the reduced costs from the heat pump and battery. Due to vulnerabilities, this was initially with the assistance of a support worker. This was unsuccessful and so NEA staff from the Warm and Safe Homes advice service took on the case. The supplier denied it was possible to remotely switch the customer to Economy 7 despite it being a 5-tail meter and said it would cost £325 to fit a new meter. Following advice from another department, they said the customer should not be switched to Economy 7 due to it being cheaper for the heat pump and battery on a single rate tariff. Resolving the issue was not straightforward due to different departments being involved at the supplier and a debt on the account which had been made worse by remaining on a single rate tariff over the period.

By January 2023, the supplier had confirmed that when the smart meter was fitted, the details were not updated on the national database. This was going to be done and then they needed to update the information with National Grid for a 2-rate meter which could take up to 6 weeks. Once that had happened the contract could be changed to a 2-rate tariff. The supplier has admitted an error on their part and their billing team will work out the correct bill going back to the date they recorded as the first request to change to Economy 7. It was still likely to take some time to resolve despite NEA first discussing the issue with the supplier in September 2022 and the household trying for months before that.

4.8.1. Pre-installation period for household B-07

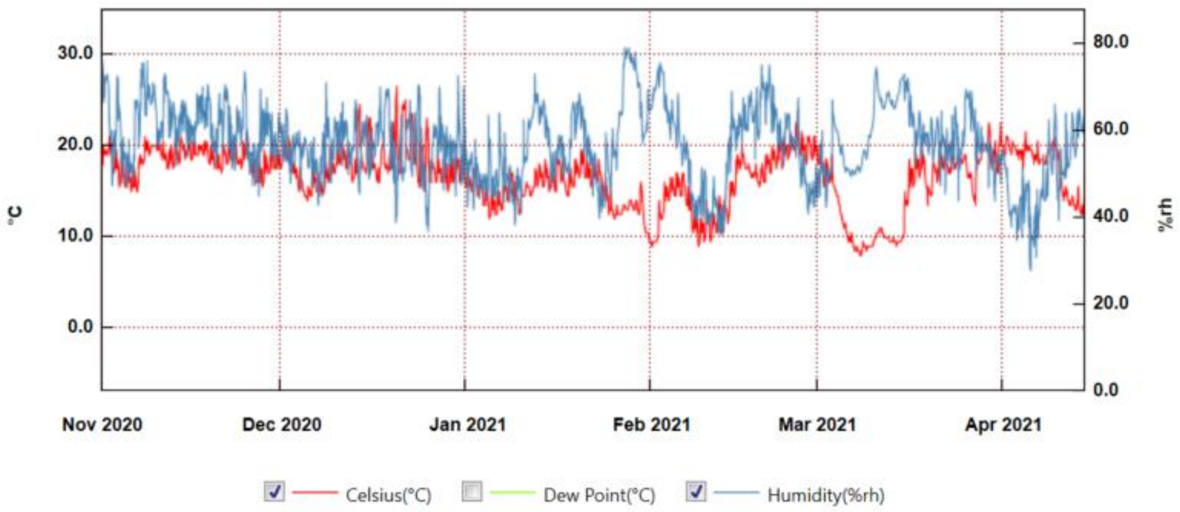


Figure 4.80 Graph of living room temperature and relative humidity for household B-07 from 1 Nov 20 to 15 Apr 21, before the Boxergy Hero installation

Figure 4.80 is a plot of the living room temperature and relative humidity for household B-07, for the period between 1 Nov 20 and 15 Apr 21 with the original heating system in place.

The room temperature fell below 10˚C on several occasions. This included a minimum of 8.0˚C on 8 Mar 21, during a period of several days (4 Mar to 15 Mar 21) when the residents was away from home. The temperature also fell below 10˚C at the beginning of February and in mid-February during a period of cold weather.

The average living room temperature over the analysis period was 16.59˚C. If the average only considered the period from 1 Nov 20 to 1 Mar 20, avoiding the period of cold temperatures while the residents were away, the average increased to 16.93˚C. The temperature went above 20˚C on a few occasions in December, reaching a maximum of 26.5˚C at 13:30 on 20 Dec 20.

The average relative humidity for the living room was 57.22%. There was a wide range between the values of maximum and minimum humidity over the analysis period. The maximum humidity was 79.0% at 18:00 on 27 Jan 21 when the temperature was 13.5˚C. The minimum in humidity of 28.0% was on 5 Apr 21 at 18:30 during a period when the living room temperature had been consistently about 19.5˚C for a few days.

Figure 4.81 shows the temperature and relative humidity for the bedroom of household B-07 over the same analysis period of 1 Nov 20 to 15 Apr 21. Again there was a dip in room temperature for the period of 4 Mar to 15 Mar 21 when the residents were away.

There were numerous spikes in room temperature over the analysis period due to use of supplementary heating without thermostatic control. The bedroom reached a maximum temperature of 29˚5C at 07:00 on 11 Dec 20. There were also significant dips in temperature, dropping to 10.5˚C at 07:00 on 9 Feb 21 during a spell of cold weather. The greater use of supplementary electric heating meant the average temperature of the bedroom was warmer than the living room at 18.0˚C.

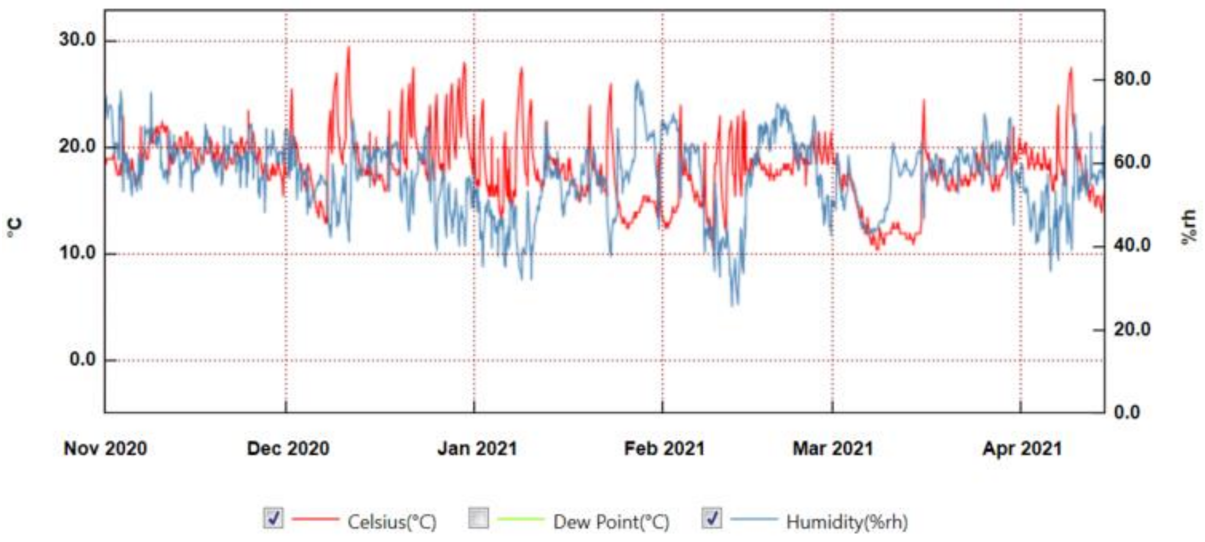


Figure 4.81 Graph of bedroom temperature and relative humidity for household B-07 from 1 Nov 20 to 15 Apr 21, before the Boxergy Hero installation

The average relative humidity of the bedroom was 56.79%, comparable to the value for the living room. There was a large range between the values for minimum and maximum humidity as for the living room.

The minimum value of relative humidity was 26.0% which occurred at 09:30 on 12 Feb 21 during an extended period of cold weather. The bedroom temperature had been at 22.5˚C for several hours and the humidity dropped from 35% overnight.

The maximum humidity of 80.0% occurred on 27 Jan 21 at 19:30. The bedroom temperature was 14.0˚C and had been that temperature or below since 24 Jan 21. The electricity consumption suggested the residents were not away during this period.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	16.59	26.5	8.0	3.16	57.22	79.0	28.0	8.34
Living Room 17:00 - 21:00	16.99	24.5	8.5		58.13	79.0	28.0	
Bedroom 24 hours	18.00	29.5	10.5	3.04	56.79	80.0	26.0	8.73
Bedroom 17:00 - 21:00	18.27	27.5	11.5		57.11	80.0	32.5	

Table 4.82 Household B-07 temperature and relative humidity between 1 Nov 20 and 15 Apr 21 Property with storage heaters and panel heaters, before Boxergy Hero installation

Month	Number of days	Total consumption (kWh)	Total consumption (kWh/day)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Degree Days	Total consumption per Degree Day (kWh/DD)
Feb-21	28	1672.0	59.72	£20.30	301.0	5.55
Mar-21	31	1000.2	32.26	£10.97	284.1	3.52
Apr-21	30	1323.8	44.13	£15.00	284.5	4.65
May-21	31	1281.2	41.33	£14.05	203.9	6.28
Jun-21	30	667.4	22.25	£7.56	58.6	11.39
Jul-21	31	601.2	19.39	£6.59	30.4	19.78
Aug-21	31	668.3	21.56	£7.33	46.7	14.31
Sep-21	30	916.5	30.55	£10.39	52.0	17.62
Oct-21	31	1049.5	33.85	£11.51	121.0	8.67
Nov-21	30	1498.4	49.95	£16.98	246.0	6.09
Dec-21	31	1469.8	47.41	£16.12	258.5	5.69
Jan-22	31	1863.7	60.12	£20.44	325.1	5.73
Year	365	14011.8	38.39	£13.05	2211.8	6.34

Table 4.83 Monthly electricity consumption and costs from Feb 2021 to Jan 2022 for household B-07, before the Boxergy Hero installation

In December 2020, household B-07 had a smart meter fitted with 5 meter tails. Despite having storage heaters and off-peak water heating and the last meter recording 2 rates, the new meter was set up as a single rate meter. As a result only total daily consumption readings were available for 2021. However, half-hourly meter readings were obtained for the whole of 2022. This allowed calculations of what would have been the peak and off-peak consumption.

The electricity consumption of household B-07 between 1 Feb 21 and 31 Jan 22 was 14,011kWh for the 12-month period. The consumption in January 2022 might have been higher than normal due to additional supplementary heating while removing the old heating system and fitting the wet central heating system.

The pre-installation annual consumption was similar to household B-03, another mid-terraced house, but with a floor area of 100m^2 instead of 87m^2. For the period 29 Oct 20 to 31 Oct 21, household B-03 used 13,910kWh or an average of 37.9kWh/day. Correcting for external temperature with Degree Days, household B-03 used 6.33kWh/DD compared to 6.34/DD for household B-07.

It was only possible to estimate costs for household B-07 using single rate Tariff 1 during the 2021. The average monthly costs ranged from £20.44/day in January 2022 to £6.59/day in July 2021. Over the full 12-month period, the average daily cost was £13.05/day or an annual bill of £4,764 using the single rate tariff for the Electricity Price Guarantee from 1 Oct 22 to 31 Mar 23. Despite this high electriicity cost, it is clear from the average room temperatures that the home was not adequately heated.

The electricity consumption of household B-07 in January 2022 was 60.12kWh/day. It was possible to assess what would have been the peak and off-peak consumption in January

2022 using half-hourly meter consumption data. The average off-peak consumption was 19.51kWh/day, making the percentage off-peak consumption 32.46%.

Figures 4.x (a) and (b) show examples of the electricity consumption by household B-07 on the 24-hour and heating circuit between 1 Dec 21 and 8 Dec 21. On the heating circuit there was a daily peak in electricity consumption overnight with a maximum value of about 23,700mA or about 5.5kW. The electricity consumption started just after midnight once the off-peak period began and lasted until between 05:00 and 07:00. The consumption sometimes dipped to 10,000 to 13,000mA. It is likely this consumption was due to one of the Dimplex XL18N storage heaters (2.55kW) and the immersion water heater.

On the 24-hour circuit, there was a baseload of about 1,400mA (325W). There were periods with consistent peaks of consumption of about 7,900mA, such as from 10:00 to 20:00 on 7 Dec 21. This might have been due to a 1.5kW electric heater. On some days like 5 Dec 21 at 19:30, there was initially greater consumption (21,500mA). This may have been due to initially using an additional 3kW electric heater to warm up the room.

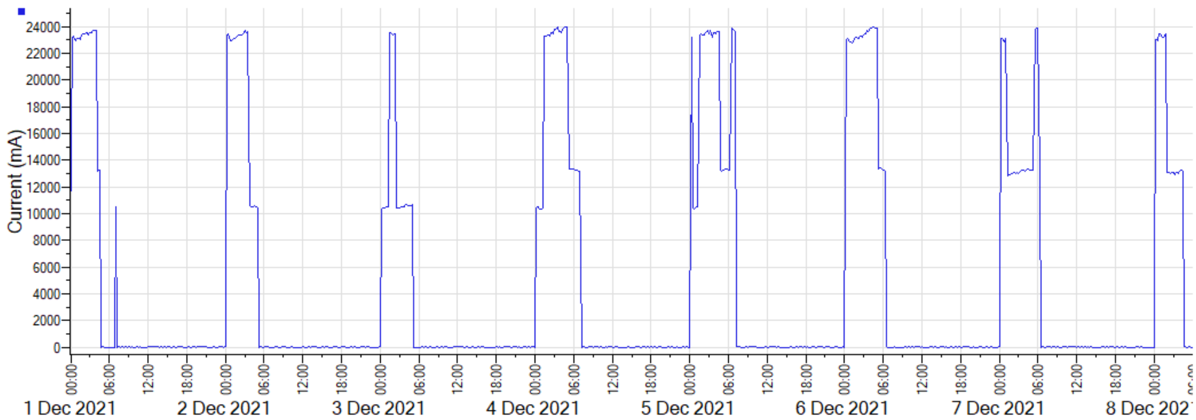


Figure 4.84 (a) Heating circuit electricity consumption for household B-07 between 1 Dec 21 and 8 Dec 21. Property with storage heaters before the Boxergy Hero installation

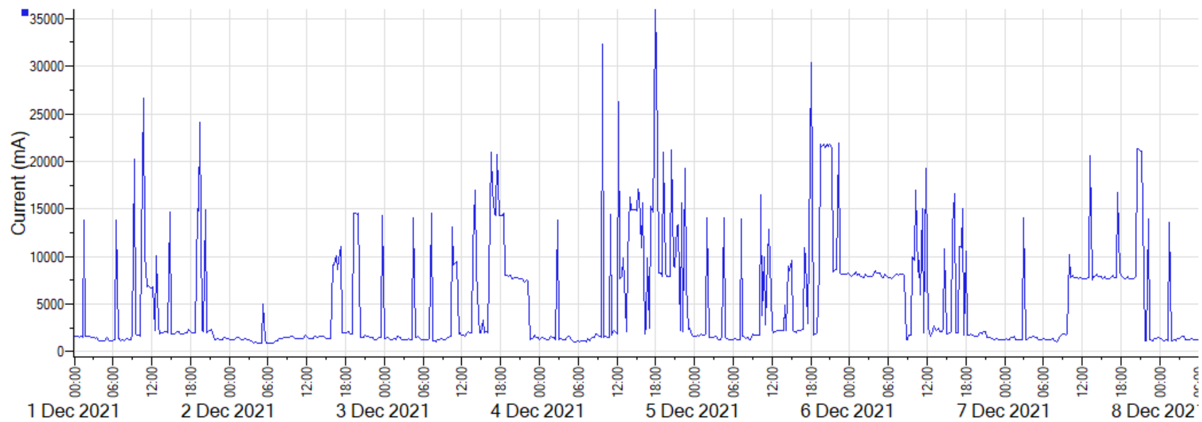


Figure 4.84 (b) 24-hour electricity circuit consumption for household B-07 between 1 Dec 21 and 8 Dec 21. Property with storage heaters before the Boxergy Hero installation

4.8.2. Post-installation period for household B-07

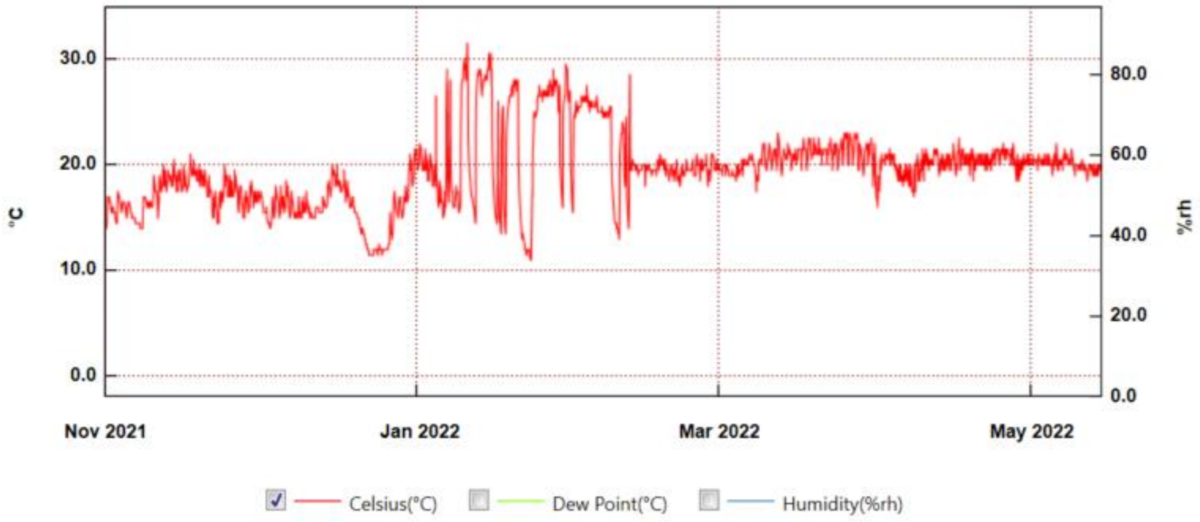


Figure 4.85 Graph of living room temperature for household B-07 from 1 Nov 21 to 15 May 22, before and after the Boxergy Hero installation

Figure 4.85 shows a graph of the living room temperature from 1 Nov 21 to 15 May 22. Between the beginning of November and the end of December, the living room temperature was rarely at or above 20˚C. The temperature dropped to 11.5˚C during an extended period over Christmas when the family was likely to have been away.

During January until the Boxergy Hero system was operational in mid-February there was a wide variation in the temperature of the living room. For example on 12 Jan 22, the temperature had fallen to 14.5˚C by 11:00. After 3 hours of supplementary heating, the living room temperature had risen to 26.0˚C and later peaked at 29.0˚C at 01:30 on 13 Jan 22. The supplementary heaters used by the household were controlled by turning them on or off rather than having a thermostat. This led to the wide range in living room temperature and periods of over and under heating.

The storage heaters were taken out during the second week of January, leading to increased use of supplementary heating. This and the way the supplementary heaters were controlled may largely explain the wider room temperature range during Janary and early February until the new heating system was running.

A plot of the living room temperature and relative humidity is shown in figure 4.86 (a) for the period 15 Feb 22 to 30 Apr 22. During this analysis period after the Boxergy Hero system was operational, there was a much more limited variation in the living room temperature, which was consistently at or close to 20˚C. The average temperature was 20.36˚C, with the temperature ranging between a minimum of 16.0˚C and a maximum of 23.0˚C. There was a clear improvement with consistent thermal comfort compared to January to mid-February 2022. It was also an improvement over the previous heating season where the average living room temperature was 16.59˚C and the temperature ranged between 8˚C and 26.5˚C.

There was a wider variation in relative humidity over the analysis period, however the humidity was within the 40 to 60% optimum level during the majority of this period. The average humidity was 50.49% and the humidity ranged between 32.0 and 72.5%.

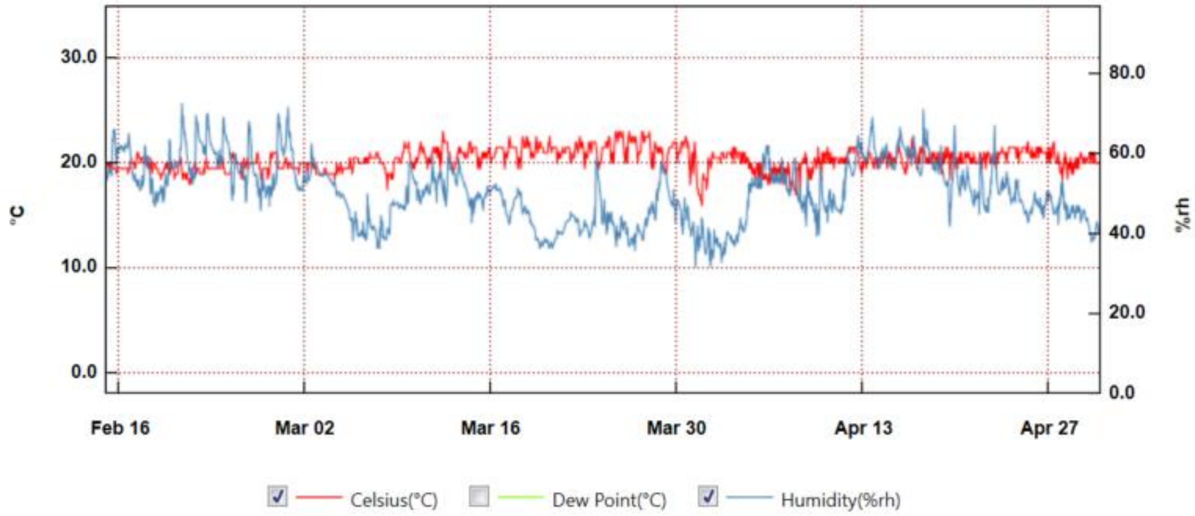


Figure 4.86 (a) Graph of living room temperature and relative humidity for household B-07 from 15 Feb 22 to 30 Apr 22, after the Boxergy Hero installation

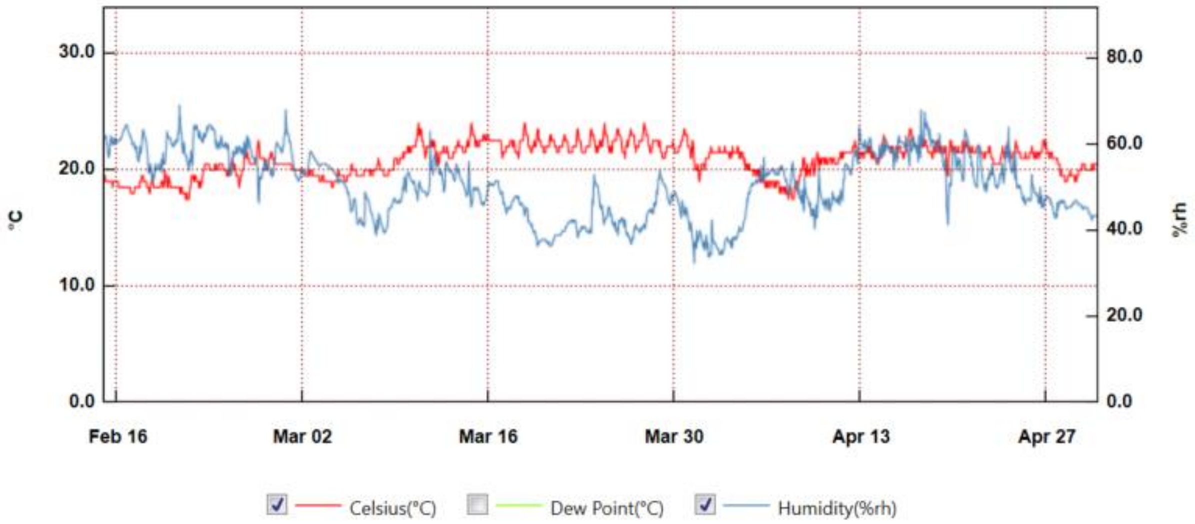


Figure 4.86 (b) Graph of bedroom temperature and relative humidity for household B-07 from 15 Feb 22 to 30 Apr 22, after the Boxergy Hero installation

Figure 4.86 (b) shows the bedroom temperature and humidity for household B-07 after the Boxergy Hero system was running. There were similarities in the profiles of the temperature and relative humidity for the bedroom and living room over the analysis period 15 Feb 22 to 30 Apr 22.

The average temperature in the bedroom was 20.88˚C, just over half a degree Celcius warmer than the living room during the same analysis period. The temperature ranged between a minimum of 17.5˚C and 24.0˚C, which was 1 to 1.5˚C warmer than the living room.

The larger peaks and troughs in the relative humidity occurred at the same time with similar levels for the 2 rooms. The average relative humidity in the bedroom was 50.64% and only marginally different to the 50.49% in the living room. The humidity ranged from 32.5% to 69.0%, again close to the values for the living room (see table 4.87).

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	20.36	23.0	16.0	1.00	50.49	72.5	32.0	7.60
Living Room 17:00 - 21:00	20.52	23.0	16.5		51.31	72.5	34.0	
Bedroom 24 hours	20.88	24.0	17.5	1.35	50.64	69.0	32.5	7.50
Bedroom 17:00 - 21:00	21.25	24.0	17.5		50.49	69.0	34.0	

Table 4.87 Household B-07 temperature and relative humidity between 15 Feb 22 and 30 Apr 22 Property after the Boxergy Hero system was operational

Table 4.88 shows the monthly electricity consumption of household B-07 after the Boxergy Hero system was operational. Although B-07 was on a single rate tariff throughout the project, it was possible to model the peak and off-peak consumption using half-hourly smart meter data.

Looking at an equivalent March to December period before and after the Boxergy Hero installation, the average consumption for this period in 2021 was 34.24kWh/day and this fell to 24.72kWh/day, a reduction of 27.8%. Taking external temperatures into account with Degree Days, the consumption for 1 Mar 21 to 31 Dec 21 was 6.61kWh/DD compared to 5.26kWh/DD for the period in 2022. This was a reduction of 20.4%.

Comparing monthly consumption before and after the Boxergy Hero installation, there was a reduction in consumption for every month apart from March and December when there was a small increase. For example in April 2021, the consumption was 44.13kWh/day (4.65kWh/DD) and this reduced to 30.90kWh/day (4.2kWh/DD) the following year.

There was consistently lower electricity consumption in the summer after the Boxergy Hero installation. In the months June to August, the reduction in monthly average consumption was between 4.9 and 8.8kWh/day. The lower consumption may be due to a combination of periods away from home and greater efficiency heating water with the heat pump.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Mar-22	31	11.85	20.91	32.76	63.82%	256.0	3.97
Apr-22	30	11.93	18.97	30.90	61.39%	220.6	4.20
May-22	31	6.73	15.50	22.24	69.72%	120.1	5.74
Jun-22	30	4.17	11.14	15.31	72.76%	73.4	6.26
Jul-22	31	1.48	9.10	10.58	85.98%	29.4	11.15
Aug-22	31	7.84	8.83	16.67	52.95%	15.9	32.50
Sep-22	30	7.32	9.55	16.87	56.58%	73.9	6.85
Oct-22	31	10.76	12.44	23.20	53.61%	93.7	7.67
Nov-22	30	10.85	19.03	29.88	63.68%	198.6	4.51
Dec-22	31	24.08	24.51	48.59	50.44%	356.2	4.23
Full period	306	9.72	15.00	24.72	60.69%	1437.8	5.26

Table 4.88 Monthly electricity consumption from Mar 22 to Dec 2022 for household B-07, after the Boxergy Hero installation

The electricity consumption in December 2022 was 48.59kWh/day which was slightly higher than the average for December 2021 of 47.41kWh/day with the old heating system. The weather was colder in December 2022 compared to the month the year before, having 356.2 Degree Days instead of 325.1. This meant the consumption after taking external temperature into account was lower following the Boxergy Hero installation at 4.23kWh/DD compared to 5.69kWh/DD in December 2021. It should be noted that in addition to this reduction in consumption, there was also likely to be an improvement in thermal comfort.

Estimates of the monthly average electricity consumption by the heat pump are shown in table 4.89 for household B-07. The consumption was highest in December 2022 as a result of the colder weather, using 29.13kWh/day. This compared to 27.42kWh/day for household B-06 and 28.13kWh/day for household B-05. All 3 of these households had the Vaillant sensoCOMFORT smart thermostat in manual mode. However household B-07 had the set point at 19.0˚C while for household B-05 it was 21.5˚C. The small difference in daily consumption despite household B-07 having a larger floor area may be largely due to the lower set point temperature.

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Mar-22	15.97	1.55	17.52	8.8%	1.93
Apr-22	9.60	2.57	12.17	21.1%	1.31
May-22	2.84	2.35	5.19	45.3%	0.73
Jun-22	1.07	2.07	3.13	66.0%	0.44
Jul-22	0.48	1.39	1.87	74.1%	0.51
Aug-22	0.19	2.23	2.42	92.0%	0.38
Sep-22	2.67	1.80	4.47	40.3%	1.08
Oct-22	5.26	1.26	6.52	19.3%	1.74
Nov-22	10.23	1.27	11.50	11.0%	1.55
Dec-22	27.29	1.84	29.13	6.3%	2.38
Total	7.58	1.83	9.41	19.4%	1.61

Table 4.89 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-07. Data derived from the Vaillant sensoAPP.

Half-hourly smart meter data showed that from the time of installation, the Alpha ESS battery was charging overnight and discharged during the day. Figure 4.90 shows a plot of half-hourly consumption from 10 May 22. It was apparent there was high consumption from about 03:00 when the battery was charging, with a drop in consumption in the middle of the day. In colder weather, when demand from the heat pump was higher, the battery would fully discharge earlier in the day with consumption subsequently from the grid.

There was an issue with the battery exporting electricity for household B-07 as well as others such as B-02, B-04 and B-06. On 18 Nov 22, the household smart meter showed there had been at total 214kWh of export to the grid since the installation.

The grid consumption was not recorded on the Alpha ESS battery portal until July. The export may have occurred during the period when the battery system may not have had an accurate value for the grid consumption.

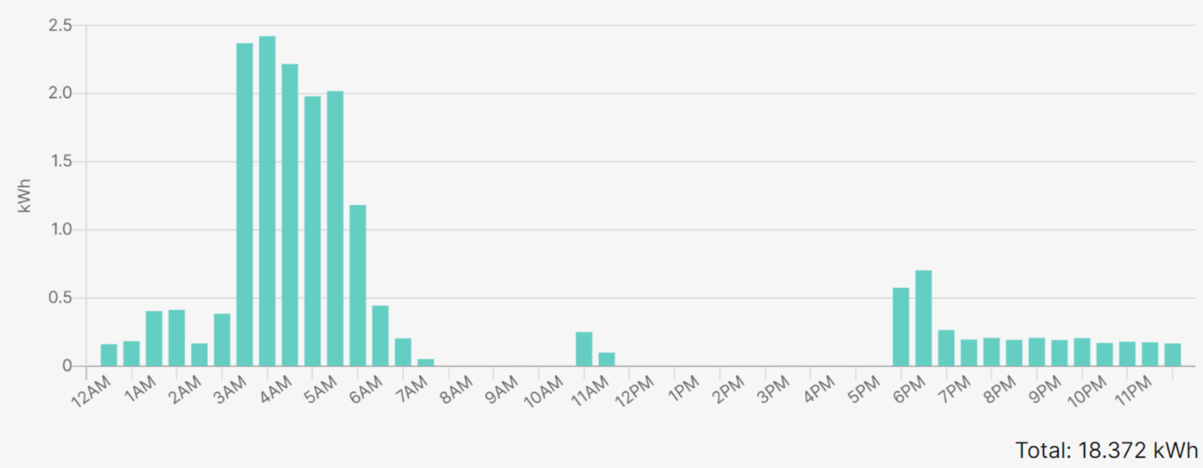


Figure 4.90 Half-hourly electricity consumption from Carbon Coop PowerShaper monitor portal for household B-07 on 10 May 22 after the Boxergy Hero installation

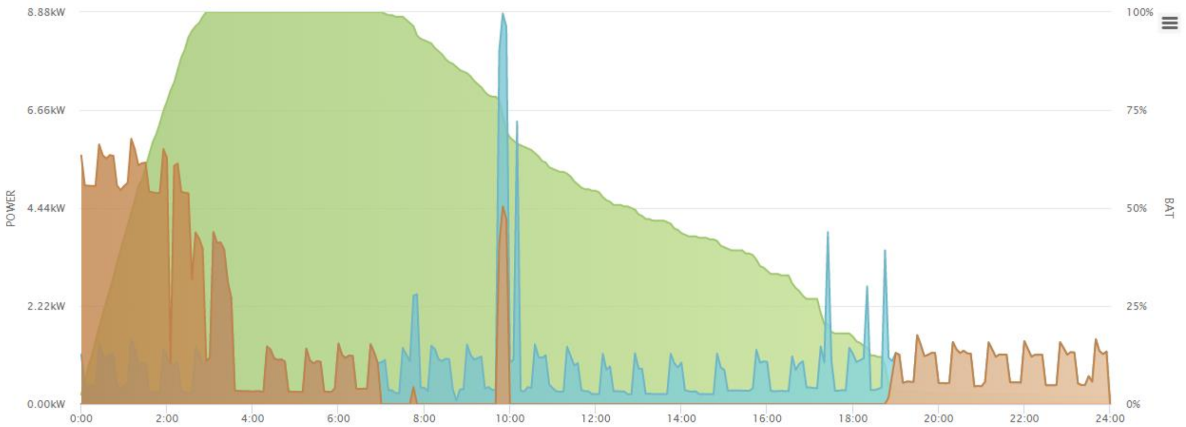


Figure 4.91 Power Diagram from the Alpha ESS battery portal for Household B-07 on 14 Oct 22 Property with Boxergy Hero system with ASHP and electrical battery operational

From the beginning of August 2022, the time for the battery to start charging was altered from 03:00 to midnight. The electricity supplier for this household had the time for off-peak electricity on Economy 7 between 00:00 and 07:00 on Greenwich Mean Time (GMT) throughout the year. This meant while on British Summer Time (BST), the off peak times were 01:00 to 08:00. Although household B-07 was still stuck on a single rate tariff at this time, this would have reduced the potential savings on Economy 7. The same issue with the battery charging outside the off-peak times also affected household B-06 between August and October.

As a result of the battery starting to charge an hour before the off-peak time, there was a drop in the modelled off-peak consumption for household B-07 from August to October. In July the percentage off-peak consumption was 86% and it fell to between 53.0 and 56.6% for the months of August, September and October.

Figure 4.91 shows a Power Diagram from the Alpha ESS battery portal for household B-07 on 14 Oct 22. There are similarities to the smart meter data from 10 May 22 in figure 4.90, except the battery charge began at 00:00 on 14 Oct 22. The battery was fully charged by 02:55 and started discharging from 07:00. This was again outside the Economy 7 times for the supplier during BST and so would have resulted in further lossed benefit from the battery.

At 09:45, the household consumption was about 8.5kW for about 10-minutes. This was due to use of the electric shower. Only about 4kW of the power could be provided by the battery and so there was additional grid consumption at that time. There was consumption shown on the smart meter plot for 10 May 22 at about 10:30, which may also have been due to use of the electric shower.

There were regular cycles of consumption from the heat pump throughout the day and night on 14 Oct 22. There was an initial peak of about 1.2kW which subsequently dropped to about 1kW before returning to the baseload consumption of about 275W. The resident typically had the smart themostat in manual mode with a constant set point temperature. As a result, the heat pump was running in regular cycles throughout the day.

The battery was fully discharged by 18:50. After this time, all household consumption was provided by the grid.

Table 4.92 shows the modelled electricity costs for household B-07 for the period after the Boxergy Hero installation. Over the period from 1 Mar 22 to 31 Dec 22, the average electricity consumption was 24.72kWh/day. This compares with an average of 34.24kWh/day for the same period the year before with the old heating system. There was a reduction in the average cost on the single rate tariff as a result. Between March and December 2021 the average electricity cost on single rate Tariff 1 was £11.64/day compared to £8.40 per day on Tariff 1 for the same period in 2022 after the Boxergy Hero system was running.

Had household B-07 managed to switch to an Economy 7 tariff, further savings would have been achieved. On Tariff 3 the average cost would have been £6.36/day, saving £2.04/day compared to the single rate tariff. There would have been a further £0.81/day saving with better value for money Tariff 4.

The consumption in March was slightly higher than in 2022 than in 2021. This meant that the consumption on single rate tariff increased from £10.97 per day to £11.14/day on Tariff 1.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Mar-22	32.76	63.82%	£11.14	£5.35	£8.14	£7.01
Apr-22	30.90	61.39%	£10.51	£5.14	£7.89	£6.87
May-22	22.24	69.72%	£7.56	£3.48	£5.15	£4.32
Jun-22	15.31	72.76%	£5.21	£2.34	£3.42	£2.82
Jul-22	10.58	85.98%	£3.60	£1.45	£1.96	£1.48
Aug-22	16.67	52.95%	£5.67	£2.94	£4.65	£4.17
Sep-22	16.87	56.58%	£5.74	£2.90	£4.54	£4.02
Oct-22	23.20	53.61%	£7.89	£4.07	£6.43	£5.76
Nov-22	29.88	63.68%	£10.16	£4.89	£7.43	£6.41
Dec-22	48.59	50.44%	£16.52	£8.72	£13.91	£12.58
Full period	24.72	60.69%	£8.40	£4.13	£6.36	£5.55

Table 4.92 Electricity consumption and costs for household B-07 using example electricity tariffs, between 1 Mar 22 and 30 Dec 22, after the Boxergy Hero system was installed

However on the Economy 7 tariffs, the average cost would be lower at £8.14/day on Tariff 3.

In July 2021 the cost on single rate tariff 1 was an average of £6.59/day. This decreased to £3.60/day the following year due to lower consumption, partly due to the household being away from home. Had the household been on Economy 7 tariff 3, the average cost would have been still lower at £1.96/day. The saving of £1.64 compared to the single rate tariff was so high due to 86% of the consumption being on the off-peak tariff.

The average consumption in August 2021 was higher than in August 2022, so the costs on Tariff 1 fell for that month from £7.33/day to £5.67/day after the Boxery Hero installation. There would have been further reductions on Economy 7 Tariff 3 with the cost falling to £4.65/day. The difference between the costs on Tariff 1 and Tariff 3 for August 2022 were smaller at £1.02 compared to the difference of £1.64 in July 2022. This was because the percentage off-peak consumption was lower in August due to the battery starting to charge and discharge an hour too early.

In December 2021, the average electricity cost on Tariff 1 would have been £16.12/day and this increased to £16.52/day (or £512) in December 2022. This increase in cost however was due to December 2022 being colder than the month the year before.

The costs would have been lower on the Economy 7 tariffs. On Tariff 3, the cost would have been £13.91/day or a total of £431. This would have been a saving of £81 over the month compared to the single rate tariff.

With a heating system like this for a medium size house, the electricity costs could be high during the coldest months. However costs would be relatively low in summer on Economy 7 such as the £1.96/day cost or £60.76 in July 2022.

Adding a solar PV array to the system could lead to significant reductions in electricitycosts. In summer savings were already being made due to lower consumption and a high proportion being shifted to off-peak times with the battery. Adding solar PV could allow the home to be powered by solar PV and battery much of the time in summer and if that is not possible with a top-up from the off-peak tariff.

In the Spring and Autumn when there are still high levels of sunshine, but the weather is colder, the solar PV system could either help power the heat pump or charge the battery during the day, significantly reducing the use of peak rate mains electricity.

In the middle of winter, the bills would still be high due to the high heating demand of the house and the associated electricity demand from the heat pump. The solar PV system would contribute only a small amount at this time of year, but the lower bills in summer could be offset against the high bills in winter.

4.9. Household C-01

Household C-01 lived in a 2-bedroom semi-detached bungalow of the same size and design as households B-01, B-04, B-05 and B-06. During the period of the study, the household used infrared heaters. The household was used as a control property to compare the performance and running costs with the other heating technologies.

At the start of the project, the bungalow had several traditional storage heaters, but the residents had stopped using these due to dissatisfaction with the running costs and the control. They initially bought an electric radiator with a digital thermostat in February 2019. This provided heat when it was needed but it was expensive to run, so they could not use it as often as they would have liked.

The household first bought foldable infrared panels for the bedroom and the hall in November 2020. The following month, an infrared panel which had thermostatic control was fitted in the living room which had the appearance of a framed picture on the wall. Over the coming months further panels were added or old ones updated (table 4.93). The panels were supplied by several companies including Kiasa, Byecold and Klarstein. The residents were very satisfied with the infrared panels, and commented that they don't distribute dust and dry the air like storage heaters. They also felt the running costs were lower.

North Devon Homes had Dimplex Quantum storage heaters fitted in the property in February 2022. They were tested on 15 Feb 22, but not used again by the household, who continued to use the infrared heating panels. The household also had a battery electric car. This caused spikes in consumption when it was charged, but it had limited use and so was charged infrequently.

There was an attempt to monitor the consumption of the infrared panels using smart plugs with monitoring. This was successful for a few weeks, but there were subsequent issues with loss of signal, loss of connection during power cuts and the smart plugs being disconnected when panels were replaced. As a result limited data was collected.

Room	Notes	Initial panel size (W)	Final panel size (W)
Living room	Fitted in December 2020. Panel in picture on wall. Has thermostatic control. Room rarely used	700	700
Hall	Initially a foldable panel which was replaced with a larger solid panel with thermostatic control in February 2022	450	650
Main bedroom	Initially had a foldable panel with no thermostatic control, but this was replaced in March 2022 with a larger thermostatically controlled panel in a picture	450	500
Bed 2/Study	Fitted before October 2021	350	350
Kitchen	Fitted before October 2021	350	350
Utility room	Fitted in March 2021 – had no thermostatic control	350	350

Table 4.93 Details of infrared heating panels used by household C-01

The temperature on infrared panels can reach between 85 and 100˚C and so emit a higher percentage of radiant heat. As a result, they are said to heat the room rather than the air within the room. Manufacturers claim that they use less energy to heat a room than most convection heaters[23]. The panels are said to shine heat like the sun and so it is possible to feel comfortable with a lower room temperature.

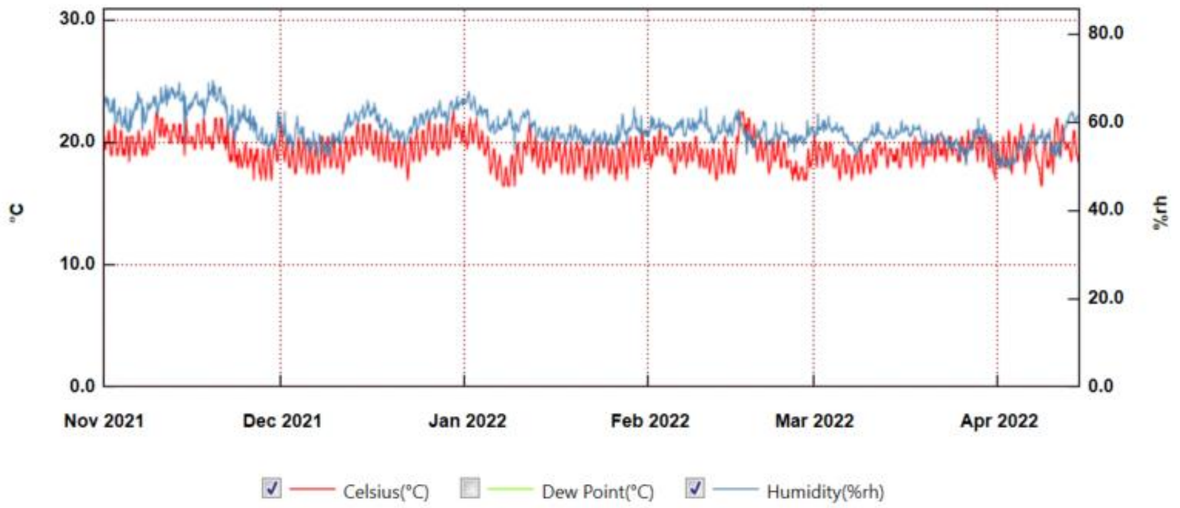


Figure 4.94 Graph of bedroom temperature and relative humidity for household C-01 from 1 Nov 21 to 15 Apr 22, using infrared heating panels

The bedroom was the main room used in the house. Figure 4.94 shows a plot of the temperature and relative humidity in the bedroom of household C-01 for the analysis period 1 Nov 21 to 15 Apr 22. There was initially a 450W foldable infrared panel on the wall and this was replaced with a 500W thermostatically controlled infrared panel in March 2022. There was no evidence of change in room temperature after the panel was changed.

The average temperature in the bedroom was 19.67˚C between 1 Nov 21 and 15 Apr 22, with the temperature ranging from 17.0 to 23.0˚C. The temperature was less comfortable for the same dates during the heating season the year before. In this case the average temperature was 18.02˚C and the temperature ranged between 14.5 and 21.0˚C (see Appendix 6). The residents noted a high degree of thermal comfort over the project and the house and this room in particular felt warm during visits by NEA staff.

The relative humidity showed a high degree of consistency during the analysis period in the 2021/22 heating season. The average relative humidity was 58.82%. The range in humidity was between a minimum of 49.5% and a maximum of 69.5%. The humidity was at the upper end of the optimum 40 to 60% range or just above. As the residents noted, the air did not get too dry with the heating.

The humidity in the bedroom was less consistent during the previous heating season for the analysis period 1 Nov 20 to 15 Apr 21. The average humidity was 64.4%. Over the 20/21 heating season, the bedroom humidity was between 42 and 78% compared to between 49.5 ad 69.5% in the 21/22 heating season.

[23] How do infrared heaters work, Herschel Infrared Heaters, https://www.herschel-infrared.co.uk/how-do-infrared-heaters-work/ (Accessed 10 Jan 23)

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	14.67	22.0	9.0	2.24	72.36	88.0	58.5	4.26
Living Room 17:00 - 21:00	15.05	22.0	9.0		72.23	88.0	58.5	
Bedroom 24 hours	18.02	21.0	14.5	1.09	64.4	78.0	42.0	5.11
Bedroom 17:00 - 21:00	18.25	21.0	15.5		62.23	77.0	44.5	

Table 4.95 Household C-01 temperature and relative humidity between 1 Nov 20 and 15 Apr 21. Property using infrared panels for heating

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	15.99	21.0	12.5	1.53	65.94	77.5	51.0	3.96
Living Room 17:00 - 21:00	16.67	21.0	13.0		65.9	76.0	51.5	
Bedroom 24 hours	19.67	23.0	17.0	1.68	57.16	76.5	34.5	6.04
Bedroom 17:00 - 21:00	19.71	22.5	17.0		56.89	76.5	36.0	

Table 4.96 Household C-01 temperature and relative humidity between 1 Nov 21 and 15 Apr 22. Property using infrared panels for heating

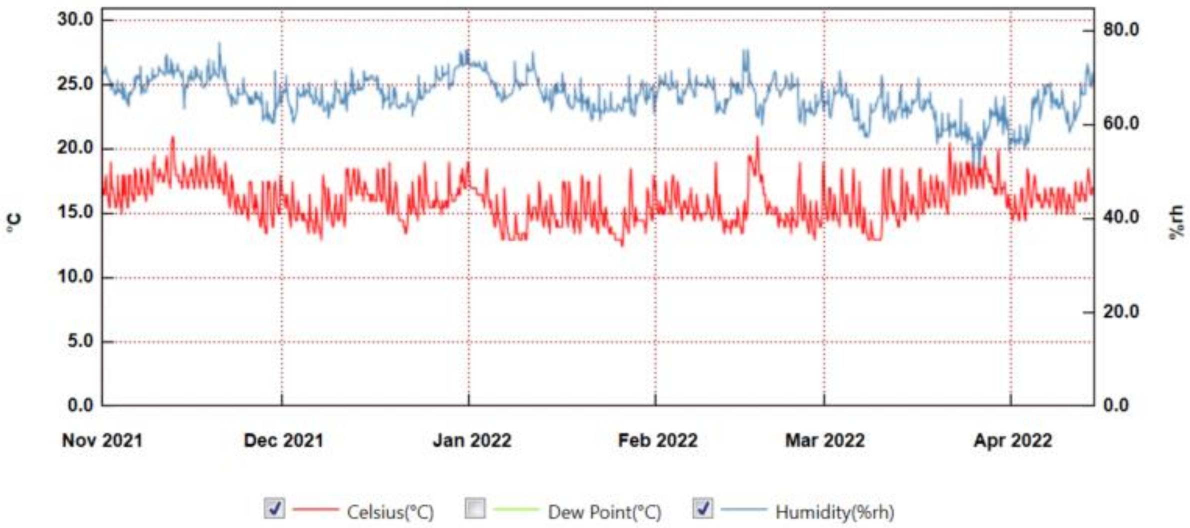


Figure 4.97 Graph of living room temperature and relative humidity for household C-01 from 1 Nov 21 to 15 Apr 22, using infrared heating panels

The heating in the living room was only occasionally turned on as the room was rarely used. There was sometimes daily heating and cooling as with the rest of the house along with some sharper increases in room temperature during times when the infrared heating panel was operating and the room was occupied.

For example from 03:00 on 9 Mar 22 until 10:30 on 10 Mar 22, the living room temperature remained at 13.0˚C. After this time the temperature began to rise, reaching a maximum of 18.5˚C at 21:00 on 10 Mar 22. On that day a smart plug recorded that the living room infrared heating panel used 4.31kWh of electricity. By 08:30 the following day, the temperature had fallen to 14.5˚C. The temperature began to rise after 11:00 and reached 18.5˚ by 16:00 and remained at that temperature until 21:00, falling to 17˚C by midnight. The living room infrared heating panel used 6.54kWh on 11 Mar 22.

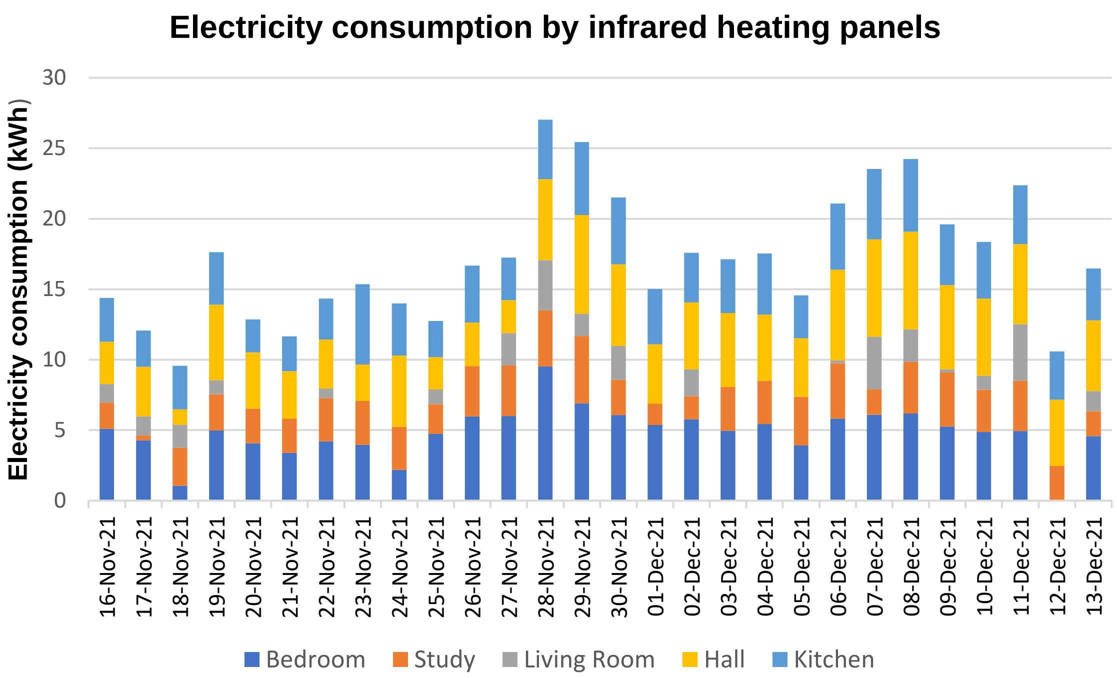


Figure 4.98 Graph showing the electricity consumption measured by smart plugs for 5 infrared heating panels used by household C-01 between 16 Nov 21 and 13 Dec 21

Figure 4.98 shows the electricity consumed by 5 of the infrared heating panels used by household C-01. Values of daily consumption were recorded by smart plugs that were fitted in mid-November. The bedroom smart plug lost connection in mid-December and limited data was collected subsequently with this plug due to connectivity issues and the heating panel being changed. The hall heating panel lost connection in February 2022 after the panel was replaced. A smart plug was fitted on the heating panel in the utility room in March 2022, but there were connectivity issues and it only collected a few weeks of data.

During the analysis period on the graph, the total electricity consumption recorded by the 5 infrared heating panels ranged from a minimum of 10.6 to a maximum of 27.04kWh/day. The average consumption was 17.16kWh/day. Smart meter data showed that the total consumption ranged from 29.32kWh on 18 Nov 21 to 44.65kWh on 28 Nov 21.

Room	Start date	End date	Average electricity consumed by panel
Bedroom	16 Nov 21	13 Dec 21	4.84 kWh/day
Living room	16 Nov 21	15 Apr 22	0.86 kWh/day
Study	16 Nov 21	15 Apr 22	3.17 kWh/day
Hall	16 Nov 21	15 Feb 22	5.0 kWh/day
Kitchen	16 Nov 21	15 Apr 22	3.31 kWh/day
Utility room	9 Mar 22	23 Mar 22	6.76 kWh/day

Table 4.99 Average daily electricity consumption of infrared heating panels for household C-01 as measured by smart plugs

Looking at individual infrared panels. the average consumption for the bedroom panel was 4.84kWh/day for the period 16 Nov 21 to 13 Dec 21. The living room infrared heating panel was rarely used and so the average consumption over the period 16 Nov 21 to 15 Apr 22 was only 0.86kWh/day. However the consumption ranged from 0 to 6.54kWh, with consumption recorded on 48 out of 150 days.

The study panel heater was used almost every day between 16 Nov 21 and 15 Apr 22 with an average consumption of 3.17kWh/day. There was a shorter monitoring period for the hall heating panel as the smart plug was removed when the new panel was fitted. For the period 16 Nov 21 to 15 Feb 22 the average consumption of the hall infrared panel was 5.0kWh/day.

There was consistent electricity consumption on the kitchen smart plug between 16 Nov 21 and 15 Apr 22 apart from 6 days in February when the other heaters were still being used. There were limited electrical sockets in the kitchen and it is possible that other appliances might have been used with this smart plug. The average consumption was 3.31kWh/day.

The utility room was the outhouse for the bungalow and traditionally an unheated space. A 350W panel heater without a thermostat had been running in the outhouse throughout the day when the smart plug was fitted. Between 9 Mar 22 and 23 Mar 22 the average consumption was 6.76kWh/day, ranging from 6.0 to 7.0kWh. There was a poor internet connection for the plug in this room. As a result there were subsequently periods when the plug was not connected to the internet. The consumption reduced in April, but it was not clear if this was due to less use of the infrared heating panel or data loss.

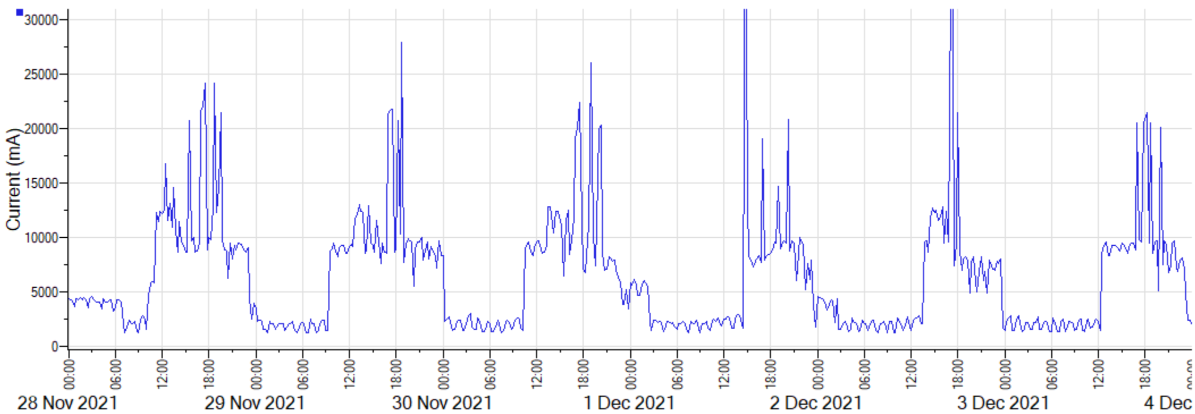


Figure 4.100 Electricity consumption for household C-01 between 28 Nov 21 and 3 Dec 21 as measured by Tinytag View 2 data loggers with current clamps. Property with infrared heating panels

The graph in figure 4.100 shows electricity consumption (in milliamps) for household C-01 for the period 28 Nov 21 to 4 Dec 21. This includes some of the days covered in figure 4.99, which shows the daily electricity consumption by 5 of the infrared heating panels.

Over the analysis period there was a typical overnight baseload which varied between 1,225mA and 2,210mA or about 282W to 508W. This might due to a small infrared panel such as the one in the utility room running 24 hours a day with the additional consumption being due to the fridge/freezer and small chest freezer cutting in and out througout the night and during the day. An infrared panel consistenly consuming 282W throughout the day would use 6.77kWh, which is close to the average consumption that was recorded for the Utility room infrared panel in March 2022.

The overnight consumption on 28 Nov 21 was higher than on the other nights, consistently reaching 4,300mA or about 990W. This may be due to also leaving the bedroom or hall infrared panel running overnight.

During the day, there was a broad consumption peak with additional sharp consumption peaks on top of that. The broad consumption peak was about 9,100mA or approximately 2.1kW. This may have been due to the bedroom, hall and study infrared panels running in addition to the utility room. On 29 Nov 22 the broad consumption peak lasted from 09:15 until midnight, suggesting that these 4 infrared panels operated for about 15 hours that day.

The additional sharp consumption peaks on top of the broad consumption peaks were likely to be due to cooking, use of the kettle and electric shower (when the consumption went above 30,000mA).

Table 4.101 shows the monthly electricity consumption of household C-01 for the period December 2021 to November 2022. The average electricity consumption was 18.49kWh/day or 7701kWh for the 12-month period. An Energy Performance Certificant for the property when it had manual charge control storage heaters estimated the space heating demand to be 7,600kWh and the water heating demand to be 2,135kWh. During the analysis period with the measured consumption, the home was well heated apart from the living room.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Dec-21	31	32.10	4.06	36.16	11.24%	258.5	4.34
Jan-22	31	30.18	6.47	36.65	17.66%	325.1	3.49
Feb-22	28	28.52	6.90	35.42	19.49%	249.7	3.97
Mar-22	31	25.11	3.10	28.21	10.99%	256.0	3.42
Apr-22	30	20.86	1.77	22.63	7.81%	220.6	3.08
May-22	31	14.86	1.30	16.16	8.03%	120.1	4.17
Jun-22	30	10.67	0.76	11.43	6.65%	73.4	4.67
Jul-22	31	10.46	0.93	11.39	8.17%	29.4	12.01
Aug-22	31	9.69	1.01	10.71	9.47%	15.9	20.88
Sep-22	30	8.76	0.96	9.73	9.92%	73.9	3.95
Oct-22	31	11.11	1.71	12.82	13.33%	93.7	4.24
Nov-22	30	20.04	2.64	22.68	11.64%	198.6	3.43
Year	365	18.49	2.61	21.10	12.38%	1914.9	4.02

Table 4.101 Monthly electricity consumption from Dec 2021 to Nov 2022 for household C-01, with infrared panel heaters

It is possible to compare the consumption with some of the other bungalows on the project, correcting for variations in external temperature using Degree Days. The consumption of household C-01 correcting for external temperature was 4.02kWh/DD. The consumption of household B-02 was 4.2kWh/DD using storage heaters and household B-01 was 2.96kWh/DD with the Vaillant aroTHERMplus air-source heat pump. The consumption of households B-04 and B-05 was higher. These were 5.36kWh/DD and 5.46kWh/DD respectively prior to having the Boxergy installation.

The household was on a single rate tariff, but it was possible to model the peak and off-peak consumption for Economy 7 from smart meter data. The off-peak consumption was low, averaging at 2.61kWh/day with an average percentage off-peak consumption of 12.38%. In the summer the average off-peak consumption was about 1kWh/day or less. In the winter it was higher at 4.1 to 6.9kWh. There seemed to be little water heating overnight, probably as there was no benefit for it on a single rate tariff. Most of the overnight consumption in winter was likely to be due to infrared heating panels running overnight and the baseload consumption from appliances like the fridge and freezers.

Figure 4.102 shows a graph of electricity consumption for household C-01 against Degree Days, which illustrates how the consumtion changes as the external temperature becomes colder. The consumption broadly increased with Degree Days with a moderate amount of scatter around the trend-line. There was a data point significantly away from the trend-line on 19 Oct 22, where the consumption was 56kWh. This was most likely due to the household charging their battery electric car that day. The gradient of the trendline was higher than for several of the Boxergy installations, but the y-intercept was lower. The intercept for the Boxergy installations tended to be 10 to 15kWh, most likely due to the battery. The consumption of B-04 and B-05 was typically under 30kWh for 10 Degree Days.

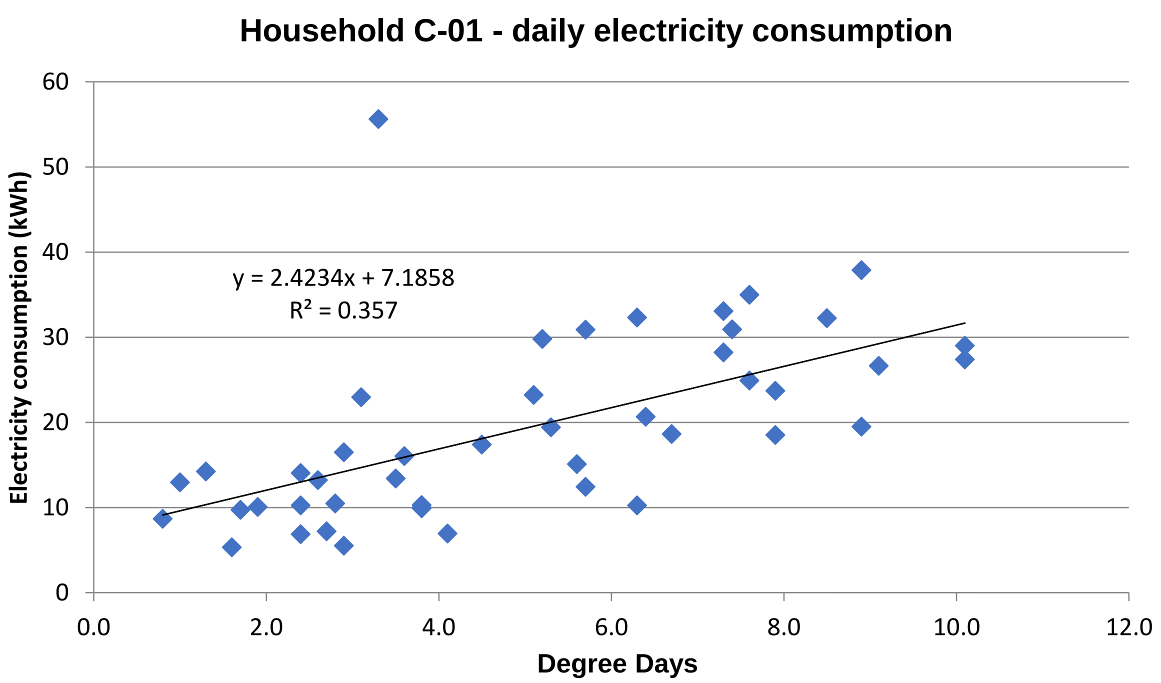


Figure 4.102 Graph showing the variation in daily total electricity consumption with Degree Days, from 15 Oct 22 to 30 Nov 22 for household C-01 with infrared heating panels and an electric vehicle charger

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Dec-21	36.16	11.24%	£12.30	£8.19	£14.36	£14.10
Jan-22	36.65	17.66%	£12.46	£8.02	£13.89	£13.50
Feb-22	35.42	19.49%	£12.04	£7.67	£13.24	£12.83
Mar-22	28.21	10.99%	£9.59	£6.40	£11.22	£11.02
Apr-22	22.63	7.81%	£7.69	£5.22	£9.21	£9.08
May-22	16.16	8.03%	£5.49	£3.72	£6.56	£6.47
Jun-22	11.43	6.65%	£3.88	£2.65	£4.69	£4.63
Jul-22	11.39	8.17%	£3.87	£2.62	£4.62	£4.56
Aug-22	10.71	9.47%	£3.64	£2.45	£4.31	£4.24
Sep-22	9.73	9.92%	£3.31	£2.22	£3.90	£3.84
Oct-22	12.82	13.33%	£4.36	£2.87	£5.02	£4.91
Nov-22	22.68	11.64%	£7.71	£5.13	£8.98	£8.81
Year	21.10	12.38%	£7.17	£4.75	£8.31	£8.14

Table 4.103 Electricity consumption and modelled costs for household C-01 with infrared heating panels using example electricity tariffs, for the period 1 Dec 21 to 30 Nov 22

The monthly average electricity consumption for household C-01 is shown in table 4.103 for the period from 1 Dec 21 to 30 Nov 22. Although C-01 was on a single rate tariff, using half-hourly smart meter data, it was possible to calculate what would have been the consumption on the peak and off-peak rates for an Economy 7 tariff.

A set of 4 different tariffs was used to model the electricity costs for household C-01. Tariff 1 was a single rate tariff with the unit rate set at the level for the Energy Price Guarantee between 1 Oct 22 and 31 Mar 23. Tariff 2 was an Economy 7 rate typical from the start of the project. Tariffs 3 and 4 were Economy 7 tariffs available at the time of the Energy Price Guarantee.

The average cost for household C-01 over the year was £7.17/day or £2,618/year. The single rate Tariff 1 was cheaper for C-01 than Economy 7 Tariffs 3 and 4 over the year and for every month. This was because the percentage off-peak consumption for C-01 was so low, never exceeding 20%. Typically a household would need an average of over 30% off-peak consumption for an Economy 7 rate to be cheaper. On Tariff 3, household C-01 would have paid £8.31/day or £3,034.

The average cost for household C-01 for the period 1 Apr 22 to 30 Nov 22 was £4.98/day on single rate Tariff 1, the cheapest of the tariffs. In comparison, for household B-05 after the Boxergy installation, the cost was £4.01/day on Tariff 3.

Household C-01 was shown to have a consistently high electricity consumption during cold weather. This was 2kW or more through much of the day. The Vaillant aroTHERM plus heat pump installed with the Boxergy Hero system tended to use up to 1 to 1.2kW and go through cycles of operation during the day and so was likely to use less electricity. Technologies like storage heaters or the Boxergy Hero system which use lower cost off-peak tariffs are likely to have lower running costs than electric heating using a single rate or peak rate tariffs.

Adding a solar PV system could reduce running costs of the infrared panel heaters, particularly during months like March and October which are sunny and cold.

4.10. Household C-02

Household C-02 lived in a 3-bedroom mid-terraced house which had storage heaters and a Tesla Powerwall 2 battery. The property dated from about 1970 and was more modern than the other terraced houses in the project, B-03 and B-07, which were built in the late 1940s.

Household C-02 had 4 traditional manual charge controlled storage heaters. These were used to provide heating during the project. As for household B-05, there was a Dimplex CXL24N storage heater in the living room. This had an input rating of 3.4kW and a maximum storage capacity of 23.8kWh. It also had a built-in convector heater which was thermostatically controlled with an output of 2kW and could be turned on with a boost/on-off switch. This heater was used during cold weather, typically from November to March. The boost on this heater or another small supplementary heater could be used in the living room for short periods in the evening in winter.

The other 3 heaters were Dimplex XLN18N heaters which had an input of 2.55kW and could store up to 17.85kWh of heat. The storage heater in the hall was turned on in early October while the heaters in the kitchen and on the upstairs landing were used from about November to March/April. There were no additional heaters in the bedrooms, so heating was provided by the storage heater on the upstairs landing.

The residents were concerned about the running cost of the heaters and that they had little flexibility in catering for changes in the external temperature. There were challenges in knowing the likely weather a day in advance to appropriately set the controls. The heat also tended to dissipate quickly after turning up the output. The residents tended to just leave the input and output controls on an appropriate setting rather than regularly adjusting them.

In 2017/18, NEA worked with North Devon Homes on a project where Tesla Powerwall 2 batteries were installed in homes with Economy 7 electricity tariffs. The properties did not have solar PV and so the batteries charged on the cheap off-peak tariff and supplied power to the home during the expensive peak rate period.

Household C-02 was one of those that received a battery in that project. The Tesla Powerwall 2 battery, which had a 13.5kWh usable capacity, was installed on 31 Jan 18 and was fully operational from 23 Mar 18.

Post-performance monitoring was carried out between 1 Apr 18 and 1 Feb 19. The average total electricity consumption ranged from 16.1kWh/day in June 2018 to 45.9kWh/day in January 2019. The average percentage off-peak consumption was between 84.3% and 96.4% for the months during post-installation monitoring. During a pre-installation period from 1 Jun 17 to 1 Mar 18, the monthly average off-peak consumption was between 36.4 and 75.5%. Further information on that project can be found in the NEA evaluation report with household C-02 described as household T-09[24].

A reading was taken from the smart meter for household C-02 to obtain the level of electricity exported to the grid since the battery was operational on 23 Mar 18. This was

[24] Paul Rogers and Michael Hamer, Tesla Powerwall 2 batteries charged using off-peak electricity, (NEA, 2019), https://www.nea.org.uk/wp-content/uploads/2020/10/CP1139-TIF-REPORT_FINAL-25-04-19-v2.pdf (Accessed 11 Jan 22)

267.9kWh on 18 Nov 22 or 0.16kWh/day. This compares to 402kWh in less than a year for household B-02 with the Alpha ESS battery that was installed with its Boxergy Hero system.

Figure 4.104 shows the temperature and relative humidity in the bedroom for the analysis period from 1 Nov 21 to 15 Apr 22. The average temperature was 19.67˚C and the temperature ranged between a minimum of 17.0˚C and a maximum of 23.0˚C. There was limited variation within a day, but longer-term variations, most likely due to changes in the weather. The thermal comfort in the bedroom during this period was better than for many of the bedrooms of other properties on this project despite relying on the storage heater at the top of the stairs for heating. The average humidity was 57.16% and the humidity ranged between 34.5% and 76.5% in the 2021/22 winter heating season.

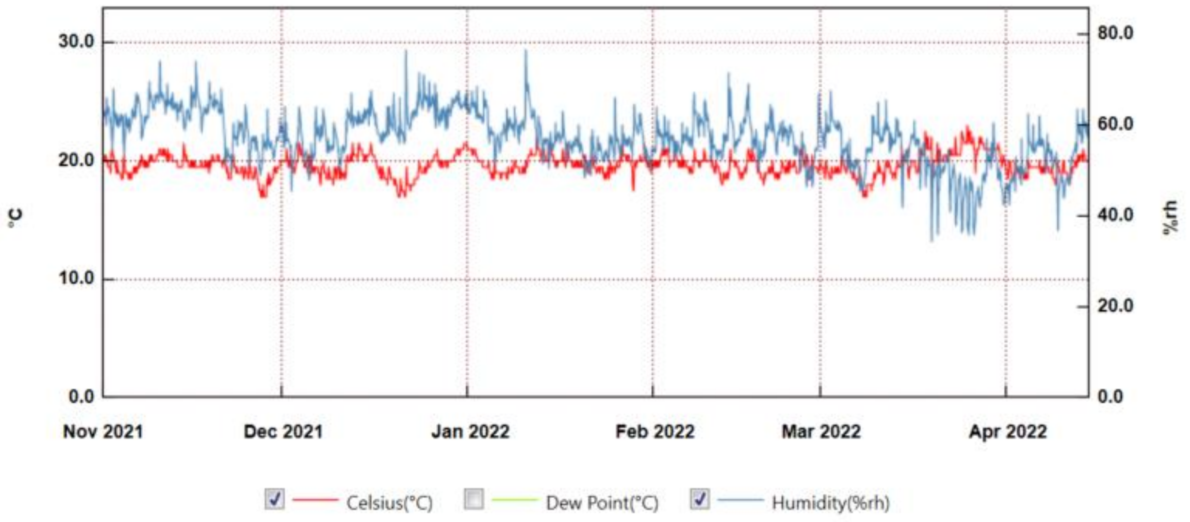


Figure 4.104 Graph of bedroom temperature and relative humidity for household C-02 from 1 Nov 21 to 15 Apr 22, using with traditional storage heaters

Thermal comfort was less good in the period from 1 Jan 21 to 30 Apr 21. A graph with temperature and relative humidity for this period is shown in Appendix 7. The average temperature was 19.02˚C, but the minimum temperature dropped as low as 14.5˚C. There were extended periods in early January and mid-February 2021 when there were lower bedroom temperatures, most likely due to a period of cold weather. The average humidity and range between minimum and maximum humidity changed little between the 2 analysis periods.

The temperature and relative humidity for the living room of household C-02 is shown in figure 4.105 for the analysis period 1 Nov 21 to 15 Apr 22. The shape of the 'trendline' for the temperature had some similarities to the temperature profile for the bedroom due to the influence of the outside temperature. However, the average temperature in the living room was warmer than the bedroom at 21.52˚C instead of 19.67˚C. Regular small temperature spikes were also apparent in the living room.

On 3 Jan 22, the living room temperature was 22.0˚C at 12:00. It continued at this temperature until falling to 21.5˚C at 17:30. From 18:00, the temperature began to rise, reaching 23.5˚C by 19:00, 24.0˚C by 20:30 and falling back to 22.0˚C by midnight. This increase in temperature was due to either use of the boost function on the storage heater or use of another supplementary electric heater.

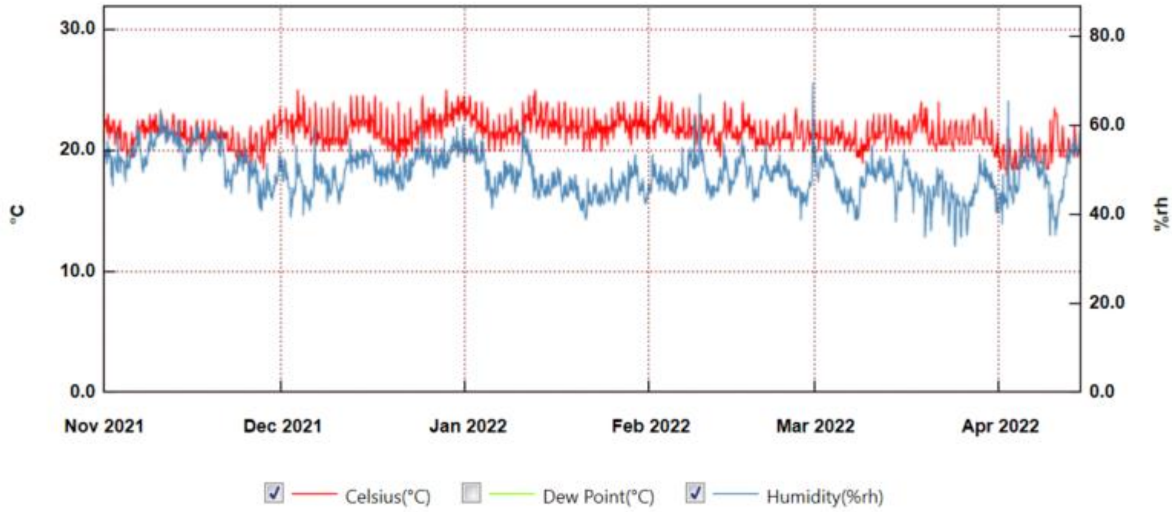


Figure 4.105 Graph of living room temperature and relative humidity for household C-02 from 1 Nov 21 to 15 Apr 22, with traditional storage heaters

The average humidity in the living room was 49.14% and much of the time, the humidity was in the optimum 40 to 60% range with a minimum of 34.5% and a maximum of 69.5%. It was drier than in the bedroom, which had a lower temperature. The better thermal comfort in this property may be due to a combination of greater storage heater use and better insulation in a more modern building.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	21.52	25.0	18.0	1.14	49.14	69.5	33.0	4.58
Living Room 17:00 - 21:00	22.2	25.0	19.0		49.16	62.0	34.5	
Bedroom 24 hours	19.67	23.0	17.0	0.89	57.16	76.5	34.5	5.65
Bedroom 17:00 - 21:00	19.71	22.5	17.0		56.89	76.5	36.0	

Table 4.106 Household C-02 temperature and relative humidity between 1 Nov 21 and 15 Apr 22. Property using traditional storage heaters for heating

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	21.02	24.5	16.5	1.18	46.39	65.2	29.0	6.27
Living Room 17:00 - 21:00	21.47	24.5	18.0		46.87	63.0	29.0	
Bedroom 24 hours	19.02	22.5	14.5	1.37	55.07	75.0	32.5	8.59
Bedroom 17:00 - 21:00	19.15	22.0	15.0		55.66	75.0	32.5	

Table 4.107 Household C-02 temperature and relative humidity between 1 Jan 21 and 30 Apr 21. Property using traditional storage heaters for heating

The living room was colder during the period 1 Jan 21 to 30 Apr 21, with an average temperature of 21.02˚C and a minimum temperature of 16.5˚C (see graph in Appendix 7). There were more dips in temperature due to cold weather and the household may have used the heating less. There was not a significant difference in the average, maximum and minimum values of relative humidity between the 2 monitoring periods. The values for humidity were about 3 to 4% lower during the earlier monitoring period.

Tinytag View 2 data loggers with current clamps were used to monitor the heating circuit and the 24-hour circuit for household C-02. Figure 4.108(a) shows the storage heaters and the water heater operating overnight between 00:00 and 07:00. On some days the consumption significantly dropped by about 03:00 due to the heaters having already reached temperature.

Figure 4.108(b) shows the 24-hour electric circuit. The Tesla battery charged between about 00:00 and 03:00 and discharged during the peak rate period after 07:00. The battery was able to fully power the home in the peak rate period between 3 Jan 22 and 6 Jan 22 apart from a few short consumption peaks. There were electric showers on 3 Jan 22 at 19:30 and 5 Jan 22 at 18:45 which both used about 30,000mA (6.9kW). There were also 3 other smaller peaks in consumption of less than 10,000mA during the peak rate period.

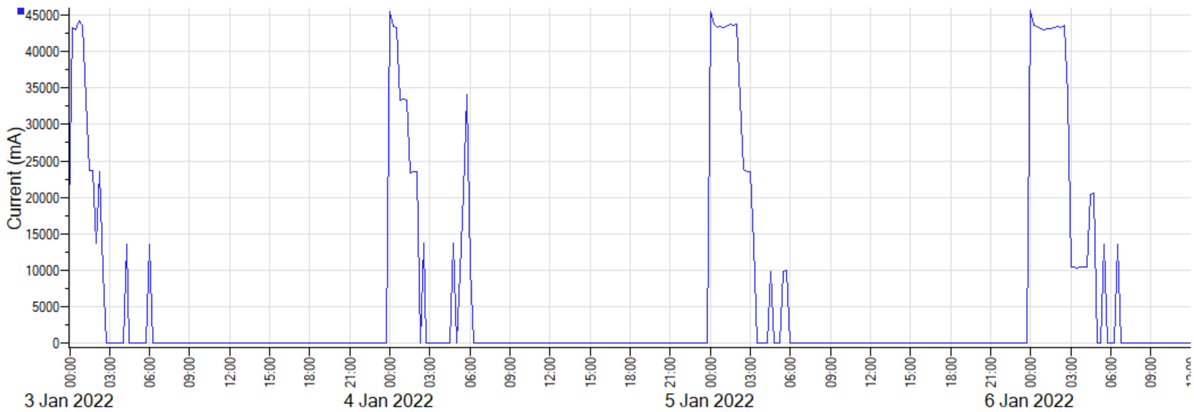


Figure 4.108 (a) Heating electricity circuit consumption for household C-02 between 3 Jan 22 and 6 Jan 22. Property with storage heaters and Tesla Powerwall 2 battery

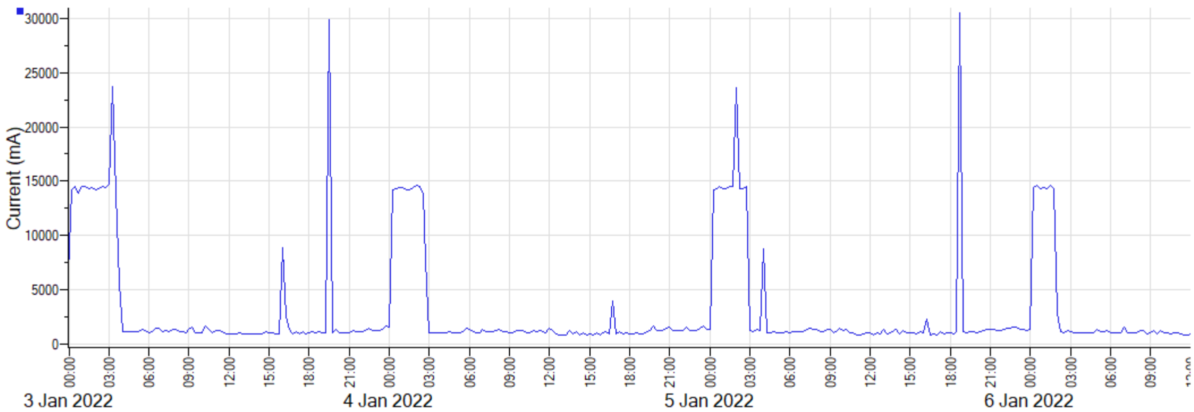


Figure 4.108 (b) 24-hour electricity circuit consumption for household C-02 between 3 Jan 22 and 6 Jan 22. Property with storage heaters and Tesla Powerwall 2 battery

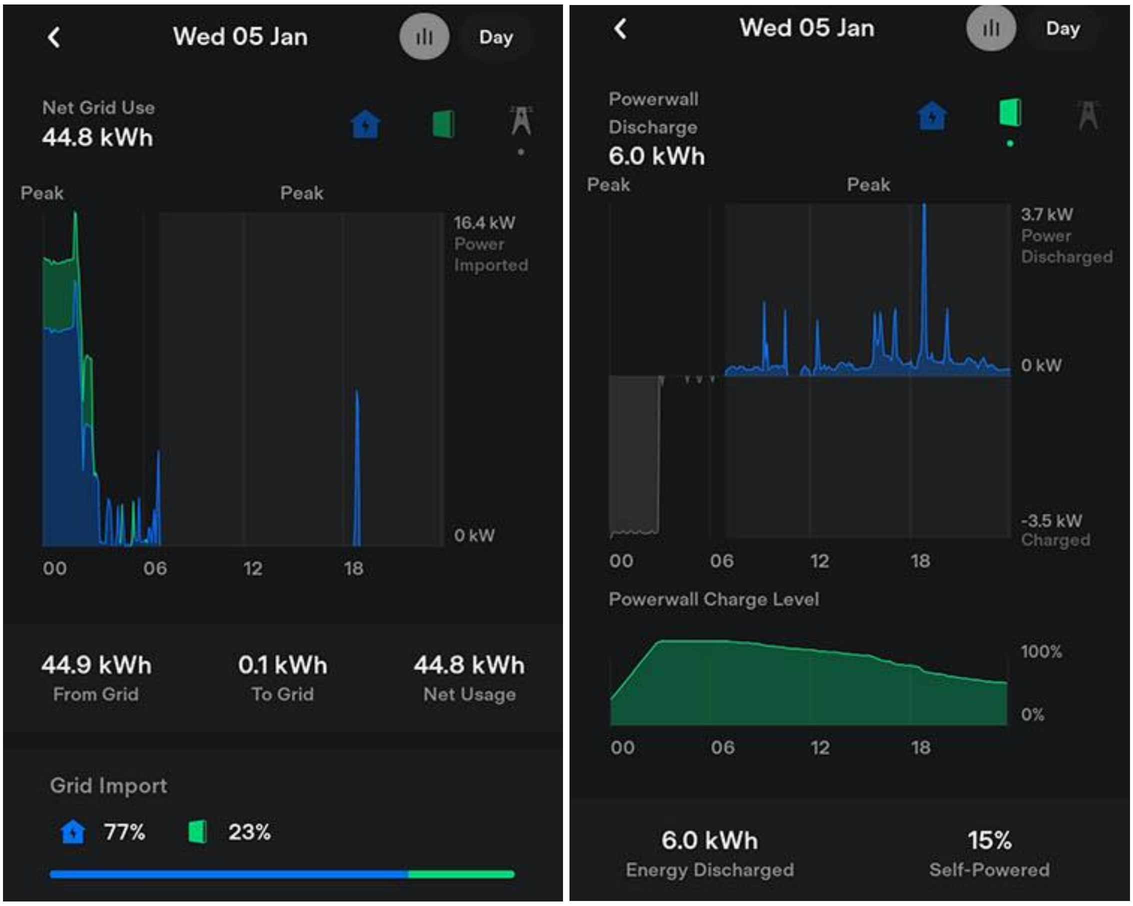


Figure 4.109 Screenshots from the Tesla app for household C-02 on 5 Jan 22
(a) Tesla app showing grid consumption (b) Tesla app showing battery charge/discharge

Screenshots from the app for the Tesla battery also illustrate the electricity consumption on 5 Jan 22. In figure 4.109 (a), the grid consumption due the home is shown in blue and the battery in green. There is charging of the storage heaters and the battey between 00:00 and 07:00. No grid consumption was recorded by the home during the peak rate period apart from at 18:40 for about 10 minutes when the consumption of the electric shower was greater than the power output from the battery. The total grid consumption recorded by the Tesla app was 44.8kWh which compares to 44.788kWh recorded by the smart meter.

Figure 4.109 (b) shows the battery charge and discharge on 5 Jan 22. The battery was fully charge by 03:00 and started to provide power to the home from 07:00, matching the consumption. The profile of the discharged power to the home is shown in blue. Only during the period of the electric shower was the battery unable to match the power consumed in the home. A total of 6.0kWh of electricity was discharged during the peak rate period. By the end of the day, the battery still had over 50% of its charge.

Table 4.110 shows the average monthly electricity consumption for household C-02 over the period 1 Dec 21 to 30 Nov 22. Over the year, the average consumption was 25.77kWh/day or a total of 9,408kWh. This can be compared over a similar time period with for households B-02 and C-01 which were both smaller 2-bedroom bungalows instead of a 3 bedroom mid-terraced house. Household C-01 with infrared panel heaters used 21.1kWh/day and household B-02 with a Boxergy Hero system with an air-source heat pump and battery used an average of 20.76kWh/day.

The electricity consumption of Household C-02 was notable due to the high percentage off-peak consumption as a result of having storage heaters and the Tesla Powerwall 2 battery. The average percentage off-peak consumption ranged from 89.06% in June to 98.13% in February. The average monthly peak rate consumption was low, in the range 0.71 to 1.72kWh/day. The off-peak consumption was high in winter averaging 43.0kWh/day in January and fell to 11.2kWh/day in August. This was because in summer there was only water heating overnight and the Tesla battery charging as the storage heaters were not used.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Dec-21	31	1.47	41.00	42.47	96.55%	258.5	5.09
Jan-22	31	1.26	42.97	44.23	97.15%	325.1	4.22
Feb-22	28	0.71	37.23	37.94	98.13%	249.7	4.25
Mar-22	31	1.05	32.68	33.72	96.89%	256.0	4.08
Apr-22	30	1.13	27.41	28.54	96.04%	220.6	3.88
May-22	31	1.72	17.16	18.88	90.88%	120.1	4.87
Jun-22	30	1.63	13.29	14.92	89.06%	73.4	6.10
Jul-22	31	1.20	11.59	12.79	90.61%	29.4	13.49
Aug-22	31	1.07	11.22	12.29	91.31%	15.9	23.96
Sep-22	30	1.68	15.08	16.76	89.99%	73.9	6.80
Oct-22	31	1.04	17.34	18.38	94.35%	93.7	6.08
Nov-22	30	0.99	28.11	29.10	96.61%	198.6	4.40
Year	365	1.25	24.53	25.77	95.16%	1914.9	4.91

Table 4.110 Monthly electricity consumption from Dec 2021 to Nov 2022 for household C-02, with traditional storage heaters and a Tesla Powerwall 2 battery

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Dec-21	42.47	96.55%	£14.44	£5.27	£6.61	£4.45
Jan-22	44.23	97.15%	£15.04	£5.46	£6.81	£4.54
Feb-22	37.94	98.13%	£12.90	£4.64	£5.74	£3.77
Mar-22	33.72	96.89%	£11.47	£4.17	£5.22	£3.49
Apr-22	28.54	96.04%	£9.70	£3.56	£4.49	£3.04
May-22	18.88	90.88%	£6.42	£2.47	£3.24	£2.34
Jun-22	14.92	89.06%	£5.07	£1.99	£2.64	£1.94
Jul-22	12.79	90.61%	£4.35	£1.68	£2.21	£1.59
Aug-22	12.29	91.31%	£4.18	£1.60	£2.10	£1.50
Sep-22	16.76	89.99%	£5.70	£2.21	£2.92	£2.12
Oct-22	18.38	94.35%	£6.25	£2.33	£2.98	£2.06
Nov-22	29.10	96.61%	£9.89	£3.61	£4.53	£3.04
Year	25.77	95.16%	£8.76	£3.24	£4.12	£2.82

Table 4.111 Electricity consumption and modelled costs for household C-02 with storage heaters and a battery using example electricity tariffs, for the period 1 Dec 21 to 30 Nov 22

Table 4.111 shows modelled costs for household C-02 using 4 example electricity tariffs. These include a single rate tariff and Economy 7 tariffs with 3 different peak and off-peak rates. Single rate Tariff 1 has a unit rate set at the level of the Energy Price Guarantee for the period 1 Oct 22 to 31 Mar 23. Tariff 2 was an Economy 7 tariff which was available at the start of the project. Tariffs 3 and 4 were more recent Economy 7 tariffs, available during the Autumn of 2022 during the period of the Energy Price Guarantee as for Tariff 1.

As discussed earlier, the average consumption of household C-02 over the year was 25.77kWh/day or a total of 9,408kWh. If this consumption was on a single rate tariff, the cost would be £8.76/day or £3,199 per year. In January 2022, the average cost on the single rate tariff was £15.04/day or £466.20 for the month.

The Economy 7 tariffs were at least 50% cheaper than the single rate tariff. Over the year, Tariff 3 was £4.12/day or £1,502/year. Normally the older Tariff 2 would be the cheapest tariff, but in this case, Tariff 4 was the cheapest due to the particularly low off-peak rate. The cost over the year for Tariff 4 was £2.82/day or £1,029/year. Tariff 4 was less than one third of the cost of single rate Tariff 1 for household C-02 due to the very high off-peak consumption and the low off-peak tariff rate. The average daily costs for C-02 in January 2022 on Tariff 4 was £4.54/day or £140.85/month. In August 2022, it was £1.50/day or £46.50/month on Tariff 4.

Comparisons can be made with 2 of the households in semi-detached bunglalows where consumption data was recorded over a similar time period. The average annual electricity cost for Household C-01 (infrared heating panels) was £7.17/day on single rate Tariff 1 and £8.31 on Economy 7 Tariff 3. For household B-02 after the Boxergy installation, the cost on single rate Tariff 1 was £7.06/day and £4.88/day on Economy 7 Tariff 3.

Therefore selecting the cheapest costs for the households out of Tariffs 1 and 3, the costs were £7.17/day for household C-01 with infrared heating panels, £4.88/day for B-02 with Boxergy Hero and £4.12/day for C-02 with storage heaters and a Tesla Powerwall battery.

Despite having a larger floor area and total consumption, household C-02 had cheaper running costs due to the greater percentage of off-peak consumption due to the storage heaters and Tesla Powerwall 2 battery. There was however less control of the heating and poorer thermal comfort compared to C-01 and B-02.

4.11. Household C-03

Household C-03 lived in a single bedroom semi-detached bungalow heated by an air-source heat pump and was recruited to take part in the project as a control property. The design and construction date of the bungalow was very similar to the bungalows which received Boxergy Hero installations such as B-04 and B-05. The main difference was that the property had a single bedroom instead of 2-bedrooms, resulting in a floor area of about 50m^2 instead of 55m^2.

The heat pump was a Daikin Altherma EDLQ05CAV3 low temperature monobloc air-source heat pump. This used R410A as a refrigerant which has a Global Warming Potential (GWP) of 2,088. This means that the release of 1kg of refrigerant would be equivalent to 2,088kg of CO_2. This compares to the R290 (propane) that was used as the refrigerant in the Vaillant aroTHERM plus heat pumps which has a GWP of only 3.

The Daikin heat pump was rated with an output of 4.4kW for an input of 0.88kW for an ambient temperature of 7˚C and a flow temperature of 35˚C. The seasonal coefficient of performance (SCOP) for the heat pump was 4.39 for a flow temperature of 35˚C and 3.2 for a flow temperature of 55˚C.

For comparison, the Vaillant aroTHERM plus air-source heat pumps installed with households B-01 to B-07 all had a rated output of 7kW and an SCOP of 3.39 for the 55˚C flow temperature used with the system.

Although household C-03 had a smart meter, it was not possible to obtain meter reading data from the electricity supplier despite many requests and consent of the resident. The smart meter in-home display had also been lost so it was not possible to obtain historic data using that. As a result, it was necessary to rely on manual meter readings during the project. This limited the results which could be obtained from this household.

Figure 4.112 Daikin Altherma EDLQ05CAV3 air-source heat pump providing heating for household C-03

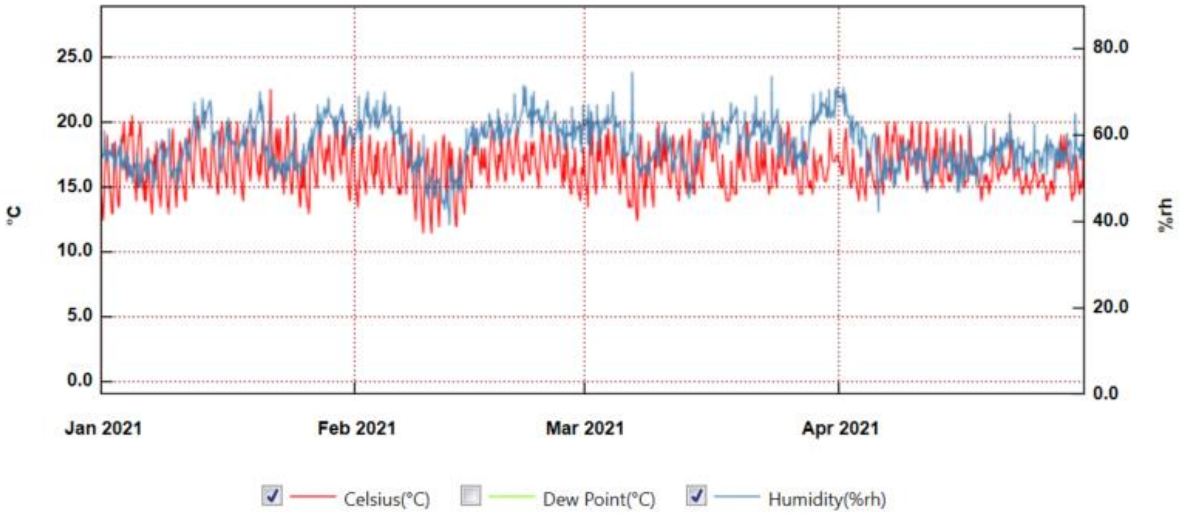


Figure 4.113 Graph of living room temperature and relative humidity for household C-03 from 1 Jan 21 to 30 Apr 21, with Daikin Altherma low temperature heat pump

Figure 4.113 shows a graph of the temperature and relative humidity in the living room for household C-03 between 1 Jan 21 and 30 Apr 21. The average temperature of the living room during this period was 16.65˚C over the full day, however in the early evening, from 17:00 to 21:00, the average temperature was a warmer 18.04˚C. Over the analysis period, the temperature ranged from a minimum of 11.5˚C to a maximum of 22.5˚C.

There was a regular heating and cooling cycle in the room during the analysis period. For example on 15 Jan 21, the temperature fell from 16.5˚C at midnight to 14.5˚C at 09:00 when the room started to warm again. It reached 18.0˚C by 12:30 and 20.0˚C by 19:00. After 20:30, the room began to cool, falling to 17.5˚C at midnight.

The temperature variation was likely to be due to the settings on the living room thermostat. The temperatures were relatively cold in the morning given that this was the room most used by the resident. The heat pump was also having to work quite hard during the day, raising the temperature from 14.5˚C up to 20.0˚C. Heat pumps are more efficient when they are maintaining a consistent temperature rather than working hard to raise the temperature.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	16.65	22.5	11.5	1.59	57.85	74.5	39.5	3.95
Living Room 17:00 - 21:00	18.04	22.5	13.5		57.65	74.5	42.5	
Bedroom 24 hours	16.93	25.0	12.0	1.67	56.26	67.5	42.5	4.77
Bedroom 17:00 - 21:00	18.53	25.0	14.5		56.02	67.5	42.5	

Table 4.114 Household C-03 temperature and relative humidity between 1 Jan 21 and 30 Apr 21. Property using a Daikin Altherma low temperature air-source heat pump

The average temperature of the bedroom was 16.93˚C and so slightly warmer than the living room at over the 1 Jan 21 to 30 Apr 21 analysis period. A graph of temperature and relative humidity for the bedroom is shown in Appendix 8 and has strong similarities to figure 4.113.

There were significant changes in the temperature profile for household C-03 during the 2021/22 heating season. Figure 4.115 shows the temperature and relative humidity for the living room between 1 Nov 21 and 15 Apr 22.

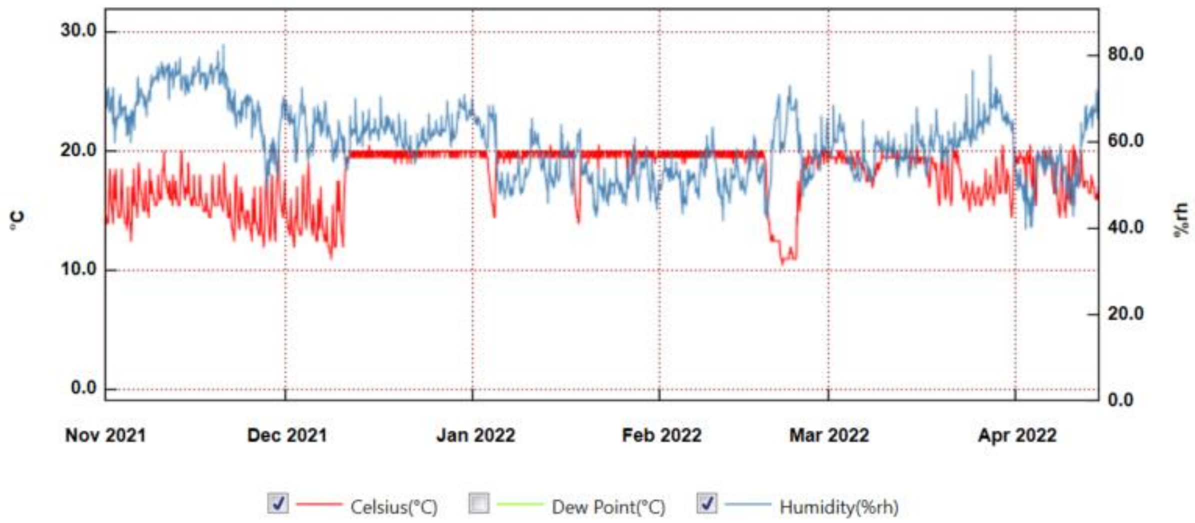


Figure 4.115 Graph of living room temperature and relative humidity for household C-03 from 1 Nov 21 to 15 Apr 22, with Daikin Altherma low temperature heat pump

From 1 Nov 21 until 10 Dec 21, the temperature profile showed similarities to figure 4.113 during the previous winter. After 10 Dec 21, the room temperature was much more narrowly regulated, normally cycling between 19.5˚C and 20˚C.

On 3 Jan 22 and 17 Jan 22, the heating seemed to have been turned off for just over 24 hours and this led the living room temperature to fall to 14.5˚C and 14.0˚C respectively. During Storm Eunice on 18 Feb 22 the outhouse roof of household C-03 blew off as for household B-05. The resident had to move out for 5 days after this while repairs were made and the living room temperature fell to a minimum of 10.5˚C during this time. After the heat pump was operational again, there was a wider living room temperature range, probably due to a further change in the settings for the thermostat.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	19.66	20.5	14.0	0.82	55.73	71.0	42.0	6.15
Living Room 17:00 - 21:00	19.68	20.5	15.0		57.08	70.5	43.5	
Bedroom 24 hours	19.58	25.0	14.5	0.8	57.14	70.5	43.5	5.53
Bedroom 17:00 - 21:00	19.59	25.0	15.5		57.47	70.5	43.5	

Table 4.116 Household C-03 temperature and relative humidity between 15 Dec 21 & 15 Feb 22. Property using a Daikin Altherma low temperature air-source heat pump

Table 4.116 shows statistics for the room temperature and relative humidity for household C-03 over the analysis period from 15 Dec 21 to 15 Feb 21 when the living room temperature was narrowly regulated. The average living room temperature was 19.66˚C, compared to an average of 15.35˚C for a 1 Nov 21 to 10 Dec 21 analysis period (table 4.117).

The behaviour in the bedroom was similar to the living room. A plot of the bedroom temperature and relative humidity for the winter 21/22 heating season is shown in Appendix 8. Between 1 Nov 21 and 10 Dec 21, the average bedroom temperature was 15.73˚C. This rose to 19.58˚C during the period 15 Dec 21 to 15 Feb 22 after the thermostat settings were changed.

The relative humidity in the living room fell from an average of 68.22% during the 1 Nov 21 to 10 Dec 21 period to 55.73% for the analysis period of 15 Dec 21 to 15 Feb 22 with the consistently warm thermostat setting.

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	15.35	20.0	11.0	1.68	68.22	82.5	49,0	6.33
Living Room 17:00 - 21:00	16.54	20.0	12.5		67.67	81.0	49.0	
Bedroom 24 hours	15.73	20.0	11.5	1.61	66.23	78.0	52.0	5.78
Bedroom 17:00 - 21:00	16.83	20.0	13.0		66.36	77.0	52.0	

Table 4.117 Household C-03 temperature and relative humidity between 1 Nov 21 & 10 Dec 21. Property using a Daikin Altherma low temperature air-source heat pump

A plot of electricity consumption (in milliamps) against time is shown in figure 4.118 for the period 6 Dec 21 to 13 Dec 21. This shows the change in electricity consumption following the alteration of the living room thermostat settings on 10 Dec 21. With the old setting, the heat pump would run constantly for extended period, such as from 10:45 until 19:15 on 27 Nov 21. After that there would be perhaps a break of a few hours with it not running.

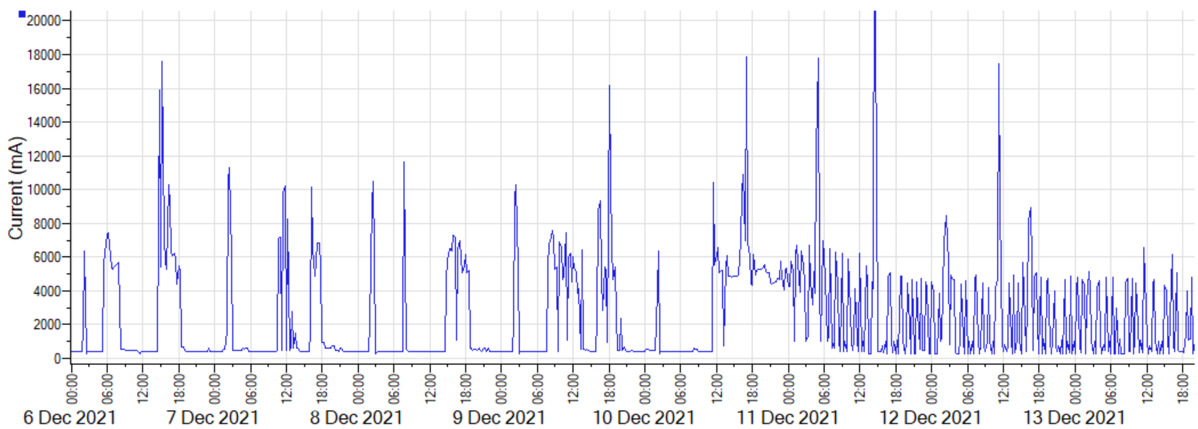


Figure 4.118 Electricity consumption for household C-03 between 6 Dec 21 and 13 Dec 21 as measured by Tinytag View 2 data loggers with Chauvin Arnoux current clamps. Property with a Daikin Altherma low temperature air-source heat pump installation

After the change in the thermostat settings, the heat pump initially ran consistently for over 12 hours, bringing the house up to temperature. It then ran in regular shorter cycles of under 30 minutes taking the consumption to about 4,500mA or about 1kW. These cycles ran through the day and the night with the heat pump peak electricity consumption lower than with the previous thermostat setting.

In addition to the regular cycles for space heating, there was a regular water heating cycle overnight which ran from 02:00 for about 45 minutes. This took place before and after the change in the thermostat settings.

Start date	End date	Number of days	Total consumption (kWh)	Total consumption (kWh/day)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Degree Days	Total consumption per Degree Day (kWh/DD)
16-Dec-20	10-Dec-21	359	3647	10.16	£3.45	2245.6	1.62
10-Dec-21	19-Dec-22	374	4152	11.10	£3.77	2082.1	1.99

Table 4.119 Electricity consumption and modelled costs for household C-03 with a Daikin Althema low temperature air-source heat pump using example electricity tariffs

Limited electricity consumption data was available for this household despite having a smart meter. The electricity supplier was unwilling to provide electricity consumption data even though the customer had provided consent for this to be obtained. Also the smart meter in-home display had been lost and so historical data could not be accessed by this method. As a result, the only consumption data available was through manual meter readings during visits.

This household had the lowest electricity consumption on the project, using 3,647kWh between 16 Dec 20 and 10 Dec 21 with an average of 10.16kWh/day. The following year from 10 Dec 21 to 19 Dec 22, household C-03 used 4,152kWh or 11.1kWh/day. This included the period from 10 Dec 21 to 18 Feb 22 where the room temperature was consistently between 19 and 20˚C. Correcting for external temperature with Degree Days, the average consumption in 2020/21 was 1.62kWh/DD compared to 1.99kWh/DD in 2021/22. The higher consumption in the second year might be due to the greater thermal comfort between mid-December and mid-February.

For comparison, household B-02, a 2-bedroom bungalow, used 26.18kWh/day or 4.2kWh/DD during monitoring year 1 with storage heaters and 20.75kWh/day or 3.96kWh/DD during monitoring year 2 with the Boxergy Hero system. The Vaillant aroTHERM plus heat pump for household B-02 used 7.31kWh/day over the period December 2021 to November 2022.

Another 2-bedroom bungalow, household B-01, used 5,605kWh or 15.36kWh per year during a 12-month period with just the Vaillant aroTHERM plus heat pump running. Correcting for external temperature, the consumption was 2.96kWh/DD.

The temperature corrected consumption of household B-01 with the Vaillant heat pump was about 50% higher than for household C-03. For B-02 with the Boxergy Hero system, it was about 100% higher.

It is possible to compare costs over similar periods for household C-03 and household B-02 with the Boxergy Hero system operating for a year. Household C-03 was on a single rate tariff and the average cost for 2021/22 was £3.77/day or an annual bill of £1,378.

If household B-02 was on single rate Tariff 1 as for C-03, due to the higher consumption, the cost would be £7.06/day or £2,576/year. However, B-02 had a high overnight consumption and was on an Economy 7 tariff, benefiting from low-cost off-peak electricity. On Tariff 3, the average daily cost was £4.88/day or £1,781/year. With the cheaper Economy 7 Tariff 4, the average cost was £4.12/day or an annual bill of £1,504.

While the total consumption for household B-02 was nearly double that for household C-03, the difference in costs were more limited due to one being on Economy 7 and the other on a single rate tariff. On Economy 7 tariff 3, the electricity cost for household B-02 was 29.3% higher than for C-03 and 9.1% higher on Economy 7 Tariff 4

Factors which led to the electricity consumption of household B-02 being higher than C-03 include a slightly larger property, a larger number of residents and a higher level of thermal comfort. The Daikin Altherma low temperature heat pump might also have operated more efficiently than the Vaillant aroTHERM plus with the Boxergy Hero system. While the electricity consumption could be 50 to 100% higher for B-02, the difference in electricity cost was smaller due to the high off-peak consumption of B-02 and being on an Economy 7 tariff.

4.12. Household C-04

Figure 4.120
Indoor unit of heat pump and instant water heater

Household C-04 lived in a single bedroom end-terraced bungalow heated by an air-source heat pump. They were recruited to take part in the project as a control property in February 2022. As a result, there was limited temperature and humidity data collected. However, it was possible to obtain more than a year of half-hourly smart meter data, which allowed more detailed analysis of the electricity consumption.

The model of heat pump was a Daikin Altherma ERLQ006CAV3 low temperature split. This had an outdoor unit with the fan which extracted heat from the air and an indoor hydrobox unit which distributed hot water around the central heating system. The heat pump had a nominal output of 6kW, but could range between a minimum of 1.8kW to 8kW output. The input was 1.27 to 1.59kW. The property also had an Ariston instant water heater and an electric shower instead of a hot water cylinder.

The residents thought it was a superb heating system which was very controllable. They preferred the wet central heating system to storage heaters including newer high heat retention models. There were issues with draughts in the property due to there being no bottom seal on the front door and they were dissatisfied with the thermostat being located in the hall which was affected by the draughts.

A graph of the temperature and relative humidity of the living room for household C-04 is shown in figure 4.121 for the period 15 Feb 22 until 31 May 22. The temperature was very consistent over this analysis period, with an average of 20.46˚C over the full day and the temperature ranging between a minimum of 17.5˚C and a maximum of 22.0˚C. During the early evening period 17:00 to 21:00, the average temperature was 0.7˚C warmer at 21.16˚C. There was more consistent relative humidity during the analysis period compared to many households. The average relative humidity in the living room was 60.11% and the humidity ranged between a minimum of 45.0% and a maximum of 71.0%. The household had an energy efficient heat pump tumble drier and so did not have washing let to dry on an airer or radiators.

There were small differences in the temperature and relative humidity between the living room and the bedroom. The average temperature in the bedroom was just 0.01˚C warmer than the living room at 20.47˚C. There was a narrower temperature range of 3˚C instead of 4.5˚C, with a minimum of 18.5˚C and a maximum of 21.5˚C.

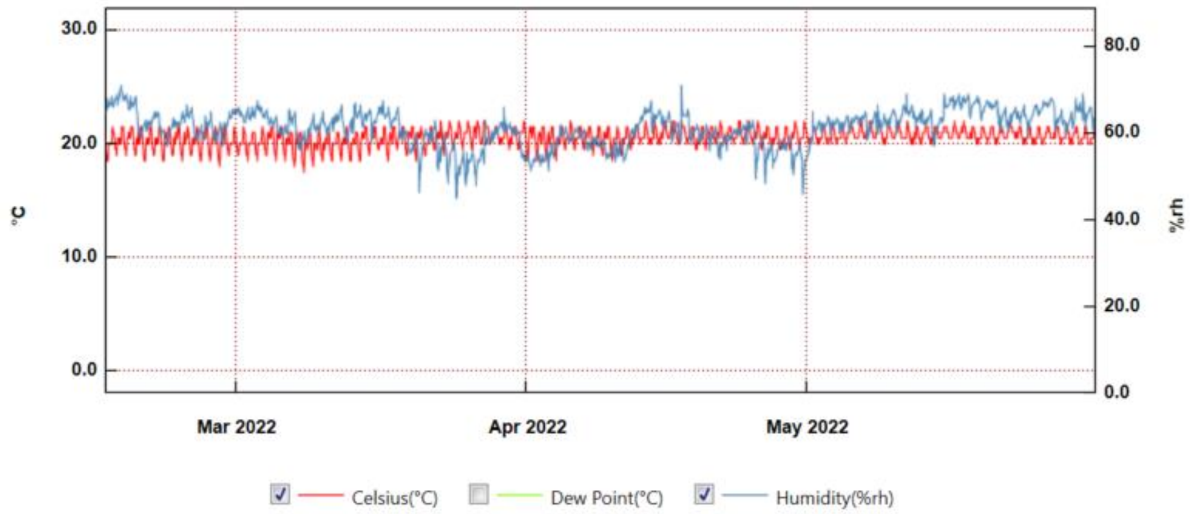


Figure 4.121 Graph of living room temperature and relative humidity for household C-04 from 15 Feb 22 to 31 May 22, with Daikin Altherma low temperature heat pump

Room	Average Temp (˚C)	Maximum Temp (˚C)	Minimum Temp (˚C)	Standard Deviation (˚C)	Average Humidity (%RH)	Maximum Humidity (%RH)	Minimum Humidity (%RH)	Standard Deviation (%RH)
Living Room 24 hours	20.46	22.0	17.5	0.8	60.11	71.0	45.0	4.02
Living Room 17:00 - 21:00	21.16	22.0	19.5		59.74	71.0	48.5	
Bedroom 24 hours	20.47	21.5	18.5	0.54	62.39	75.0	45.5	3.62
Bedroom 17:00 - 21:00	20.83	21.5	19.0		61.31	71.0	50.5	

Table 4.122 Household C-04 temperature and relative humidity between 15 Feb 22 & 30 Apr 22. Property using a Daikin Altherma low temperature air-source heat pump

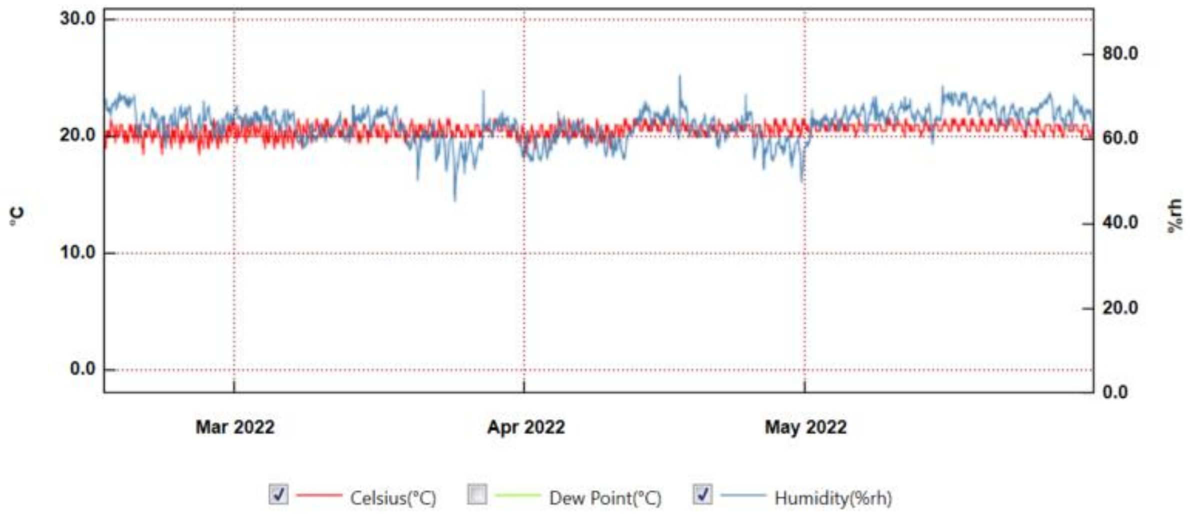


Figure 4.123 Graph of bedroom temperature and relative humidity for household C-04 from 15 Feb 22 to 31 May 22, with Daikin Altherma low temperature heat pump

The average humidity in the bedroom was 62.39%, which was 2.28% higher than in the living room. There was a slightly wider range in humidity, with a minimum of 45.5% and a maximum of 75.0%.

Figure 4.124 shows the variation in living room temperature and relative humidity during the first week of March 2022 with a daily heating and cooling cycle apparent. On 1 Mar 22 at midnight, the temperature was 21.0˚C. This fell overnight to 19.0˚C by 05:30 and had risen back to 20.0˚C by 09:00. It remained at 20.0˚C until 18:30 and reached 21.5˚C by 19:30, falling back to 21.0˚C at 20:30 and remained at this temperature until midnight. For comparison, table 4.125 shows the heating schedule for the thermostat for the heating system.

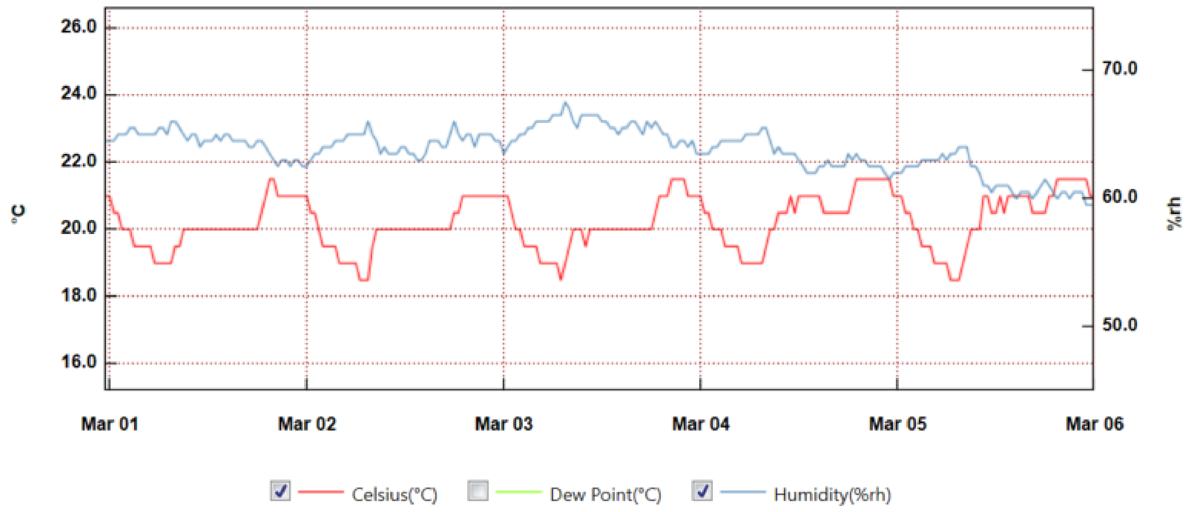


Figure 4.124 Graph of living room temperature and relative humidity for household C-04 from 1 Mar 22 to 6 Mar 22, with Daikin Altherma low temperature heat pump

Start Time	End Time	Set Point Temperature
06:30	09:30	20˚C
09:30	18:30	20˚C
18:30	22:30	21˚C
22:30	06:30	18˚C

Table 4.125 Thermostat setting of heat pump for Household C-04

Figure 4.126 shows the electricity consumption (in milliamps) for household C-04 for the same analysis period of 1 Mar 22 to 6 Mar 22 as for the temperature and relative humidity in figure 4.124. There was a baseload consumption of about 900mA or about 205W. Normally there were no peaks in consumption overnight from the heat pump as the set-point temperature was reduced overnight and the room temperature did not fall below 18˚C during this period. There was a sharp increase in consumption to about 13,000mA or 3kW at 06:30 as the heat pump started up. After the initial period, the consumption tended to drop back to about 9,000mA or about 2kW.

There were consumption peaks from the heat pump spread across the day, with the heat pump running for typically less than 30-minutes at a time. There were more peaks in the late afternoon/early evening as the external temperature fell and the set-point temperature increased by 1˚C to 21˚C at 18:30.

Over the day, the consumption peaks for the heat pump for household C-04 were generally around 6,000 to 9,000mA or about 1.4 to 2kW. This compares to the heat pump for household C-03 where the consumption peaks were about 4,500mA or about 1kW when the temperature was closely regulated. For the Vaillant aroTHERM plus heat pumps the consumption recorded during a cycle with the heat pump running could be about 1.2kW.

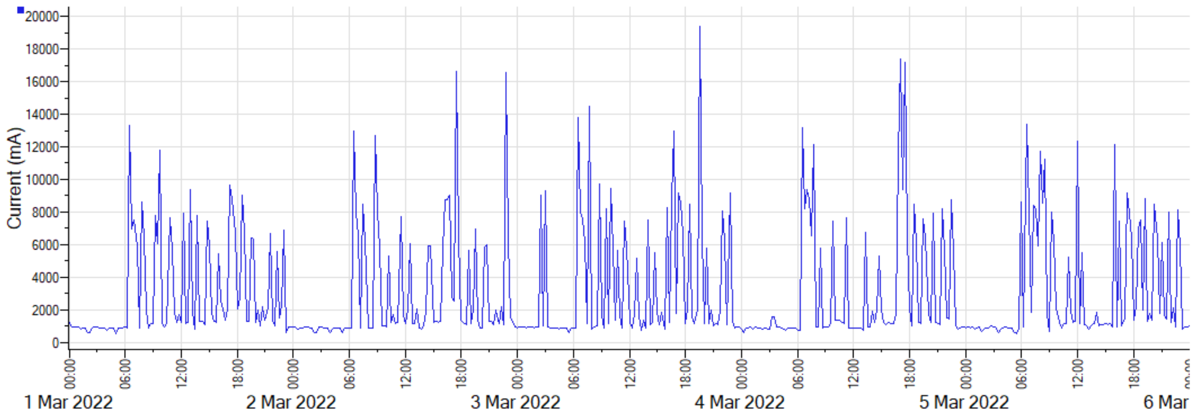


Figure 4.126 Electricity consumption for household C-04 between 1 Mar 22 and 6 Mar 22 as measured by Tinytag View 2 data loggers with Chauvin Arnoux current clamps. Property with a Daikin Altherma low temperature air-source heat pump installation

Start Date	End Date	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
01-Dec-20	01-Dec-21	12.32	2.35	14.67	16.02%	2306.8	2.32
01-Dec-21	01-Dec-22	10.42	2.10	12.53	16.80%	1914.9	2.39

Table 4.127 Annual electricity consumption for household C-04 for 2020/21 and 2021/22, with a Daikin Altherma low temperature air-source heat pump

Table 4.127 shows the annual electricity consumption of household C-04 for the period December through to November for the years 2020/21 and 2021/22. The total consumption from midnight 1 Dec 2020 until midnight 1 Dec 21 was 5,354kWh or an average of 14.67kWh/day. The following year the consumption was 4,573kWh or 12.53kWh/day.

The weather was colder from 1 Dec 20 to 1 Dec 21 with 2306.8 Degree Days compared to 1914.6 the following year. This meant that despite the 2021/22 period having lower electricity consumption, once external temperature was taken into account, the temperature adjusted consumption was higher at 2.39kWh/DD compared to 2.32kWh/DD in 2020/21.

Household C-03 was another single bedroom bungalow also with a low temperature air-source heat pump. The temperature adjusted consumption was lower than for C-04 with a value of 1.62kWh/DD in 2020/21, which was 30% lower and 1.99kWh/DD in 2021/22.

Over a similar 2021/22 time period, household B-02 in a 2-bedroom bungalow with a Boxergy Hero installation had a temperature corrected consumption of 3.94kWh/DD.

It was not possible to model the percentage off-peak consumption for household C-03 as smart meter data was not available, with only manual meter readings taken during visits. For household C-04 the percentage off-peak consumption over the year was 16-17%. The electricity consumption profile for household C-04 in early March 2022 showed that very little electricity was used overnight. If electricity was used equally throughout the 24 hours, the percentage off-peak consumption on Economy 7 would be 29.2%. Household B-01 had a Vaillant heat pump with the Boxergy Hero system running without the electrical battery for a full year. During this period, the percentage off-peak consumption was 24%. This was higher than for household C-04 most likely due to heat pump starting earlier in the morning and charging of the heat battery overnight.

Monthly values of electricity consumption for household C-04 are shown in table 4.128 for the period December 2021 to November 2022. Monthly consumption varied from 7.42kWh/day in August 2022 to 18.86kWh/day in January 2022. While there was a small rise in off-peak consumption from summer to winter of about 1kWh, this rise was nearly 10.5kWh on the peak rate period comparing August with January.

For household B-02 with the Boxergy Hero system, the total consumption was about 12.25kWh/day in summer with about 90% of this consumption using off-peak electricity. During the winter period of 25 Nov 21 to 22 Jan 22, the average total consumption for B-02 was 35.85kWh/day, about double the consumption of C-04. However, 52.6% of this consumption was at the off-peak rate.

Household B-05, also with a Boxergy Hero system running, used 9.21kWh/day in July 22, compared to 7.89kWh/day for C-04. The difference was more substantial in November 22, where B-05 used 22.26kWh/day compared to 15.28kWh/day. However, the percentage of off-peak consumption was significantly higher for B-05, using 79.7% in November compared to 17.5% for household C-04. This was due to B-05 having the battery charge and the heat pump run overnight.

Month	Number of days	Peak consumption (kWh/day)	Off-Peak consumption (kWh/day)	Total consumption (kWh/day)	% Off-peak	Degree Days	Total consumption per Degree Day (kWh/DD)
Dec-21	31	15.24	2.40	17.64	13.62%	258.5	2.12
Jan-22	31	16.25	2.61	18.86	13.82%	325.1	1.80
Feb-22	28	15.22	2.43	17.65	13.76%	249.7	1.98
Mar-22	31	13.27	2.34	15.61	14.96%	256.0	1.89
Apr-22	30	11.08	2.17	13.25	16.41%	220.6	1.80
May-22	31	7.69	1.89	9.58	19.70%	120.1	2.47
Jun-22	30	6.69	1.76	8.45	20.86%	73.4	3.45
Jul-22	31	6.25	1.64	7.89	20.75%	29.4	8.32
Aug-22	31	5.77	1.65	7.42	22.24%	15.9	14.48
Sep-22	30	6.90	1.73	8.63	20.08%	73.9	3.50
Oct-22	31	8.42	1.99	10.41	19.14%	93.7	3.45
Nov-22	30	12.60	2.68	15.28	17.52%	198.6	2.31
Year	365	10.42	2.10	12.53	16.80%	1914.9	2.39

Table 4.128 Monthly electricity consumption from Dec 2021 to Nov 2022 for household C-04, with a Daikin Altherma low temperature air-source heat pump

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Dec-21	17.64	13.62%	£6.00	£3.95	£6.89	£6.74
Jan-22	18.86	13.82%	£6.41	£4.21	£7.35	£7.19
Feb-22	17.65	13.76%	£6.00	£3.94	£6.88	£6.73
Mar-22	15.61	14.96%	£5.31	£3.47	£6.03	£5.89
Apr-22	13.25	16.41%	£4.51	£2.92	£5.07	£4.94
May-22	9.58	19.70%	£3.26	£2.07	£3.57	£3.46
Jun-22	8.45	20.86%	£2.87	£1.82	£3.13	£3.02
Jul-22	7.89	20.75%	£2.68	£1.70	£2.92	£2.82
Aug-22	7.42	22.24%	£2.52	£1.58	£2.72	£2.62
Sep-22	8.63	20.08%	£2.93	£1.86	£3.21	£3.11
Oct-22	10.41	19.14%	£3.54	£2.26	£3.90	£3.78
Nov-22	15.28	17.52%	£5.19	£3.35	£5.80	£5.64
Year	12.53	16.80%	£4.26	£2.75	£4.78	£4.65

Table 4.129 Electricity consumption and modelled costs for household C-04 with a Daikin Altherma low temperature air-source heat pump, for the period 1 Dec 21 to 30 Nov 22

Modelled electricity costs using example tariffs are shown in table 4.129 for household C-04. Over the year and for each month, single rate Tariff 1 was cheaper than Economy 7 Tariffs 3 and 4 due to the low percentage off-peak consumption. Economy 7 Tariff 2 was the cheapest tariff for all months, but that was due to it being a historic tariff typical of the rates paid by households at the start of the project.

The average electricity cost for household C-04 on Tariff 3 for the analysis period was £4.78/day or an annual cost of £1744/year. This compares to £4.26/day or £1554.50/year on single rate Tariff 1. Household C-04 was on Economy 7 Tariff 3 as they thought they might benefit from lower costs when using appliances like the dishwasher overnight. They have since been advised that a single rate tariff would be cheaper.

Household B-02 had a Boxergy Hero system operational for a year from 25 Nov 21 to 22 Nov 22. The electricity cost would have been £7.06/day on a single rate tariff, but £4.88/day or £1781/year on Economy 7 Tariff 3. While this would have been only £37 more than for household C-04 also on Tariff 3, if C-04 was on single rate Tariff 1, it would have been £226.50 cheaper.

There was not a full year of data available for household B-05 after having the Boxergy Hero system fully operational. During November 2022, B-05 used 22.26kWh/day compared to 15.28kWh/day for C-04. However the cost for B-05 was £4.53/day on Tariff 3 compared to £5.19/day for C-04 on Tariff 1. Note that it was even more expensive at £5.80/day for C-04 on Tariff 3. The lower costs for B-05 despite the higher total consumption was due to the high percentage off-peak consumption.

The average electricity consumption of household C-04 was 7.9kWh/day in July 2022 compared to 10.0kWh/day for household B-05. The average cost for C-04 would have been £2.68/day on single rate Tariff 1, but the cost would have been cheaper for B-05 on Tariff 3 at only £1.79/day. For other months such as October, September and August, C-04 on single rate Tariff 1 had cheaper electricity costs than household B-05.

5. Conclusions, recommendations and future work

5.1. Conclusions

The project installed 7 Boxergy Hero heating systems with air-source heat pumps and batteries in socially rented off-gas grid homes in North Devon which had night storage heaters

- The Boxergy Hero system consisted of a high temperature air-source heat pump (ASHP) along with an external box. The Hero box contained an electrical battery, a heat battery along with monitoring and control systems
- Interviews were carried out with households before and after the Boxergy Hero installation to assess their satisfaction with the heating systems
- NEA staff fitted loggers to record temperature/humidity and electricity consumption during a winter heating season with the old heating system and for the following heating season where the Boxergy Hero system was installed part way through
- The data loggers for the second year were collected in October 2022 and electricity consumption data was collect up until November/December 2022
- For this project, the Boxergy Hero system used a 7kW Vaillant aroTHERM plus ASHP, along with a 9.5 or 12.6kWh Sunamp heat battery and an Alpha ESS electrical battery system with either a total capacity of 10.1kWh or 11.4kWh
- Households having the system should be on a time of use tariff such as Economy 7 with BOXERGY set up to maximise the benefits of the cheap electricity period.
- The battery charges at lower cost off-peak times and supplies electricity to the home and the heat pump during more expensive peak rate times
- The project started in March 2020, but the COVID-19 pandemic caused delays to the project, limiting household visits, testing of prototypes, production of systems and obtaining components due supply chain issues
- Among the initial aims was for 2 of the Boxergy Hero systems to each provide heating to 2 homes. This was not possible due to complexities over installing a new grid connection for the shared systems and potential restrictions over providing a shared heating system in properties which were still mortgaged.
- The 7 Boxergy Hero systems were installed in 5 bungalows and 2 mid-terraced houses owned by North Devon Homes
- The homes were all off the gas grid and had storage heaters. It was necessary to remove the storage heaters and fit a wet central heating system with radiators before the Boxergy Hero system could be connected
- The first system, B-01, was fitted in June 2021, but due to a failed battery and supply chain issues, it operated as an ASHP only for a year before the 10.1kWh electrical battery was running as planned
- Due to the high costs fitting the wet central heating system and removing the storage heaters for the first installation, a new heating engineer was selected for the later installations. Costs were still higher than had been budgeted for and so a plan to include 2 solar PV installations was dropped.
- The second Boxergy Hero system, B-02 was installed on 25 Nov 21 and operated for a year with both the ASHP and the battery before the end of the project

- The third phase of the installations took place in January and February 2022, where the remaining 5 wet central heating systems and Boxergy Hero systems (B-03 to B-07) were installed
- The electrical battery for B-01 was replaced in July 2022. Work was also carried out at this time to allow the batteries of 2 systems to charge and discharge (as planned) and for others to record the grid consumption on the Alpha ESS monitoring portal

There was a significant improvement in satisfaction with the heating after the Boxergy Hero system was installed

- Only 1 out of 7 households said they could keep the whole house comfortably warm in winter with the old heating system, but this improved to all 7 after the Boxergy Hero system was fitted
- All 7 households used supplementary electric heating with their old heating system, but this reduced to 1 who might use if for short periods with the new system
- 5 of the households were very dissatisfied with how warm their home got when it was cold outside with the old heating system and a further household was dissatisfied
- Following the Boxergy Hero installation, 4 households were very satisfied and the other 3 were satisfied with how warm the home got when it was cold
- 4 households were very dissatisfied and 2 dissatisfied with the amount of control with the old heating system but with the Boxergy Hero system, 4 were very satisfied and 3 satisfied
- 6 of the households were very dissatisfied and 1 dissatisfied with the running costs with the old heating system. Following the Boxergy Hero installation, 3 were very satisfied and 2 satisfied with the costs, although most had not experienced a full year of operation.
- All 7 households strongly agreed that the new Boxergy Hero heating system was better than their old one and that they now had whole house heating rather than room heating
- 6 of the 7 households strongly agreed that they felt warmer with the new heating system and it benefited their physical health while the other household also agreed with this statement
- A resident commented that ‘it was completely different heating to night storage heaters and 100% better. The house feels warm whichever room you go in. There is no longer an issue with the heating being ineffective in the evening.’

There was an improvement in thermal comfort after the Boxergy Hero system was installed, with an increase in average and minimum room temperatures and a shift from room heating to whole house heating

- The average bedroom temperature for household B-01 increased by 2.89˚C from 16.97 to 19.86˚C after the air-source heat pump was operating as planned, with the *minimum temperature* increasing from 13.0 to 17.5˚C
- There was a change in the average temperature and temperature range after the thermostat for the Vaillant heat pump was altered, so performance after the installation depended on the thermostat settings

- There was limited improvement to the average living room temperature for household B-02 as there had previously been a Dimplex Quantum high heat retention storage heater with a thermostat in the room, with the average temperature increasing from 20.75˚C to 21.3˚C
- The bedroom of household B-02 was on average 3.47˚C warmer at 19.74˚C after the Boxergy Hero installation, with the minimum room temperature increasing from 11.5˚C to 15.5˚C
- There was an improvement in the average and minimum room temperatures of household B-04. The average living room temperature increased from 17.54 to 19.68˚C while the average bedroom temperature increased by 3.3˚C to 19.59˚C. The minimum room temperatures increased from 12.5˚C and 11.5˚C for the living room and bedroom to 16.0˚C for both rooms.
- Household B-05 had regularly used the storage heater and supplementary heating in in the living room and as a result, there was only a small increase in the average temperature from 22.14˚C to 22.36˚C, but the minimum room temperature improved from 17.0˚C to 20.5˚C after the Boxergy Hero installation
- Previously, Household B-05 had not heated the bedroom and the average temperature was 16.33˚C, with the room temperature highly dependent on the external temperature, dropping to a minimum of 12.0˚C. Following the Boxergy Hero installation, the average bedroom temperature increased by 3.74˚C to 20.07˚C and the minimum room temperature increased from 12.0 to 16.0˚C
- The average room temperatures for household B-06 were the lowest of the households on the project, with the average for the living room at 15.03˚C and the bedroom 15.82˚C with the old heating system. The minimum temperature for both rooms was 12.0˚C.
- Following the Boxergy Hero installation, the average living room temperature for household B-06 fell slightly to 14.68˚C, but the average bedroom temperature rose by 2.87˚C to 18.69˚C. The residents often left one of the external doors open for an extended period and this could have been a factor in the low room temperatures.
- There was a wide range in room temperature for household B-07 before the Boxergy Hero installation. The average temperature of the living room was 16.59˚C, but the temperature ranged between a minimum of 8.0˚C and a maximum of 26.5˚C. For the bedroom, the average was a warmer 18.0˚C, with a minimum temperature of 10.5˚C and sharp peaks in temperature which reached as high as 29.5˚C due to supplementary heating without thermostatic control.
- After the Boxergy Hero installation, the average living room temperature of household B-07 increased by 3.77˚C to 20.36˚C, with the minimum temperature increasing from 8.0 to 16.0˚C. For the bedroom, the average temperature improved by 2.88˚C to 20.88˚C. The range between the maximum and minimum temperature for the bedroom decreased from 19˚C to 6.5˚C.

There was typically a decrease in the electricity consumption after the Boxergy Hero system was installed. The electrical battery, when operating helped maintain a high off-peak consumption as long as the household consumption was not too high

- Electricity meter readings were obtained from suppliers, portals and meter readings taken throughout the project. Consumption was corrected for external temperature using Degree Days for Dunkeswell Airport and for consistency across the sample - shown as consumption per Degree Day (kWh/DD)

- Household B-01 had the first Boxergy Hero installation and this ran for the first year with just the heat pump and heat battery operational. Over the full year of operation with the heat pump, the electricity consumption of B-01 was 5,605kWh or 15.4kWh/day with 24% of the consumption at the off-peak rate
- Comparing consumption during the winter heating seasons before and after the air-source heat pump installation, the consumption of B-01 fell from 27.7kWh/day to 20.5kWh/day or from 2.88kWh/DD to 2.38kWh/DD
- After the electrical battery was fitted, the off-peak consumption for B-01 rose to 68.3% for the period July to December 2022
- Household B-02 was the only installation where the heat pump and electrical battery for the Boxergy Hero system was monitored for a full year. With the old storage heater system, the average consumption over the year was 26.18kWh/day with 69.6% of the consumption off-peak.
- During the year with the Boxergy Hero system, B-02 used an average of 20.75kWh/day with 68.7% of the consumption still on the off-peak tariff. The reduction in consumption was smaller taking external temperature into account, falling from 4.2kWh/DD to 3.96kWh/DD, a reduction of 5.7%.
- The space and water heating demand for the mid-terraced houses, B-03 and B-07 with the old heating system was 13 to 15,000kWh/year. Since these homes were electrically heated, the annual electricity consumption was high at about 13,500kWh to 14,000kWh/year. The households had little faith in the storage heater systems and frequently used supplementary heating at the higher peak rate cost
- Household B-03 used on average 42.1kWh/day over a pre-installation analysis period of 340 days with 34.4% of the consumption off-peak. The consumption ranged from approximately monthly averages of 19.2kWh/day in June 2021 to 73.1kWh/day in January 2021
- Following the Boxergy Hero installation, there was a reduction in consumption for household B-03 and an increase in the percentage off-peak consumption but this was still relatively low. Between February and December 2022 the average consumption was 31.74kWh/day with 46% of the consumption off-peak. The consumption ranged from 19.8kWh/day in August to 60.8kWh/day in December.
- The high household electricity consumption limited the consumption that could be shifted to off-peak times. The system could have benefited from a larger battery (an expensive option), solar PV or a tariff like Economy 10 with more than a single off-peak period per day
- Over a period of a year before the Boxergy Hero installation, household B-04 used 12,354kWh or an average of 33.8kWh/day, which was particularly high since the property was a 2-bedroom bungalow. The percentage off-peak consumption was low at 32.5% due to extensive use of supplementary heating
- There was a significant drop in electricity consumption as well as an improvement in thermal comfort for B-04 after the Boxergy Hero system was installed. Over the months February to November, the average consumption was 19.4kWh/day or 4.4kWh/DD. This compared to 30.3kWh/day and 5.6kWh/DD for the equivalent period with the old heating system.

- As for B-04, household B-05 had a high consumption during the pre-installation period, using 12,896kWh in a year or an average of 35.3kWh/day. A higher percentage of this consumption was off-peak at 57.4% due to greater use of storage heaters.
- Over an analysis period of April to November 2022 after the Boxergy Hero installation, B-05 used an average of 14.8kWh/day with 55.7% off-peak. Comparing consumption before and after the installation, in November 2021, the average consumption was 43.2kWh/day compared to 22.3kWh/day the following year. Correcting for external temperature, the consumption with the old heating system was 6.07kWh/DD, falling to 3.36kWh/DD with the new heating, a reduction of nearly 45%.
- The battery was not charging and discharging for households B-04 and B-05 until early July. While running with just the heat pump, the monthly percentage off peak consumption was 20.8 to 30.1% for B-04 and 33 to 34% for B-05. After the battery was fully operational, the monthly off-peak consumption was between 49 and 88% for B-05 and 52 to 65% for B-04
- Household B-06 used 7,796kWh or 21.4kWh/day during a 12-month period before the Boxergy Hero installation. 69% of the consumption was on the off-peak tariff due to mainly heating the home with storage heaters. Between March and December 2022, following the Boxergy Hero installation, the average consumption was 22.5kWh/day with 61% off-peak.
- In November 2021, household B-06 used 23.2kWh/day (2.82kWh/DD) with the old heating system. For the same month in November 2022, the consumption was 26.7kWh/day (4.0kWh/DD). The battery charge as high as 26.1kWh on 14 Dec 22 despite the battery capacity being 11.4kWh. There seem to be ongoing issues with this system leading to greater consumption and likely export to the grid.
- Household B-07 lived in the other mid-terraced house with a high heating demand. During the 12-month period before the Boxergy Hero installation, the consumption was 14,012kWh or 38.4kWh/day. Correcting for external temperature, this was 6.34kWh/DD. The average pre-installation monthly consumption ranged from 19.4kWh/day to 60.1kWh/day.
- For the period from March through to December 2022 with the Boxergy Hero system operational, B-07 used 7,564kWh or 24.7kWh/day. During the equivalent March to December period before the Boxergy Hero installation, the consumption was 34.2kWh/day. Correcting for external temperature, there was a reduction in consumption of 20.4% from 6.61kWh/DD with the old heating to 5.26kWh/DD with the Boxergy Hero system.

Thermal comfort and electricity consumption was compared with 4 control properties with infrared heating panels, storage heaters and a battery and air-source heat pumps

- There were 4 control properties to compare with the 7 households that received Boxergy Hero installations. There were 2 households with low temperature ASHPs, a household with infrared heating panels and a household with traditional storage heaters with a Tesla Powerwall 2 battery charging on the off-peak tariff with no PV system

- Household C-01 lived in a 2-bedroom semi-detached bungalow which had storage heaters. The residents were dissatisfied with the running cost and the level of control of the heating and bought their own infrared heating panels and switched to a single rate tariff. The average temperature in the bedroom, the most used room was 18.0˚C in the first winter heating season and 19.7˚C in the second. The living room was rarely used and the average temperature was 14.7˚C for the first heating season and 16.0˚C for the second.
- Smart plugs were used to monitor the consumption of the heating panels with an average of 4.8kWh/day used in the bedroom, 5kWh/day in the hall, 3.2kWh/day in the study, 3.3kWh/day in the kitchen and about 6.8kWh/day used when heating a utility room. During the heating season, there was a consistent consumption of at least 2.1kW through most of the day, with 3 or 4 of the infrared heating panels running.
- Over a year, the electricity consumption of C-01 was 7,701kWh or an average of 21.1kWh/day, with 12.4% of the consumption occurring at what would have been off-peak times had the household been on Economy 7. Compensating for external temperature, the consumption was 4.0kWh/DD. The residents were very satisfied with the thermal comfort, control and running costs of the infrared heating panels. The electricity consumption was slightly higher than B-02 with the Boxergy Hero system which used 3.96kWh/DD over a similar time period.
- Household C-02 lived in a mid-terraced house with traditional storage heaters and a Tesla Powerwall 2 battery. Like the households before the Boxergy Hero systems were installed they were very dissatisfied with the level of control and running costs for the heating system.
- The average temperature of the living room in heating season 1 was 21.02˚C and 21.52˚C in season 2. For the bedroom it was 19.02˚C and 19.67˚C for seasons 1 and 2. The average and minimum room temperatures were typically higher than for the households before the Boxergy Hero installations.
- The annual electricity consumption for C-02 was 9,408kWh or an average of 25.8kWh/day, with 95.2% of the consumption at the off-peak rate. Such a high percentage off-peak consumption was achieved due to the Tesla Powerwall 2 battery charging overnight and supplying up to 13.5kWh of electricity to the home during the peak rate period. The electricity consumption was less than for the other mid-terraced houses with their old heating systems (4.9kWh/DD compared to about 6.3 for B-03 and B-07). Also, the thermal comfort improved. This might be due to a combination of greater use of the storage heaters, better insulation with a more modern building and lower occupancy.
- Household C-03 lived in a single bedroom bungalow with a low temperature ASHP. The thermal comfort varied over the monitoring period, primarily due to changes to the thermostat temperature and heating schedule.
- During November and early December 2021, the average living room temperature was 15.4˚C and the temperature ranged between a minimum of 11˚C and a maximum of 20.0˚C. On 10 Dec 21, the thermostat settings were changed leading the heat pump to run more consistently throughout the day and for the temperature to be more narrowly regulated, normally cycling between 19.5 and 20.0˚C over the day. During a period from 15 Dec 21 to 15 Feb 22, the average living room temperature was 19.7˚C.

- The average electricity consumption of C-03 over monitoring year 1 was 10.2kWh/day and 11.1kWh/day in year 2. Correcting for external temperature the consumption was 1.62kWh/DD in the first year and 1.99kWh/DD in the second. The greater consumption in year 2 might be due to the improved thermal comfort in December to February. Overall, the consumption of household C-03 was the lowest of all the households on the project.
- Household C-04 lived in another single bedroom bungalow with a low temperature ASHP. The average temperature of the living room was 20.5˚C and over the analysis period, the temperature ranged between a minimum of 17.5˚C and a maximum of 22.0˚. The heating schedule on the thermostat had a set-point temperature of 18˚C overnight and 21˚C in the early evening.
- The electricity consumption during monitoring year 1 was 5,354kWh, averaging at 14.67kWh/day and 4,573kWh in year 2 or an average of 12.53kWh/day. Taking into account external temperature, the consumption was 2.32kWh/DD in year 1 and 2.39kWh/DD in year 2. Households C-03 and C-04 lived in the smallest properties in the study with 1-bedroom bungalows. They also had lower electricity consumption than the other households. The next lowest was household B-01 living in a 2-bedroom bungalow, where during a full year with the ASHP, the consumption was 2.81kWh/DD.

Electricity costs were typically lower following the Boxergy Hero installation. The only household where there was a full year of monitoring with storage heaters and the Boxergy Hero system saw the annual bill on Economy 7 fall from £2,218 to £1,718 the following year

- Electricity costs were calculated before and after the Boxergy Hero installations for the households using 4 model tariffs. These included a single rate tariff and 3 different Economy 7 tariffs. The main ones discussed were single rate Tariff 1 with a unit rate of 34p/kWh and Economy 7 Tariff 3 with a cost during peak periods of 42.9p/kWh and 14.6p/kWh during off-peak periods
- The average cost of B-01 on Economy 7 tariff 3 with storage heaters from 30 July 20 to 1 Jun 21 was £5.70/day. After the Vaillant aroTHERM plus heat pump of the Boxergy Hero system was operating, this cost reduced to an average of £5.55/day (£2,025/year). Had the household been on single rate Tariff 1, this cost would have reduced to £5.22/day due to the low percentage of off-peak consumption with just the heat pump. After the Alpha electrical battery was running, for the period of 1 Aug 22 to 1 Dec 22, the average consumption on Tariff 3 fell to £3.29/day due to the percentage off-peak consumption rising to 68.3%
- For household B-02, there was a full year of monitoring with storage heaters followed by a full year with Boxergy Hero with both the heat pump and battery operational. With the storage heaters, the cost on Economy 7 Tariff 3 was £6.08/day (£2,218/year) and this fell to £4.88/day (£1,781/year) the following year with the Boxergy Hero system.
- Household B-03 lived in a mid-terraced house. The heating demand for the property was high. Despite only 34.4% of the consumption being on the off-peak rate, during the pre-installation monitoring period, costs were cheaper on Economy 7 tariff 3 at £13.97/day than on single rate Tariff 1.

- Comparing costs before and after the Boxergy Hero installation for B-03, the average cost in the summer before was £7.18/day between 6 Jun 21 and 10 Jul 21. For the period of 19 May 22 to 29 Jul 22 after the installation, the cost was £5.72/day on Economy 7 Tariff 3. Looking at a colder weather period, between 2 Nov 20 and 1 Dec 20 with the old heating system the cost was £13.86/day on Tariff 3 and £11.51/day between 28 Oct 22 and 27 Nov 22 with the Boxergy Hero system.
- For household B-04, in a 2-bedroom bungalow, during the year from 1 Dec 20 to 30 Nov 21 with the old heating system, the average electricity consumption was 22.8kWh/day. On Economy 7 Tariff 3, the average cost was £11.41/day (£4,163/year). The relatively low percentage off-peak consumption of 32.5% meant the cost was only slightly more on single rate Tariff 1 at £11.51/day
- Comparing a period from 1st February to 30th November in 2021 and 2022, before and after the Boxergy Hero installation, the average cost on Economy 7 tariff 3 was £10.00/day with the old heating system and £6.24/day with the Boxergy Hero system. Savings would have been higher had there not been issues with the battery during this period
- Household B-05, again in a 2-bedroom bungalow, used on average 35.3kWh/day over a year with the old heating system. Due to regular use of the storage heaters, the average cost was lower than for B-04 at £9.42/day on Tariff 3 or £3,439/year.
- A limited period of monitoring was available for B-05 with Boxergy Hero fully operational. Comparing average costs before and after the Boxergy Hero installation, in July 2020, the average electricity cost was £2.80/day and this fell to £1.79/day in July 2022 with the Boxergy Hero system. In November 2020, the cost with the old heating system was £11.79/day compared to £4.53/day with the Boxergy Hero system.
- With the old storage heaters, the average annual electricity cost for household B-06 was £4.99/day on Economy 7 Tariff 3 or £1,823/year. An assessment of how the costs have changed after the Boxergy Hero installation can be made by comparing average costs in July and November before and after the installation
- The costs in July on Economy 7 Tariff 3 fell from £3.24/day in 2021 to £2.57/day in 2022 despite the total consumption increasing. This was due to a higher percentage off-peak consumption. In November, the cost was £5.29/day on Economy 7 Tariff 3 in 2021 and £6.58/day in 2022. There seem to be ongoing issues with this installation which were raising the consumption and also often costs.
- Household B-07 had been switched to a single rate tariff after a smart meter was fitted. For the period 1 Feb 21 to 31 Jan 22 before the Boxergy Hero installation, the electricity cost on single rate Tariff 1 was on average £13.05/day or an annual bill of £4,764
- Comparing the costs for the months March to December before and after the Boxergy Hero installation, in 2021 with the old heating system, the average cost on single rate Tariff 1 was £11.64/day. This fell to £8.40/day for these months in 2022 with the Boxergy Hero system. The cost reduced still further to £6.36/day had the household been on Economy 7 Tariff 3.
- Household C-01 with infrared heating panels used only 12.4% off-peak consumption over a year, which meant that single rate Tariff 1 was cheaper than Economy 7 Tariff 3. The average cost was £7.17/day or an annual bill of £2,618. For comparison, the annual cost for household B-02 with storage heaters was £2,218 and this reduced

further to £1,781 over a similar time period to C-01 with the Boxergy Hero system. Household C-01 occasionally charged a battery electric vehicle, but the majority of the cost was due to the heating.

- Household C-02 had storage heaters and a Tesla Powerwall 2 battery both charging on off-peak electricity. The average cost over the year was £4.12/day or £1,502/year. Despite a relatively high consumption of 9,408kWh, the costs were the second lowest due to 95% of the consumption being off-peak.
- Household C-03 lived in a single bedroom bungalow with a low temperature ASHP. The electricity costs on single rate Tariff 1 were £3.45/day and £3.77/day for the 2 periods of monitoring of about a year. These costs were the lowest among all the households on the project but were for a single person living in one of the smallest homes.
- Household C-04 also lived in a single bedroom bungalow with a low temperature ASHP. The average cost on single rate Tariff 1 was £4.26/day or £1,554/year for the same analysis period of 1 Dec 21 to 30 Nov 22 as C-01 and C-02. While the electricity costs were one of the cheapest on the project, it is interesting that the costs were lower for household C-02 with the storage heaters and Tesla Powerwall 2 battery despite being a larger property. Household B-02 lived in a larger 2-bedroom bungalow and the costs with Boxergy Hero were £227 more over the year at £1,781 over a similar analysis period.

There were reduced savings due to issues with the battery installations and also the Economy 7 tariff

- The batteries for households B-04 and B-05 were not charging and discharging as planned, until after a maintenance visit on 5 Jul 22
- It was not possible for the CT clamp for the battery for B-04 to monitor the full household load due to the wiring configuration of the electricity meter and consumer units. As a result, the battery would charge overnight and rapidly discharge from the start of the peak rate period. This was only fully resolved in late August when a new consumer unit was fitted and some reconfiguration of the wiring allowed the full household load to be accurately measured by the battery
- NEA staff noticed that some of the household smart meters were recording electricity export. This was the total electricity that had been exported to the grid since the meter had been fitted. Since no solar PV system had been fitted, this was due to erroneous export from the battery
- Readings for the export to the grid were taken on 18 Nov 22. For household B-04 a total of 249kWh had been exported. This was likely to have occurred during the period when the full household load was not measured by the battery system and the battery was rapidly discharging each morning
- The level of export for household B-05 was much lower at 11.1kWh. Here, the battery was set to charge and discharge at the same time as B-04 in July, but there was not the same problem measuring the full household load. The export for B-01 was 12kWh on 18 Nov 22. Here the replacement battery was also operational from July
- Other battery systems had recorded high levels of export of between 214 and 402kWh on 18 Nov 22. There had been issues with some of these systems not initially recording the grid consumption on the Alpha ESS portal. Issues with the

battery system not correctly monitoring consumption may have led to export from the battery to the grid

- On 18 Nov 22, the export recorded for B-02 was 402kWh after nearly a year of operation. The issue of high levels of export seems to have been a historic one for this installation as an export reading from 19 Dec 22 was 405kWh, only increasing 3kWh in a month
- For comparison, the Tesla Powerwall 2 battery from household C-02, which was also charging purely using off-peak electricity, had exported 268kWh to the grid by 18 Nov 22. However, this was after more than 4.5 years of operation with an average export of 0.16kWh/day
- The times for off-peak electricity on Economy 7 can vary with supplier, meter and the time of year. For example, for household B-05 the time for off-peak electricity was between 00:00 and 07:00 every day of the year. However, for B-06, which also had a smart meter, the times were from 00:00 to 07:00 Greenwich Mean Time (GMT). This meant that from March to October, off-peak electricity was from 01:00 to 08:00 British Summer Time (BST).
- When the charge time for the batteries was changed to start at 00:00 in August 2022, this meant the battery for B-06 charged for an hour during the peak rate time on BST. The discharge also began at 07:00, an hour before the start of peak rate for household B-06 during BST. About 4.5 to 5kWh of the battery charge was on the peak rate, which meant only about half the battery was charging on off-peak electricity during the period from August to late October
- Household B-07 had been switched to a single rate tariff when a smart meter was fitted a few months into the project. The resident requested to be switched back to Economy 7 a few weeks after the Boxergy Hero installation as electricity costs were more on the single rate tariff. This was initially refused by the supplier, but with support from NEA it should now take place. It has however taken over 6 months since the initial request. Compensation should be paid by the supplier for the increased cost on the single rate tariff since the date the supplier acknowledged the request

5.2. Recommendations and future work

- There was dissatisfaction over thermal comfort and running costs among many of the households with storage heaters. Those who achieved more comfortable room temperatures and lower bills made greater use of the storage heaters with only limited use of supplementary heating. Greater engagement with households on existing systems could lead to better outcomes.
- Modern high heat retention storage heaters were better able to maintain room temperatures, but the complexity of controls could be an issue. Those with young children may need storage heater guards to avoid the risk of burns
- Households on this project preferred a wet central heating system which was more controllable and did not run out of heat towards the end of the day. Room temperatures were often several degrees Celsius warmer with a heat pump and wet central heating system, which should offer health benefits, particularly for older residents and those with health conditions. A resident with a respiratory condition noted that the air was less dry and dusty which made it easier to breathe.
- Poor thermal comfort can also occur with a heat pump if the thermostat is not set appropriately. Engagement with households may be necessary to avoid having a

heating schedule more appropriate for a gas boiler, with bursts of heating. It is better to run a heat pump more consistently through the day. If there is a setback during the day or overnight, it should be no more than 2˚C. A heat pump runs more efficiently if it is maintaining the room temperature rather than having to work hard raising the room temperature.

- The Boxergy Hero system combines a heat pump with a battery and the household is on a time of use tariff. The cost of electricity is cheaper overnight, so there may be limited benefit in having a setback temperature overnight. It may be better for the thermostat to be set with the room temperature constant over the full day or to start heating after an overnight setback at least 2 hours before the end of the low-cost off-peak period.
- The electrical battery with the Boxergy Hero system charges overnight during the period of lower cost off-peak electricity. The times for off-peak electricity can vary with supplier, meter and time of year. It may be possible to obtain these times from an electricity statement, a label on a meter or by calling the supplier. It can however be a challenge for installers and landlords to ensure the correct times are obtained. Also there could be the risk of these changing if the household switches supplier. If the settings are wrong, the household could lose much or all the benefit of charging on an off-peak tariff.
- It may be best for a system on Economy 7 to stop discharging at midnight and only start to charge after 01:00. The battery should only start discharging after 08:00. While this would not necessarily optimise the system, it would avoid the risk of the battery charging during peak rate times and discharging during off-peak times in most cases. In some parts of the UK the times for off-peak electricity might be outside the 00:00 to 07:00 and 01:00 to 08:00 periods considered here.
- An automated process for setting the charge/discharge times on a battery would be ideal. Some suppliers such as Octopus provide an API which allows technologies to interact with their tariff. However, something more universal may be needed for systems in social housing to avoid limiting households from switching in the future.
- On this project, a household was trying to switch back from a single rate tariff to Economy 7 for over 6 months. With smart meters and modern technologies aimed at taking advantage of off-peak tariffs, energy companies need to make it easier to switch between a single rate tariff and a time of use tariff. There needs to be the ability to switch tariff types at no cost and in a mattery of days rather than months. This could allow households to switch to more appropriate tariffs at different times of year – for example moving to a time of use tariff in the winter to charge a battery with a solar PV system.
- Households on this project were on Economy 7 tariffs. For those with high consumption, particularly in the winter, the battery discharged quite early in the day, limiting the benefit the battery could provide to the home. An Economy 10 tariff may be more appropriate in such cases with 3 separate off-peak periods in the day, allowing the battery to charge more than once a day. This could allow households with a high demand to use a higher percentage of lower cost off-peak electricity. It could also help shift consumption away from the 16:00 to 20:00 period with high network demand. More electricity suppliers should offer smart Economy 10 tariffs.
- Measurement of household consumption by the battery with CT clamps is a risk. This project has shown that quite high levels of export to the grid can occur if a system is not recording the correct value. There might be challenges installing a battery system if the CT clamp cannot fit over a single cable with the full load for a household on Economy 7. Other issues can occur if a smart meter is fitted or electrical work carried

out in the home and the battery CT clamp is not replaced correctly. There is a need for greater education of electricians and for battery manufacturers to consider other options for measuring the household load such as a DIN rail meter in the consumer unit.

- The project highlighted some households who had an electricity consumption of 12,000 to 14,000kWh/year, with a high proportion of this being at peak rate times. For one household. the annual electricity bill would have been £4,764 on a single rate tariff.
- Electrically heated homes typically have higher costs due to the price of electricity being several times higher than for gas. This situation has become critical during the recent energy crisis potentially taking many into fuel debt.
- It is important that support is provided to ensure that households are using their heating system as efficiently as possible and can also make savings through behavioural change
- Improving the energy efficiency of homes and quality of heating systems must be a long term prioity for minimising cost and improving thermal comfort for households while decarbonising the housing sector
- Targeting electrically heated homes with a high heating use for external wall insulation will help reduce demand. This will also make a property better suited for installation of a heat pump. Electrically heated homes are those that will most benefit from having a solar PV installation
- North Devon Homes and NEA have a follow up project where solar PV will be installed on all 11 homes in this project and a further 7 which will assess the benefits the solar PV can provide to electrically heated homes
- Technologies like heat pumps and infrared heating panels run through the day and would particularly benefit from solar PV. Households with storage heaters would also see some benefit, reducing their consumption of high cost peak rate electricity
- The project also aims to reduce the cost of water heating, fitting Mixergy smart hot water cylinders, using excess PV generation to heat the water
- Solar PV and batteries are particularly complementary, minimising the excess generation exported to the grid. Adding solar PV to the Boxergy Hero system will help households power their homes primarily from solar generated electricity in summer. It will also help significantly reduce the grid import needed to power the heat pump, particularly in Spring and Autumn
- The current project shows that while infrared panels can provide good thermal comfort and control, the electricity cost can be quite high. The follow-on project will include 2 installations of Wondrwall, a technology that combines infrared heating panels with solar PV, a battery and smart heating controls. This will determine whether this combination of technologies on a time of use tariff will significantly reduce bills.

6. Appendix 1 - Technologies

Data sheets on technologies installed

Vaillant aroTHERM plus air-source heat pump[25]

aroTHERM plus	Unit	3.5kW VWL 35 / 6	5kW VWL 55 / 6	7kW VWL 75 / 6	10kW VWL 105 / 6	12kW VWL 125 / 6
General						
Width	mm	1,100				
Height	mm	765		965	1,565	
Depth	mm	450				
Weight, ready for operation	kg	114		128	194	
Connection, heating circuit		G 1 1/4"				
Rated voltage	V	230 V (+10%/- 15%), 50 Hz, 1~/N/PE				
Rated current, maximum	A	14.3		15.0	23.3	
Fuse size		16			25	
Fuse type	A	C/D				
RCD type		A				
eBUS (2-core communication cable)	mm2	0.75				
Maximum length eBUS cable (communication cable)	m	50				
IP rating		IP 15 B				
Fan, power consumption	W	40			50	
Fan quantity		1			2	
Fan, air flow , maximum	m³ /h	2,300			5,100	
Heating pump, power consumption	W	2 - 50			3 - 87	
Heating circuit						
Heating water temperature, minimum/maximum	° C	20 - 75				
Basic length of the heating water pipe, maximum, between the outdoor unit and indoor unit	m	20				
Operating pressure, minimum	bar	0.50				
Operating pressure, maximum	bar	3.00				
Volume flow, minimum	l/h	400		540	995	
Volume flow, maximum	l/h	860		1,205	2,065	
Water volume, in the outdoor unit	l	1.5		2.0	2.5	
Water volume, in the heating circuit, minimum, thawing mode, activated/deactivated back-up heater	l	15 / 40		20 / 55	45 / 150	
Remaining feed pressure, hydraulic	kPa (mbar)	56.0 (560.0)		44.0 (440.0)	55.0 (550.0)	

Table A.1 Technical specification for Vaillant aroTHERM plus air-source heat pump

[25] Vaillant aroTHERM plus specification sheet, https://www.vaillant.co.uk/downloads/aproducts/renewables-1/arotherm-plus/arotherm-plus-spec-sheet-1892564.pdf (Accessed 21 Dec 22)

aroTHERM output		35°C flow Output	35°C flow SCOP	40°C flow Output	40°C flow SCOP	45°C flow Output	45°C flow SCOP	50°C flow Output	50°C flow SCOP	55°C flow Output	55°C flow SCOP
3.5kW	-5°C	4.2	4.41	4.1	4.03	4	3.65	3.9	3.37	3.8	3.10
	-3°C	4.6		4.4		4.3		4.2		4	
	0°C	4.7		4.7		4.6		4.5		4.4	
	2°C	4.9		4.9		4.9		4.7		4.6	
5kW	-5°C	6.3	4.48	6	4.13	5.6	3.77	5.5	3.41	5.4	3.06
	-3°C	6.8		6.4		6.1		5.9		5.8	
	0°C	6.9		6.7		6.6		6.4		6.2	
	2°C	7.1		7		6.9		6.7		6.5	
7kW	-5°C	8.2	4.36	8.1	4.13	8	3.91	7.5	3.65	7	3.39
	-3°C	8.8		8.6		8.4		7.9		7.4	
	0°C	9.5		9.3		9.1		8.6		8.1	
	2°C	10		9.8		9.6		9		8.5	
10kW	-5°C	9.9	5.03	9.7	4.58	9.4	4.13	9.1	3.85	8.8	3.58
	-3°C	10.7		10.3		10		9.6		9.2	
	0°C	11.9		11.6		11.3		10.7		10.2	
	2°C	12.8		12.5		12.1		11.5		10.9	
12kW	-5°C	13.1	4.88	12.8	4.55	12.5	4.21	11.7	3.92	10.8	3.63
	-3°C	13.9		13.4		12.9		12.1		11.2	
	0°C	15.2		14.6		14.1		13.2		12.3	
	2°C	16		15.5		14.9		13.9		13	

Table A.2 Seasonal Coefficient of Performance (SCOP) and heating output for Vaillant aroTHERM plus air-source heat pump

aroTHERM plus	Unit	3.5kW VWL 35 / 6	5kW VWL 55 / 6	7kW VWL 75 / 6	10kW VWL 105 / 6	12kW VWL 125 / 6
Refrigerant circuit						
Fluid type		R290				
Fluid fill quantity	kg	0.6		0.9	1.3	
Refrigerant, Global Warming Potential (GWP)		3				
CO_2 equivalent	t	0.0018		0.0027	0.0039	
Permissable operating pressure	bar	31.5				
Compressor type		Rotary piston			Scroll compressor	
Compressor oil type		Specific polyalkylene glycol (PAG				
Compressor, control		Electronic				
Noise emissions, heating mode						
Sound power, EN 12102, EN 14511 LWA, A7/W35	dB(A)	51		53	58	
Sound power, EN 12102, EN 14511 LWA, A7/W45	dB(A)	53			58	
Sound power, EN 12102, EN 14511 LWA, A7/W55	dB(A)	54		55	60	
Efficiency						
Energy efficiency class 35°C	(A+++ to F)	A+++				
Energy efficiency class 55°C	(A+++ to F)	A++				

Table A.3 Refrigerant circuit, noise emissions and efficiency for Vaillant aroTHERM plus

Alpha ESS inverter and battery

INVERTER
SMILE5-INV
RESIDENTIAL SERIES

General	
Model	SMILE5-INV
Dimensions (W x D x H)	610 x 236 x 615 mm
Net Weight	60 kg
Interace	
Communication	Ethernet
Ambient Conditions	
Humidity	15% ~ 85% (No Condensing)
Operating Temperature	-20°C ~ 60 °C
IP Protection Class	IP65

Technical Specification	
PV Input (DC)	
Maximum Input PV Power	2 x 3300 W
Maximum DC Voltage	580 V
Nominal DC Voltage	360 V
Start-up DC Voltage	125 V
MPPT Voltage Range	125 ~ 550 V
MPPT Number	2
Maximum Input Current	2 x 12 A
Maximum Short-circuit Current	2 x 15 A
Grid Output (AC)	
Rated Power	4600 W
UPS(Resistive load)	Yes
Nominal Output Voltage	230 V
Output Voltage Range	180 ~ 270 V
Maximum Output Current	22 A
Output Power Factor	0.8 leading to 0.8 lagging
Grid Connection	Single-phase
Battery Input (DC)	
Nominal DC Voltage	48 V
DC Voltage Range	40 ~ 60 V
Maximum Charging Current	100 A
Maximum Discharging Power	4600 W
Compatible Chemistry	LFP
Efficiency	
Maximum Efficiency	97.6%
EURO Efficiency	97.0%

Table A.4 Technical specification for the Alpha ESS Smile 5 inverter

BATTERY

SMILE-BAT-10.1P

Alpha·ESS

Model	SMILE-BAT-10.1P
Physical	
Battery Type	LFP (LiFePO4)
Cell Manufacturer	EVE
System Weight	92 kg
Dimension (W x D x H)	610 x 236 x 693 mm
IP Protection	IP21 (Indoor) / IP65 (outdoor)
Warranty	5 Year Product Warranty, 10 Year Performance Warranty
Electrical	
Energy Capacity	10.1 kWh
Usable Capacity	9.1 kWh
Depth of Discharge (DoD)	90%
Nominal Voltage	48 V
Operating Voltage Range	45 ~ 54 V
Internal Resistance	≤ 30 mΩ
Cycle Life	8000
Operation	
Max. Charging Current	100 A (0.5C)
Max. Discharging Current	100 A (0.5C)
Max. Short-circuit Current	200 A
Operating Temperature Range	-10 °C ~ 50 °C*
Humidity	15% ~ 85%
BMS	
Modules Connection	1 ~ 6 in parallel
Capacity	10.1 / 20.2 / 30.2 / 40.3 / 50.4 / 60.5 kWh
Usable Capacity	9.1 / 18.1 / 27.2 / 36.3 / 45.4 / 54.4 kWh
Monitoring Parameters	System voltage, current, cell voltage, cell temperature, PCBA temperature
Communication	CAN and RS-485 compatible
Certification	
Transportation	UN38.3
Safety	IEC 62619 (Cell), IEC 62619 (Pack)

* When the temperature is below 0 °C or above 40 °C, the performance will be limited.

CE IEC

Table A.5 Technical specification for the Alpha ESS SMILE-BAT-10.1P battery[26]

[26] Alpha ESS SMILE_BAT-10.1P data sheet https://it.alpha-ess.com/Upload/Images/20200903021609_196971.pdf (Accessed 21 Dec 22)

BATTERY
SMILE5-BAT

Alpha·ESS

Model	SMILE5-BAT
Physical	
Battery Type	LFP (LiFePO4)
Cell Manufacturer	EVE
System Weight	65 kg
Dimension (W x D x H)	600 x 250 x 600 mm
IP Protection	IP21 (Indoor) / IP65 (outdoor)
Warranty	10 Year Battery Warranty
Electrical	
Energy Capacity	5.7 kWh
Usable Capacity	5.5 kWh
Depth of Discharge (DoD)	96%
Nominal Voltage	51.2 V
Operating Voltage Range	48 ~ 57.6 V
Internal Resistance	≤ 30 mΩ
Cycle Life	10 000*
Operation	
Max. Charging Current	56 A (0.5C)
Max. Discharging Current	56 A (0.5C)
Max. Short-circuit Current	200 A
Operating Temperature Range	-10 °C ~ 50 °C**
Humidity	15% ~ 85%
BMS	
Modules Connection	1 ~ 6 in parallel
Capacity	5.7 / 11.5 / 17.2 / 22.9 / 28.7 / 34.4 kWh
Usable Capacity	5.5 / 11.0 / 16.5 / 22.0 / 27.5 / 33.0 kWh
Monitoring Parameters	System voltage, current, cell voltage, cell temperature, PCBA temperature
Communication	CAN and RS-485 compatible
Certification	
Transportation	UN38.3
Safety	IEC 62619 (Cell), IEC 62619 (Pack)

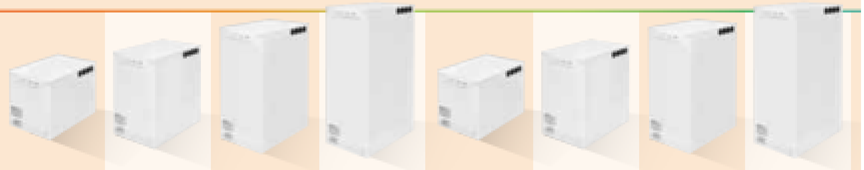
*Under specific test conditions
**When the temperature is below 0 °C or above 40 °C, the performance will be limited.

CE IEC

Table A.6 Technical specification for the Alpha ESS SMILE5-BAT battery[27]

[27] Alpha ESS SMILE_BAT-10.1P data sheet https://it.alpha-ess.com/Upload/Images/20200903021609_196971.pdf (Accessed 21 Dec 22)

Sunamp heat battery



UniQ	eHW 3 +iPV	eHW 6 +iPV	eHW 9 +iPV	eHW 12 +iPV	HW 3 +iPV	HW 6 +iPV	HW 9 +iPV	HW 12 +iPV
MPN/Order Code								
With myenergi eddi	SGP-BAW-AWZ	SKP-BAW-AWZ	SNP-BAW-AWZ	DRP-BAW-AWY	DGP-DBW-AWZ	DKP-DBW-AWZ	DNP-DBW-AWZ	DRP-DBW-AWZ
Without myenergi eddi	SGP-BAW-ATZ	SKP-BAW-ATZ	SNP-BAW-ATZ	DRP-BAW-ATY	DGP-DBW-ATZ	DKP-DBW-ATZ	DNP-DBW-ATZ	DRP-DBW-ATZ
Heat Storage Capacity (kWh)[1]	3.5	7	10.5	14	3.5	7	10.5	14
Equivalent Hot Water Cylinder Size[2]	71	142	212	284	71	142	212	284
V40, Volume of Hot water available at 40°C (L)	85	185	300	370	85	185	300	370
Standby heat loss rate (kWh/24h | [W])	0.48 [20]	0.68 [28]	0.77 [32]	0.84 [35]	0.48 [20]	0.68 [28]	0.77 [32]	0.84 [35]
Energy Efficiency Rating	C	C	C	C	A+	A+	A+	A+
Heater Power Rating (~230V)	2.8 kW	2.8 kW	2.8 kW	2.8 kW	2.8 kW	2.8 kW	2.8 kW	2.8 kW
Height (mm)	455	650	860	1070	455	650	860	1070
Width x Depth (mm)	365 x 575	365 x 575	365 x 575	365 x 575	365 x 575	365 x 575	365 x 575	365 x 575

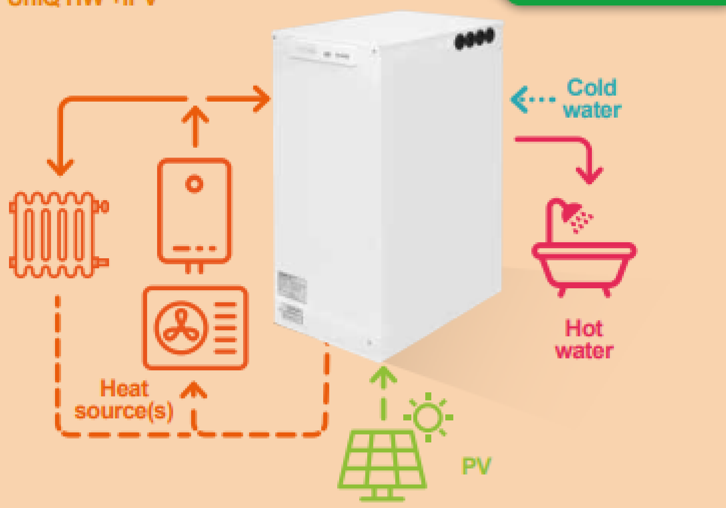
1 Heat Battery charged to design operating temperature and then discharged using inlet water temperature at 10°C, until the outlet water temperature dropped to 40°C.

2 Calculated from the storage capacity of the Heat Battery and assuming that the hot water cylinder thermostat is set at 60°C, mains cold water inlet temperature is at 10°C and the stored energy utilisation factor of cylinder is 0.85.

How it works

A+ ErP Rating

UniQ HW +iPV



Key Features

- Saves cost and carbon by using electricity from Solar PV
- Instant hot water at mains pressure
- Failsafe: backup internal electric heating element
- Extremely low heat losses
- Significantly reduced legionella risk
- Quicker and less costly installation
- No mandatory annual maintenance
- Space-saving: up to 4 times smaller than the equivalent hot water cylinders
- Reliable: Market-leading 10-year warranty
- Modular: easily combined to increase storage capacity

Table A.7 Technical specification for the Sunamp UniQ HW + iPV series

7. Appendix 2 - Household B-01

During the first heating season that was monitored, the household used a combination of traditional storage heaters and supplementary heating. Figures A.8 and A.9 show how electricity consumption on the 24-hour circuit and heating circuit varied with Degree Days.

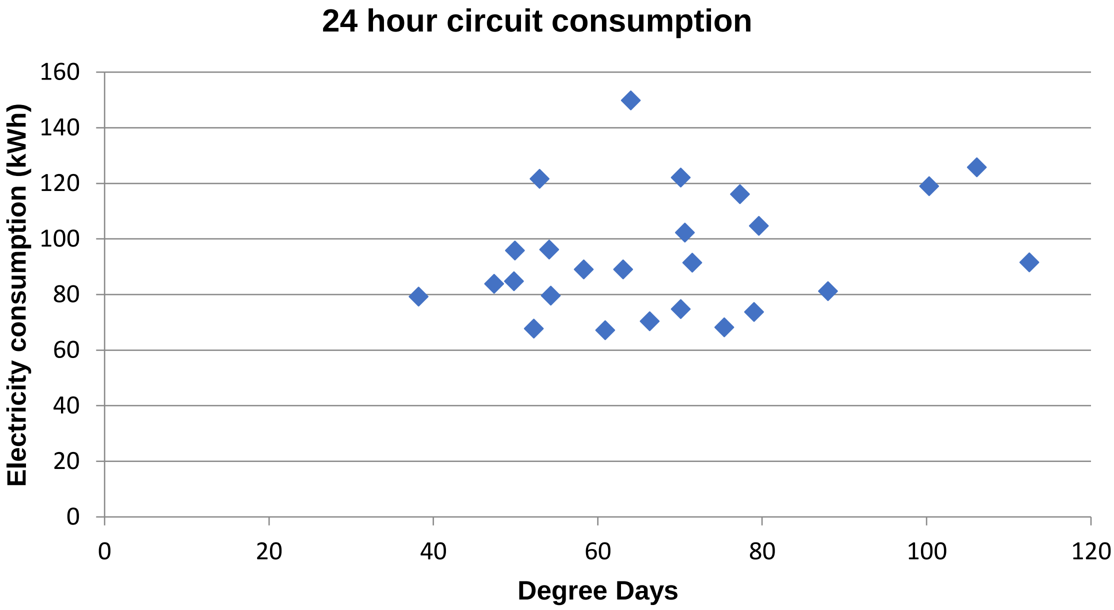


Figure A.8 Graph showing the variation in weekly electricity consumption on the 24-hour circuit with Degree Days, based on 15-minute data from Tinytag View 2 loggers with current clamps. Data from 1 Nov 20 to 25 Apr 21, before the Boxergy installation

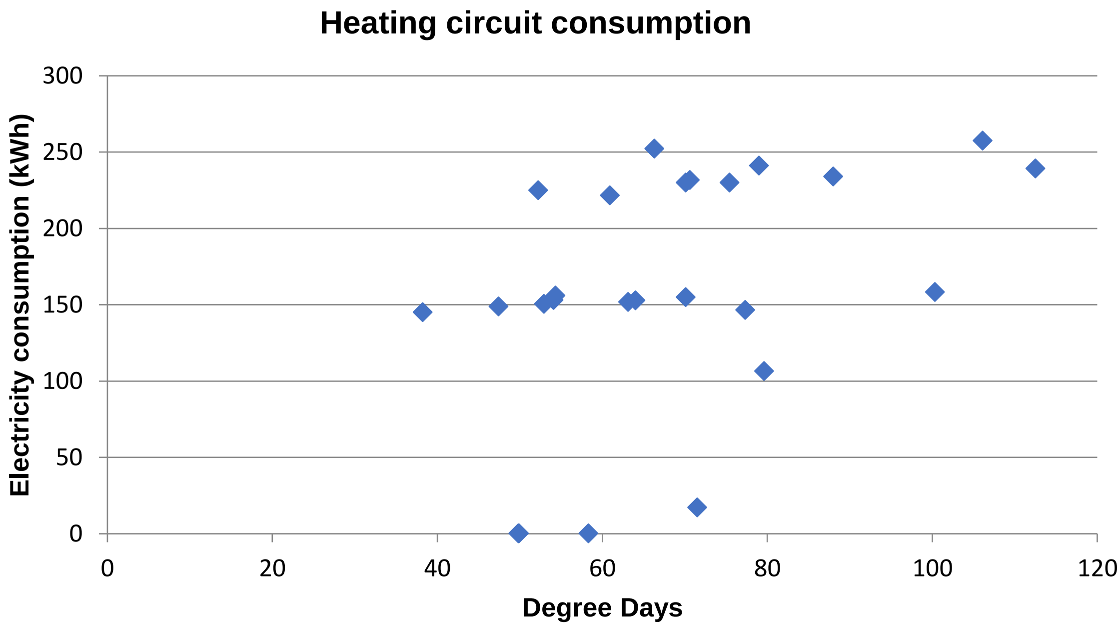


Figure A.9 Graph showing the variation in weekly electricity consumption on the heating circuit with Degree Days, based on 15-minute data from Tinytag View 2 loggers with current clamps. Data from 1 Nov 20 to 25 Apr 21, before the Boxergy installation

Much of the increase in electricity consumption on the 24-hour circuit during the heating season was due to use of supplementary heating. Figure A.8 shows there was considerable scatter in the data points with no strong relationship between the electricity consumption and external temperature. There were however consecutive weeks with similar levels of consumption. For example, the consumption for the weeks in November 2020 was in the range 79 to 96 kWh while from December 2020 to mid-January 2021 it was in the range 116 to 150 kWh. In February and March 2021, consumption was in the range 68 to 92 kWh. This suggests the household gradually changed their use of supplementary heating through the heating season, with more supplementary heating used during December and early January.

Figure A.9 shows the variation in heating circuit electricity consumption with Degree Days for household B-01 using weekly data from 1 Nov 20 to 25 Apr 21. The graph has data points which are approximately on 3 horizontal lines. In November and December, the weekly electricity consumption on the off-peak heating circuit was in the range 145 to 153 kWh. This was due to use of a single storage heater and heating of water by the immersion heater.

Figure A.9 showed that the off-peak electricity consumption increased on 5 Jan 21. From that period until mid-March 2021, the weekly heating circuit electricity consumption was in the range 221 to 257 kWh, with the additional consumption due to running a second storage heater. Towards the end of March 2021, the storage heaters were turned off, but operational again for a period in mid-April 2021. This accounts for the period with low or close to zero weekly off-peak consumption. There was a poor correlation between electricity consumption and Heating Degree Days. This is because there was little control of the output of the heaters with external temperature apart from turning a heater on or off during over the heating season.

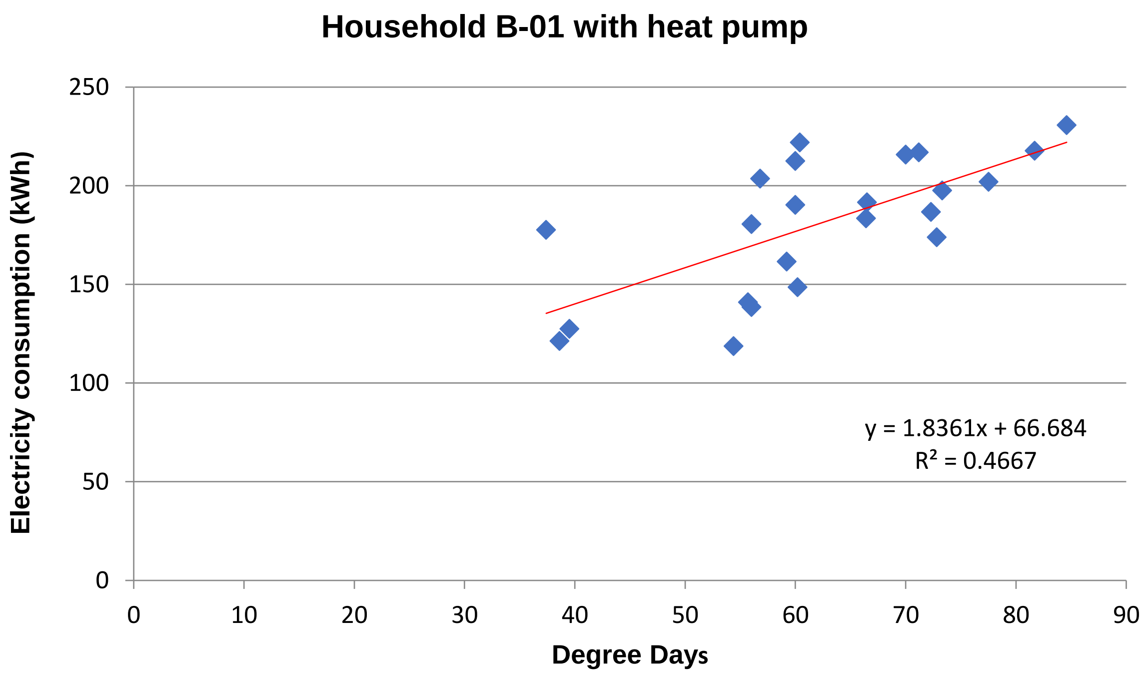


Figure A.10 Graph showing the variation in weekly electricity consumption with Degree Days, based on estimates from 15-minute data from Tinytag View 2 loggers with current clamps. Data from 1 Nov 21 to 25 Apr 22, with air-source heat pump

The variation of electricity consumption with Degree Days is shown in Figure A.10 for household B-01 for the period 1 Nov 21 to 25 Apr 22. This was after the Vaillant aroTHERM plus heat pump was operational. There was quite a lot of scatter in data points which shows there was not a high correlation between electricity consumption and Degree Days. However, there was a stronger correlation than for the data for the storage heaters and the electricity consumption typically rose as the Degree Days increased (colder external temperatures).

The 10.1kWh Alpha electrical battery for household B-01 was replaced on 5 Jul 22 and charged overnight on 6 Jul 22. From this period, the battery was able to supply electricity to the home during peak rate periods, lowering peak rate electricity consumption. Figure A.11 shows electricity consumption on the 24-hour circuit for household B-01 from 1 Jul 22 to 12 Jul 22. It is apparent that after 6 Jul 22, there was an increase in off-peak consumption with the battery charging every night and lower consumption during the peak rate period.

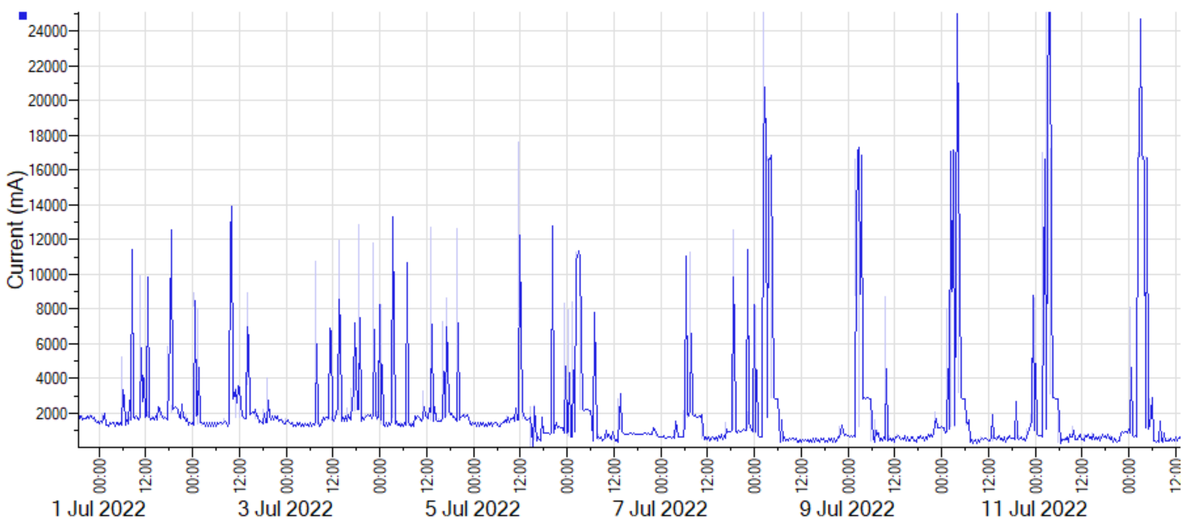


Figure A.11 24-hour electricity circuit for household B-01 between 1 Jul 22 and 12 Jul 22

The grid consumption for household B-01 on 9 Jul 22 is shown brown in the Power Diagram for the Alpha ESS battery in figure A.12. At midnight, the battery had a charge level of 43.2% (shown in green). The battery began charging at 03:00 and was 100% charged by 05:30. From 07:00, the battery was able to supply the household load (in blue) until the battery reached a minimum charge level of 12% at 23:00. From this time, the household load was supplied by the grid. On this particular day, only the 1-hour period from 23:00 used peak rate electricity. This assumes there was a perfect match between battery output and household load, which is not in practice the case.

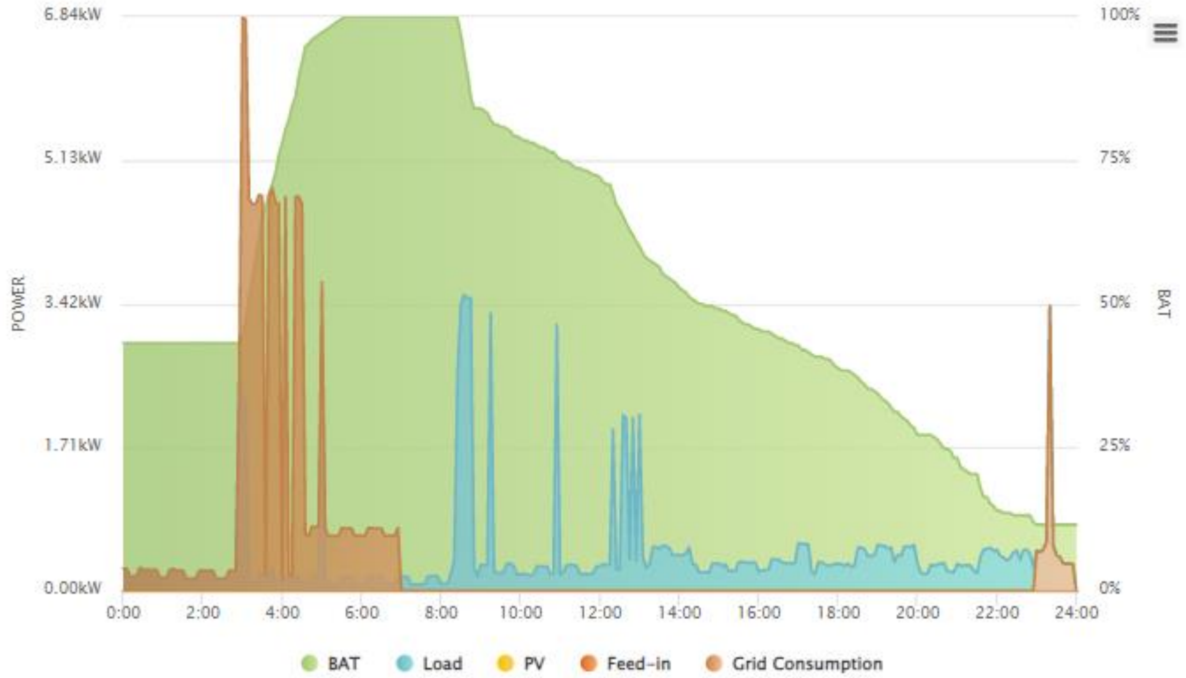


Figure A.12 Power Diagram from the Alpha ESS battery portal for Household B-01 on 9 Jul 22

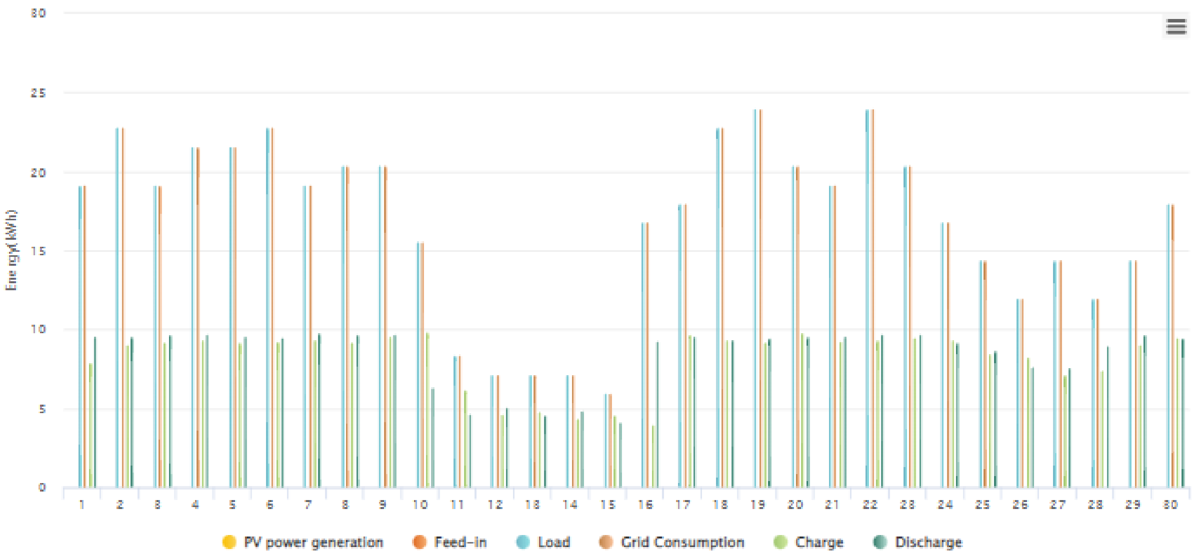


Figure A.13 Statistical Diagram from the Alpha ESS battery portal for Household B-01 for Nov 22

The daily values of household load, grid consumption, battery charge and battery discharge are plotted in the Statistical Diagram for Household B-01 for November 2022. The values of household load and grid consumption are in multiples of 1.2kWh due to the electricity meter fitted with the Alpha Smile battery system. This will lead to errors in the daily measured values compared to a smart meter. The Alpha portal can also show the Statistical Diagram with monthly values. These values are compared to monthly smart meter readings for Household B-01 in table A.14.

Month	Smart Meter Peak consumption (kWh)	Smart Meter Off-Peak consumption (kWh)	Smart Meter Total consumption (kWh)	Alpha battery Household load (kWh)	Alpha battery Grid consumption (kWh)	Alpha battery Battery Charge (kWh)	Alpha battery Battery Discharge (kWh)	Alpha battery Export to grid (kWh)	Percentage error in grid consumption (%)
Mar-22	317.1	181.5	498.6	493.2	493.20	0	0	0	1.08%
Apr-22	270.8	160.5	431.3	429.6	429.60	0	0	0	0.40%
May-22	255.7	100.4	356.2	354.0	354.00	0	0	0	0.61%
Jun-22	235.2	69.3	304.6	303.6	303.60	0	0	0	0.32%
Jul-22	78.9	303.3	382.2	362.4	363.60	203.2	207.7	1.2	4.88%
Aug-22	141.5	214.2	355.7	342.0	343.20	212.4	219.3	1.2	3.53%
Sep-22	135.9	203.0	338.9	322.8	324.00	205.5	220.5	1.2	4.40%
Oct-22	178.1	319.8	497.9	488.4	488.40	262.6	277.0	0	1.90%
Nov-22	93.3	424.8	518.1	506.4	506.40	246.8	254.6	0	2.26%

Table A.14 Electricity consumption and battery performance data derived from smart meter readings and the Alpha ESS battery portal

Although the Alpha Smile 5 hybrid inverter was monitoring the system during the whole of 2022, a fully functioning battery was not fitted until July. This explains why charge and discharge data begins from this date. The battery discharge values were higher than the values for battery charge every month apart from November. While a battery can discharge more on an individual day than it is charged, this cannot happen over the long term and suggests errors in the measurement of battery charge and discharge.

As discussed earlier, the Alpha ESS portal recorded daily readings of grid consumption in multiples of 1.2kWh which will lead to errors in the daily readings compared to a smart meter. Table X shows the monthly grid consumption recorded by the Alpha portal as well as the total electricity consumption from the grid recorded by the household smart meter. The error was quite low before the battery was fitted. In March 2022 the Alpha portal recorded the grid consumption as 493.2kWh compared to 498.6kWh from the smart meter, an error of 1.08%. The error in measuring the grid consumption increased once the 10.1kWh battery was operational in July 2022. In September 2022, the Alpha portal recorded the grid consumption to be 324kWh compared to 338.9kWh for the smart meter, an error of 4.4%. The percentage error was lower in October and November and might decrease as the grid consumption increases in the winter.

The Alpha portal recorded 1.2kWh of export in July, August and September. Normally a battery is fitted with a solar PV system and the monitoring system is recording export to the grid from the solar PV. In this case the values recorded are low and are likely to be due to periods with a mismatch between household load and battery discharge.

The smart meter was fitted in June 2021 and on 18 Nov 22, it had recorded an export of 12kWh as a result of the battery. The battery had only been fully operational from 5 Jul 22 and so had only been running for 4.5 months. The smart meters of some other households had recorded considerably higher export. This may in part be due to the batteries running for longer, but may also be due to the current clamps for the battery not initially recording the household load correctly.

Month	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
Jul-21	8.95	15.26%	£3.04	£1.98	£3.45	£3.37
Aug-21	8.19	16.29%	£2.78	£1.80	£3.13	£3.05
Sep-21	9.09	14.58%	£3.09	£2.02	£3.53	£3.44
Oct-21	14.06	12.76%	£4.78	£3.16	£5.52	£5.41
Nov-21	19.63	21.33%	£6.67	£4.21	£7.24	£6.99
Dec-21	24.08	22.08%	£8.19	£5.14	£8.82	£8.51
Jan-22	25.20	24.23%	£8.57	£5.32	£9.08	£8.73
Feb-22	23.50	26.20%	£7.99	£4.90	£8.34	£7.99
Mar-22	16.08	36.40%	£5.47	£3.16	£5.24	£4.92
Apr-22	14.38	37.21%	£4.89	£2.81	£4.65	£4.36
May-22	11.49	28.20%	£3.91	£2.37	£4.01	£3.83
Jun-22	10.15	22.76%	£3.45	£2.16	£3.70	£3.57
Jul-22	12.33	79.35%	£4.19	£1.79	£2.52	£2.00
Aug-22	11.48	60.22%	£3.90	£1.92	£2.97	£2.60
Sep-22	11.30	59.90%	£3.84	£1.90	£2.93	£2.57
Oct-22	16.06	64.24%	£5.46	£2.62	£3.97	£3.42
Nov-22	17.27	81.99%	£5.87	£2.45	£3.40	£2.65

Table A.15 Average daily electricity consumption and example costs for household B-01

Table A.15 shows average daily electricity consumption of household B-01 based on smart meter data and shows the percentage coming from the off-peak tariff. It also includes daily average costs for 4 example electricity tariffs. Tariff 1 was a typical single rate tariff at the time of writing. Tariff 2 was a lower cost Economy 7 tariff that was available while the project was running. Tariffs 3 and 4 were Economy 7 tariffs available from 2 large energy suppliers around the time of writing. The costs did not include the daily standing charge which was about 52p/day at the time of writing.

Between July 2021 and the end of June 2022, household B-01 was using the air-source heat pump without the electrical battery. Tariff 1 (single rate) was cheaper than Tariffs 3 and 4 (recent Economy 7) during most of this period. The cost of the electricity with Tariff 4 on Economy 7 was cheaper in March, April and May 2022, once the percentage off peak consumption had risen above 26.2%. It was also cheaper in March and April 2022 for the less generous Tariff 3 which was cheaper than the single rate tariff once the off-peak percentage was greater than 31.45%.

The Alpha battery was running from the end of June 2022, charging on the off-peak tariff and discharging during the peak rate period. For the months July to November 2022, the percentage off-peak consumption was in the range 59.9 to 82%. With such a high percentage off-peak consumption, the daily cost of consumption on Tariffs 3 and 4 (recent Economy 7) was always cheaper than for the single rate tariff (Tariff 1).

8. Appendix 3 - Household B-02

Monitoring for household B-02 started at the end of October 2020 when the household had storage heaters. The Boxergy Hero heating system was commissioned on 25 Nov 21 and the home was heated by an air-source heat pump with a wet central heating system from that time.

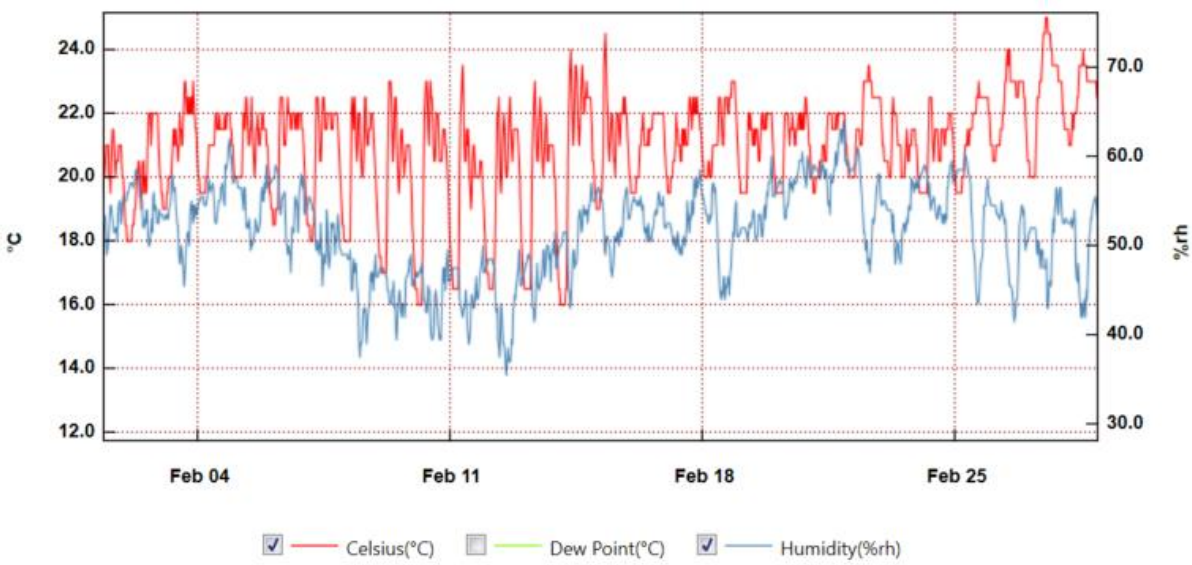


Figure A.16 Graph of Living room temperature and relative humidity for household B-02 Property with storage heaters before Boxergy Hero installation

The graph in figure A.16 shows a plot of the temperature and relative humidity in the living room of household B-02 during February 2021 when the home was being heated by storage heaters. The living room had a Dimplex Quantum QM150 storage heater with an input power of 3.3kW, storing 23.1kWh of heat. The rated power output was 1.5kW. The household also used some supplementary electric heating.

In the second week of February 2021, there was a spell of cold weather and this led to greater falls in room temperature overnight. On 14 Feb 21, the living room temperature had fallen to 16.0˚C by 01:30 and was maintained at that temperature until 05:00 when the temperature began to rise. It reached 22.0˚C at 07:00 and 24.0˚C at 08:30. There was some oscillation in the room temperature between 21.0˚C and 23.5˚C during the day and the temperature fell in the evening from 22.5˚C at 21:30 to 20.0˚C at 00:00.

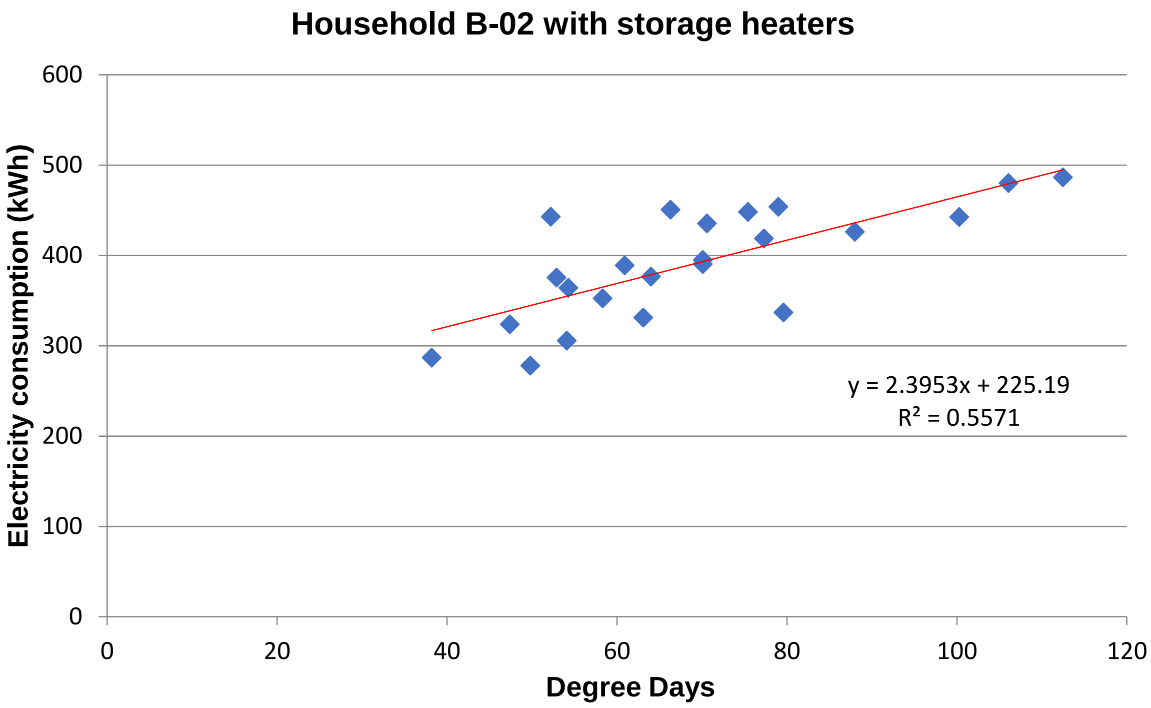


Figure A.17 Graph showing the variation in total weekly electricity consumption with Degree Days, based on estimates from 15-minute data from Tinytag View 2 loggers with current clamps. Data from 1 Nov 20 to 11 Apr 21, with storage heaters

Figure A.17 shows the variation in total weekly electricity consumption with Degree Days for household B-02 with storage heaters. This was derived using data from Tinytag View 2 loggers with current clamps for the period 1 Nov 20 to 11 Apr 21. The storage heaters were turned off after 12 Apr 21. There is a trend for the electricity consumption to increase with Degree Days and better control of the heating with temperature than for household B-01 with storage heaters. This may be due to household B-02 having a Dimplex Quantum QM150 in the living room, which provides a better controlled output than the traditional storage heaters which were used by household B-01.

A similar graph is plotted below in figure A.18. This shows the variation in weekly electricity consumption with Degree Days for household B-02 with the Boxergy Hero system for the period 29 Nov 21 until 25 Apr 22. The graph shows more scatter than figure A.17 above and a lower correlation between electricity consumption and Degree Days. This may be due to settings on the Vaillant sensoCOMFORT smart thermostat being changed a number of times over the winter heating season. This household tended to have the smart thermostat set to manual control. The gradient of the trend-line at 3.422 was higher after the Boxergy Hero installation than with the storage heater system (2.395). However, due to the higher intercept for the graph with the storage heaters, the electricity consumption on the trend-line for the Boxergy Hero system would only be above that for the trend-line for the storage heaters when the number of Degree Days reached 129.

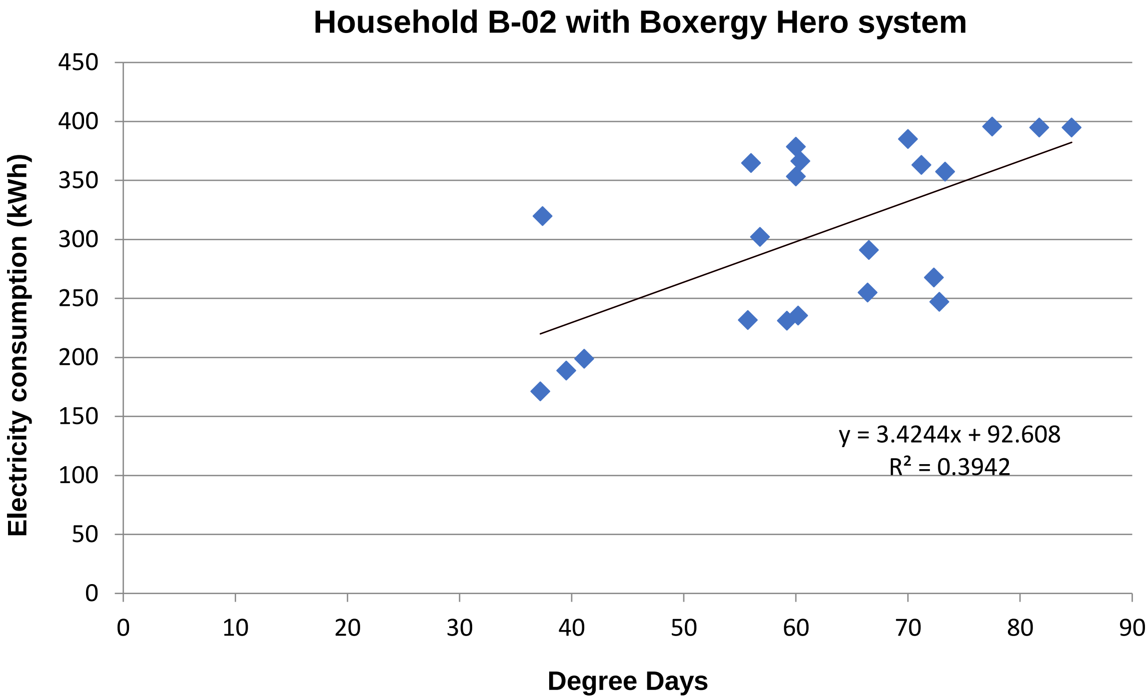


Figure A.18 Graph showing the variation in total weekly electricity consumption with Degree Days, based on estimates from 15-minute data from Tinytag View 2 loggers with current clamps. Data from 29 Nov 21 to 25 Apr 22, with Boxergy Hero system

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Dec-21	14.13	2.03	16.16	12.6%	1.69
Jan-22	15.23	2.00	17.23	11.6%	1.45
Feb-22	13.21	1.32	14.54	9.1%	1.48
Mar-22	9.94	1.48	11.42	13.0%	1.20
Apr-22	7.20	1.60	8.80	18.2%	0.98
May-22	0.23	1.94	2.16	89.6%	0.06
Jun-22	0.23	0.93	1.17	80.0%	0.10
Jul-22	0.19	0.65	0.84	76.9%	0.20
Aug-22	0.16	0.97	1.13	85.7%	0.31
Sep-22	0.53	1.47	2.00	73.3%	0.22
Oct-22	2.19	1.90	4.10	46.5%	0.73
Nov-22	7.50	1.10	8.60	12.8%	1.13
12 months	5.86	1.45	7.31	19.9%	1.12

Table A.19 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-02. Data derived from the Vaillant sensoAPP.

Estimates of the electricity consumption by the Vaillant aroTHERM plus heat pump that makes up part of the Boxergy Hero system are shown in table A.19 for household B-02. In total, data from the sensoAPP suggested that the heat pump consumed on average 7.31kWh/day. This compared to an average of 20.76kWh/day for the whole house over a similar time period. Vaillant note that while the onboard meter meets Ofgem's requirements for metering for performance, depending on the conditions the actual consumption can vary by up to 20% from the displayed value.

In the summer, water heating made up at least 75% of the electricity consumption by the heat pump. In practice the space heating recorded by the heat pump in the summer may have been within the margin of error as the space heating was likely to have been turned off over this period. This may have meant that all the consumption by the heat pump in May to August was from water heating.

The coefficient of performance for the heat pump for household B-02 was estimated to be 1.91 in June when most if not all the heating was water heating. In October it was estimated to be 3.07 when 46.55 of the heating was water heating.

The electricity consumed while heating water was typically 1 to 2 kWh/day. When the household had storage heaters, the off-peak consumption in the summer was about 5kWh/day. Some of this was from appliance use, but most was due to water heating by the immersion heater. While the sensoAPP might have underestimated the consumption from water heating by the heat pump, savings are likely. This is due to the coefficient of performance of the heat pump producing around 2 units of heat while water heating for each unit of electricity consumed. Also, less heat is likely to have been lost per day by the Sunamp heat battery compared to the hot water cylinder that was in the house with the storage heaters.

Table A.20 shows the electricity consumption per day over 1 to 3 month time intervals along with the percentage of the consumption from the off-peak tariff. This includes an approximately 12-month period of 29 Oct 20 to 22 Oct 21 with storage heaters and another from 25 Nov 21 to 22 Nov 22 with the Boxergy Hero system.

The daily average costs have been calculated using 4 different example electricity tariffs which have been used by suppliers during the project. Tariff 1 is a single rate tariff set at the energy price guarantee from 1 Oct 22 to 31 Mar 23. The other tariffs are Economy 7 tariffs, with tariff 2 an example from earlier in the project before large increases in energy prices due to the geopolitical factors. Tariff 3 was a standard variable tariff for Economy 7 used by a large supplier and Tariff 4 was another Economy 7 tariff with a low off-peak rate which was offered in South West England by a supplier in Autumn 2022.

If the off-peak consumption is above 31.56% for tariff 3 and 26.2% for tariff 4, these Economy 7 tariffs are cheaper than single rate tariff 1. Since the off-peak consumption was always at least 38.34%, the Economy 7 tariffs were cheaper than the single rate tariff for all the periods with the storage heaters and the Boxergy Hero system.

In the winter, while the total electricity consumption with the Boxergy Hero system was always lower than for the storage heaters, the amount of peak rate consumption could be higher during colder periods when there was greater use of the heat pump during the peak rate period. This meant that on tariffs 3 and 4 the running costs could be higher than with the storage heaters. Between 21 Nov 20 and 22 Feb 21 the total electricity consumption with storage heaters was 47.58kWh/day, with 81% of this off-peak. On tariff 4, the cost was £7.46

per day. For a shorter period with the Boxergy Hero system from 25 Nov 21 to 22 Jan 22, the average total consumption was 35.85kWh/day with 52.62% off-peak. The cost on tariff 4 during this period was £9.02/day. The period analysed with the storage heaters was colder with an average of 10.79 Degree Days per day compared to 9.37 Degree Days per day for the period with the Boxergy Hero system.

Start	End	Total electricity consumption (kWh/day)	Percentage off-peak (%)	Tariff 1 Single Rate R = 34p/kWh Cost per day (£)	Tariff 2 Economy 7 R1 = 24p/kWh R2 = 12p/kWh Cost per day (£)	Tariff 3 Economy 7 R1 = 42.9p/kWh R2 = 14.6p/kWh Cost per day (£)	Tariff 4 Economy 7 R1 = 42.74p/kWh R2 = 9.32p/kWh Cost per day (£)
29-Oct-20	21-Nov-20	30.74	64.78%	£10.45	£4.99	£7.55	£6.48
21-Nov-20	22-Feb-21	47.58	80.99%	£16.18	£6.79	£9.51	£7.46
22-Feb-21	22-Mar-21	41.69	84.00%	£14.17	£5.80	£7.97	£6.12
22-Mar-21	22-Apr-21	27.92	76.29%	£9.49	£4.14	£5.95	£4.81
22-Apr-21	22-May-21	14.01	38.34%	£4.76	£2.72	£4.49	£4.19
22-May-21	22-Jun-21	11.62	42.45%	£3.95	£2.20	£3.59	£3.32
22-Jun-21	22-Jul-21	11.10	43.89%	£3.78	£2.08	£3.38	£3.12
22-Jul-21	22-Oct-21	12.22	38.59%	£4.16	£2.37	£3.91	£3.65
25-Nov-21	22-Jan-22	35.85	52.62%	£12.19	£6.34	£10.04	£9.02
22-Jan-22	22-Feb-22	32.38	55.20%	£11.01	£5.63	£8.83	£7.87
22-Feb-22	22-Apr-22	23.34	71.72%	£7.93	£3.59	£5.28	£4.38
22-Apr-22	22-May-22	15.18	86.51%	£5.16	£2.07	£2.80	£2.10
22-May-22	22-Jun-22	12.93	91.37%	£4.40	£1.69	£2.20	£1.58
22-Jun-22	22-Jul-22	12.19	89.86%	£4.14	£1.61	£2.13	£1.55
22-Jul-22	22-Aug-22	12.24	90.64%	£4.16	£1.61	£2.11	£1.52
22-Aug-22	22-Sep-22	12.32	91.78%	£4.19	£1.60	£2.09	£1.49
22-Sep-22	22-Oct-22	15.97	72.64%	£5.43	£2.44	£3.57	£2.95
22-Oct-22	22-Nov-22	19.08	64.26%	£6.49	£3.11	£4.72	£4.06

Table A.20 Average daily electricity consumption before and after the Boxergy Hero installation for household B-02, showing daily costs with example tariffs

From April to September, the Boxergy Hero system was cheaper than the storage heaters on all the Economy 7 tariffs. This was due to the battery allowing the percentage off-peak consumption to be higher. In the summer, the consumption with the Boxergy Hero system was slightly higher than for the storage heaters, but high off-peak consumption led to lower costs on all the Economy 7 tariffs, but not the single rate tariff.

For the period 22 Jun 21 to 22 Jul 21 the total electricity consumption for household B-02 with storage heaters was 11.1kWh/day with 43.9% of the consumption off-peak. With tariff 3, the average daily cost was £3.38/day for the period. During the same period a year later with the Boxergy Hero system, the total electricity consumption for household B-02 was 12.19kWh/day with 89.9% of the consumption off-peak. Since the average electricity consumption per day was 1.09kWh higher with the Boxergy Hero system, the electricity cost was £0.37/day more expensive when on a single rate tariff. However, there were significant savings on an Economy 7 tariff due to the high percentage of off-peak consumption. Instead of £3.38/day with storage heaters, the electricity cost fell to £2.13/day with the Boxergy Hero system.

Over a full year, as shown in the main report, the electricity costs were cheaper with the Boxergy Hero system than with the storage heaters. The electricity cost for household B-02 with storage heaters was £6.08/day on tariff 3 over a full year compared to £4.88/day with the Boxergy Hero system. These lower running costs were in addition to providing improved thermal comfort.

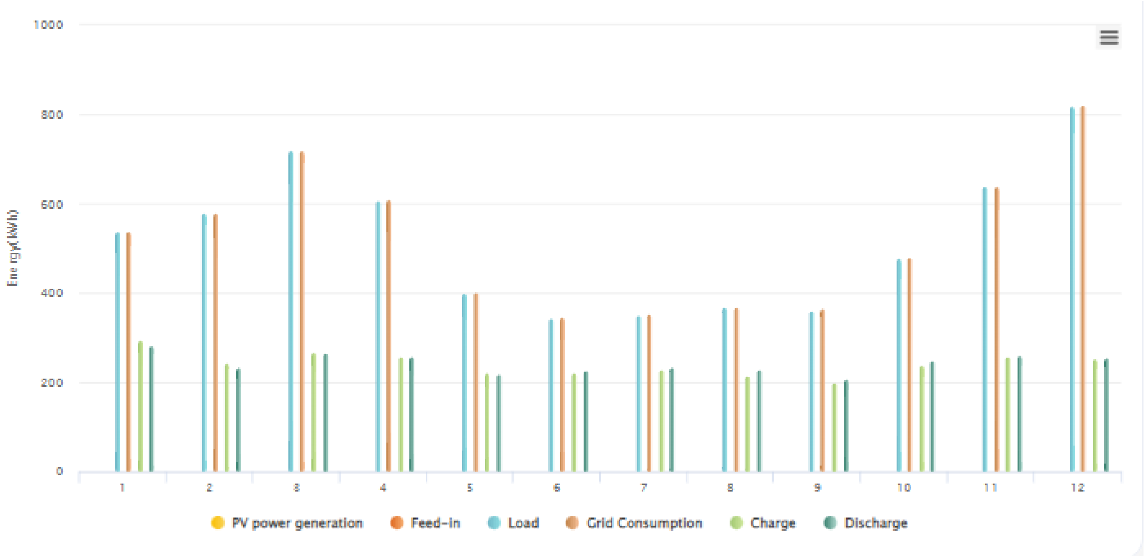


Figure A.21 Statistical Diagram from the Alpha ESS battery portal for Household B-02 for 2022

The Alpha ESS battery portal statistical diagram can provide daily, monthly or annual data with the household load, grid consumption, battery charge, battery discharge and export to the grid (feed-in). Figure A.21 shows such a plot for 2022 for household B-02 with monthly data. The values are also shown in table A.22.

As for household B-01, the battery discharge recorded was lower than the battery charge over the monitoring period, which suggests some error in the measurement. The export to the grid measured in 2022 was 21.6kWh. This compares to a value of 402kWh export recorded on 18 Nov 22 since the installation on the household smart meter. This increased to 405kWh by 19 Dec 22. The increase in export of 3kWh between 18 Nov 22 and 19 Dec 22 was of the same magnitude as the values of export recorded by the Alpha portal in November and December. It is therefore likely that the high levels of export occurred before the battery system was correctly monitoring the household load on 12 Feb 22.

Month	Alpha battery Household load (kWh)	Alpha battery Grid consumption (kWh)	Alpha battery Battery Charge (kWh)	Alpha battery Battery Discharge (kWh)	Alpha battery Export to grid (kWh)
Jan-22	538.8	538.8	295.7	283.6	0.0
Feb-22	579.6	579.6	243.9	235.3	0.0
Mar-22	718.8	720.0	268.5	265.9	1.2
Apr-22	607.2	610.8	259.5	258.4	3.6
May-22	400.8	403.2	223.1	220.1	2.4
Jun-22	343.2	345.6	220.9	226.5	2.4
Jul-22	350.4	352.8	228.8	234.1	2.4
Aug-22	367.2	368.4	215.3	230.2	1.2
Sep-22	361.2	364.8	200.6	208.4	3.6
Oct-22	478.8	480.0	238.4	249.3	1.2
Nov-22	638.4	639.6	258.0	261.8	1.2
Dec-22	818.4	820.8	254.7	255.8	2.4
Total	**6202.8**	**6224.4**	**2907.4**	**2929.4**	**21.6**

Table A.22 Data from the Alpha ESS portal statistical diagram for household B-02 for 2022

9. Appendix 4 - Household B-03

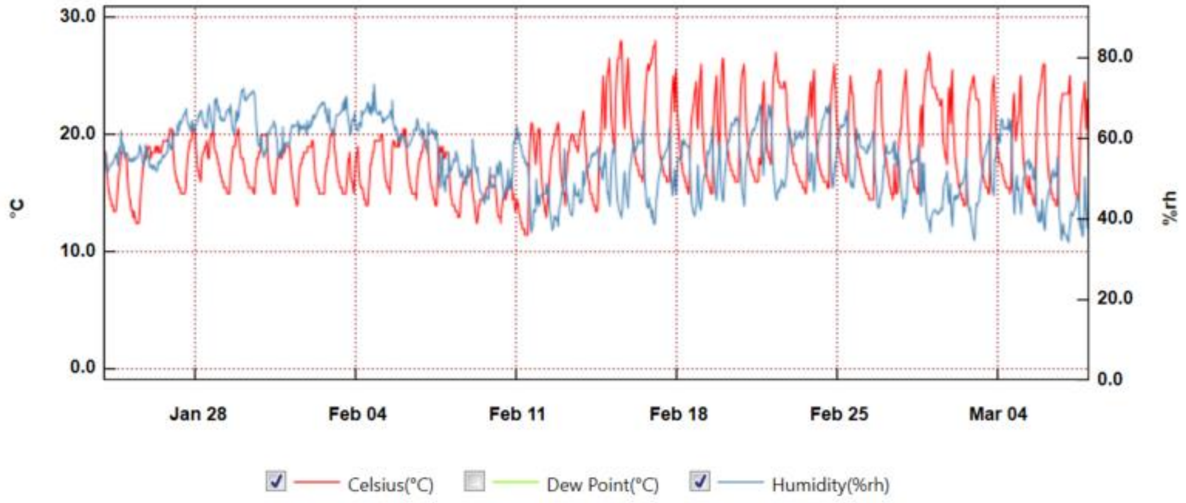


Figure A.23 Graph of living room temperature and relative humidity for household B-03 from 24 Jan 21 to 8 Mar 21, while the property had storage heaters, before the Boxergy Hero installation

The graph of temperature and relative humidity in figure A.23 shows a change in the temperature profile which occurred on 14 Feb 21. Household B-03 normally used a peak rate electric heater to warm the living room before the Boxergy Hero system was installed. During the winter of 2020/21 the electric fire in the living room was replaced. The change in temperature profile is likely to have occurred at this time.

The average temperature between 1 Nov 20 and 1 Feb 20 was 17.81˚C over the full day and 19.39˚C during the early evening (17:00 to 21:00). The standard deviation in temperature was 2.36˚C. It is apparent from figure A.23 there was a lower daily variation in temperature before the change on 14 Feb 21.

The minimum temperature normally occurred in the morning with the heating on after lunch and until the late evening, with the maximum temperature often after midnight. An example was on 5 Feb 21, where the temperature was 19.5˚C at midnight and rose to 20˚C between 01:30 and 03:30. The temperature gradually fell to 15.0˚C at 11:30 and started to rise again after 12:00 once the heating was turned on. By 15:00, it had reached 19.5˚C and stayed between 19.0 and 19.5 until 23:30 when it reached 20.0˚C and a peak of 20.5˚C at 01:30 the next morning.

There was a wider temperature range after 14 Feb 21 and also a higher average temperature. Over the period 15 Feb 21 to 15 Apr 21, the average temperature in the living room was 19.29˚C over the whole day and 21.41˚C in the early evening period of 17:00 to 21:00. The temperature ranged from 13.0˚C to 28.0˚C and the standard deviation in temperature was 3.25˚C.

On 16 Feb 21 at midnight, the living room temperature was 20.5˚C. This fell to 16.0˚C at 11:30 and the heating was turned on again after noon. The temperature reached 20.0˚C by 13:00 and rose to 25.5˚C by 16:30. It continued to rise through the evening and reached

28.0˚C by 01:00 the next morning. By 13:00 the next day, the living room temperature had fallen to 16.0˚C again, with a drop of 12˚C in 12 hours.

The new electric fire that was likely to have been fitted on 14 Feb 21 led to a higher average room temperature. However, the fire had no thermostat and poor temperature control. This meant the living room reached uncomfortably high temperatures such as 28˚C. With most of the heating during peak rate times, this will have increased bills.

The heat loss from the living room was likely to have been quite high and residents may feel draughts. The doors to the living room are close to the front door and lead out to the kitchen which has an external door to an unheated outhouse. The living room has 3 external walls as a result of a passage-way or ginnel between the terraced houses. The level of insulation in this wall may not be high. Being built in the 1940s, the cavity in the wall is likely to be narrow. Some properties in the village have suffered from damp in the cavity wall and the residents mentioned this was a concern. There may be limited insulation provided with this wall as a result.

Start Date	End Date	Total consumption Prepayment meter (kWh/day)	Alpha ESS portal Grid consumption (kWh/day)	Wibeee logger Grid consumption (kWh/day)	Wibeee logger Downstairs sockets (kWh/day)	Wibeee logger Electric Shower (kWh/day)
19-May-22	29-Jul-22	21.90		21.92	2.96	1.03
29-Jul-22	01-Sep-22	19.76	19.73	19.91	2.88	0.76
01-Sep-22	28-Sep-22	27.44	26.67	27.21	4.30	1.06
28-Sep-22	28-Oct-22	26.83	26.44	26.86	3.77	0.81
28-Oct-22	27-Nov-22	37.00	39.00			

Table A.24 Comparing electricity meter reading data with consumption recorded by data loggers

Household B-03 were concerned that their prepayment electricity meter had not been accurately recorded their consumption for several years. A Wibeee Box electricity logger was fitted before the Boxergy Hero system was installed to better understand the household consumption. Unfortunately, there was a loss of data due to the household switching broadband supplier and Wibeee switching their monitoring platform. It was possible to reconnect the Wibeee Box on 19 May 22 after setting up the logger with a new account on the Wibeee Nest monitoring platform. Unfortunately, the household switched broadband supplier again on 28 Oct 22 and the Wibeee logger once again lost connection. It was not possible to monitor the electricity consumption with the Wibeee logger during cold weather, but data was still recorded for over 5 months. It was possible to compare this consumption data with prepayment meter readings and grid consumption data recorded by the Alpha ESS battery portal.

Table A.24 shows that the grid consumption calculated from the Wibeee Box data closely matched consumption from the household meter readings. For example, the average consumption recorded from meter readings for the period 28 Sep 22 to 28 Oct 22 was 26.83kWh/day compared to 26.86kWh/day with the Wibeee logger. The error between the meter readings and Wibeee data for the 4 intervals analysed ranged from 0.07 to 0.86%. This verifies the consumption readings from the prepayment meter and suggests the Wibeee data logger had a high level of accuracy.

A comparison was also made with the measurements of grid consumption on the Alpha ESS battery portal. An issue with the readings from the Alpha portal is that they are only in intervals of 1.2kWh. However, for the approximately monthly intervals analysed, the error in the grid consumption recorded by the Alpha portal was still relatively low. For the 4 intervals where the consumption from meter readings was compared to the consumption recorded by the Alpha ESS portal, the error between the readings ranged from 0.18 to 5.4%.

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Feb-22	18.19	2.28	20.47	11.1%	2.04
Mar-22	17.10	2.26	19.35	11.7%	2.07
Apr-22	12.03	2.77	14.80	18.7%	1.64
May-22	2.61	4.08	6.69	61.0%	0.67
Jun-22	1.30	3.30	4.59	71.8%	0.53
Jul-22	0.24	2.41	2.65	91.1%	0.25
Aug-22	0.16	2.13	2.29	93.0%	0.31
Sep-22	5.50	2.13	7.63	27.9%	2.23
Oct-22	7.82	2.61	10.44	25.0%	2.59
Nov-22	17.47	2.83	20.30	14.0%	2.64
Total	8.13	2.68	10.81	24.8%	1.85

Table A.25 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-03. Data derived from the Vaillant sensoAPP.

Estimates of the electricity consumption by the Vaillant aroTHERM plus heat pump for household B-03 are shown in table A.25. The data is derived from the Vaillant sensoAPP which provides an indication of consumption and may normally differ by up to 20% from the actual consumption. However there were periods in February, May, June and November when the Boxergy Hero system including the Vaillant heat pump was not connected to the internet. The measurement error might be higher than 20% during these periods.

The average consumption from water heating was typically in the range 2 to 3 kWh/day. The consumption in May 22 was particularly high due to a single day which recorded over 18kWh consumption. This might be due to a data error or a day with particularly high hot water consumption. As would be expected the percentage of the consumption from water heating was higher in the summer reaching over 90% in July and August. The values of space heating consumption for those months were within the margin of error and so all the heating may have been from water heating those months.

Estimates of the Coefficient of Performance (CoP) of the heat pump were made using monthly consumption and environmental yield data from the sensoCOMFORT thermostat. In April 2022 the CoP was about 2.67. It fell to 2.28 in June when much of the heating was water heating. In September and October the CoP was 3.3 and 3.4 respectively.

The estimated total heat pump consumption in February 2022 was 20.47kWh/day. This compares with an average total household electricity consumption for household B-03 of 39.4kWh/day. For comparison, in February 2022, the total heat pump consumption for household B-02 was 14.54kWh/day. Over the February to November 2022 period, the total heat pump consumption for household B-03 averaged at 10.8kWh/day. Over the same February to November period, the total heat pump consumption for household B-02 was 5.4kWh/day, half the value to household B-03.

10. Appendix 5 - Household B-04

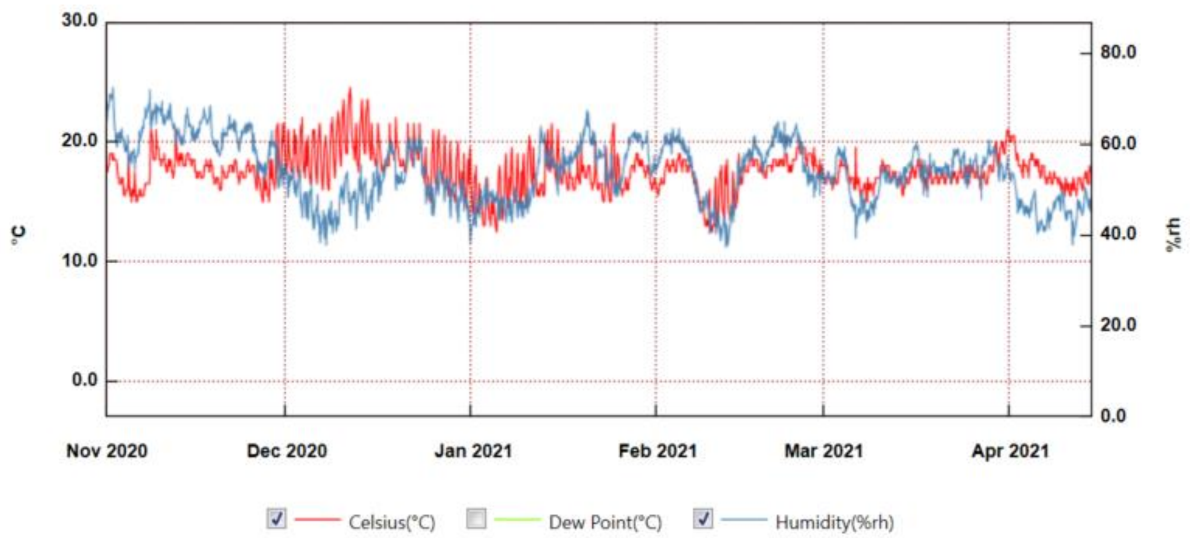


Figure A.26 Graph of living room temperature and relative humidity for household B-04 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

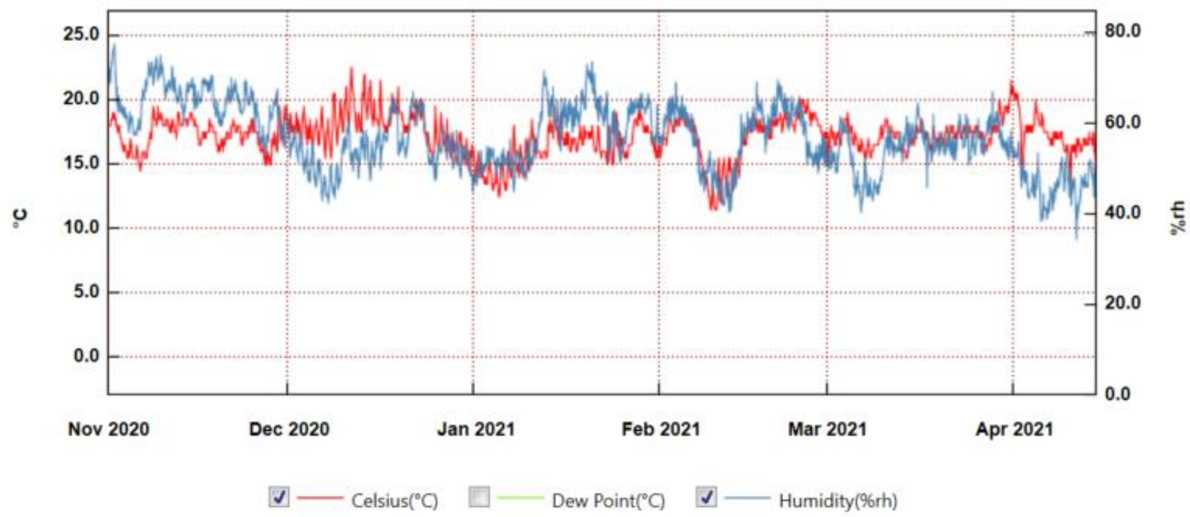


Figure A.27 Graph of bedroom temperature and relative humidity for household B-04 from 1 Nov 20 to 15 Apr 21, while the property had storage heaters, before the Boxergy Hero installation

Figures A.26 and A.27 show graphs of temperature and relative humidity for the living room and bedroom of household B-04 before the Boxergy Hero installation. Both graphs show similar characteristics with a variation in the temperature over the longer term. The periods with low room temperature correspond to periods where the external temperature was colder. These periods include 3 to 5 Nov 20, 27 Dec 20 to 10 Jan 21 and 5 to 14 Feb 21.

A plot of weekly peak rate electricity consumption against Degree Days is shown in figure A.28 for household B-04 during the winter heating season with the old heating system. It is apparent there was an increase in peak rate electricity consumption as the external temperature became colder. This was due to extensive use of electric heaters during the peak rate period. The consumption on the off-peak tariff in figure A.29 showed little or no relationship with external temperature. It was in the range 73 to 104kWh, between 12 Nov 20 and 28 Jan 21. It then was in the range 108 to 125kWh between 4 Feb 21 and 22 Apr 21, perhaps due to greater storage heater use.

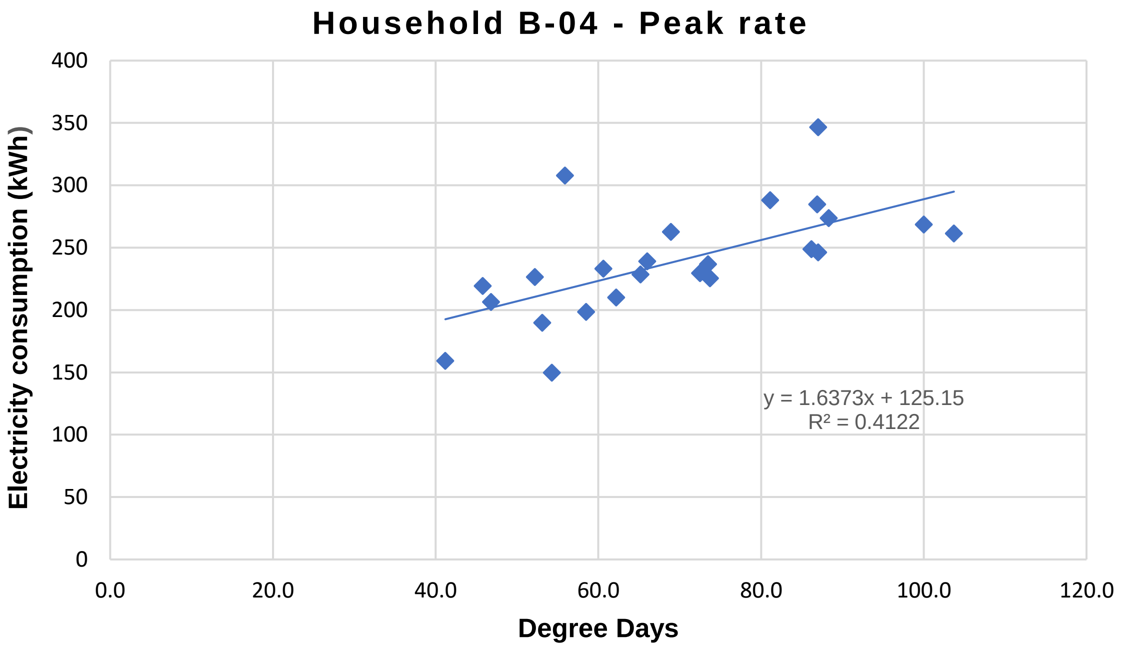


Figure A.28 Graph showing the variation in weekly peak rate electricity consumption with Degree Days, from 12 Nov 20 to 29 Apr 21, with previous heating system

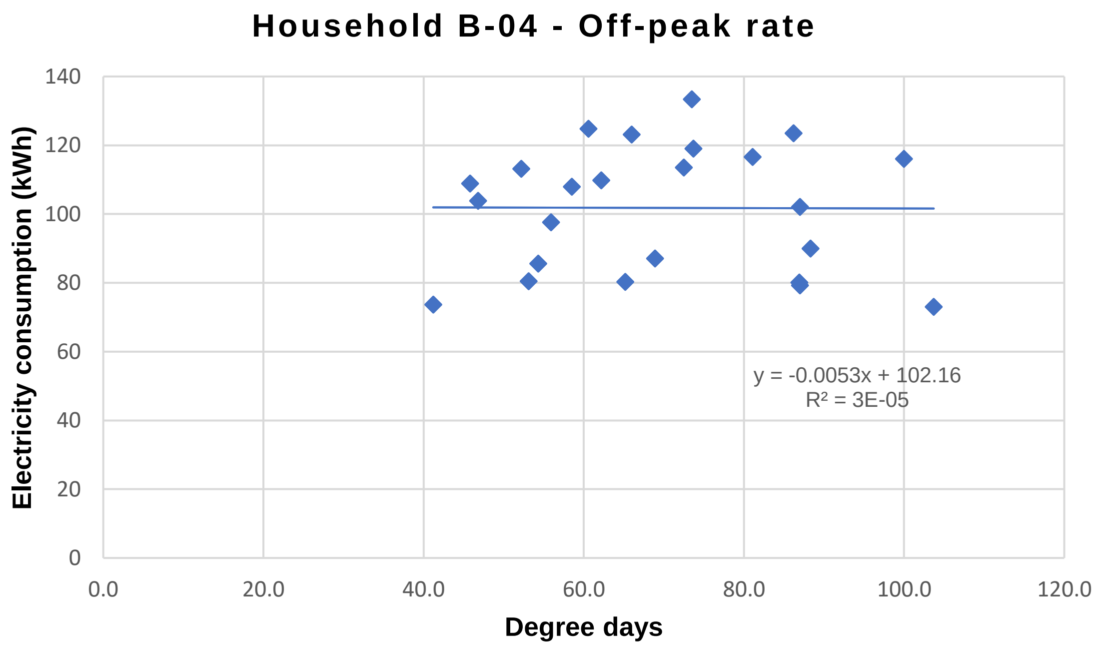


Figure A.29 Graph showing the variation in weekly peak rate electricity consumption with Degree Days, from 12 Nov 20 to 29 Apr 21, with previous heating system

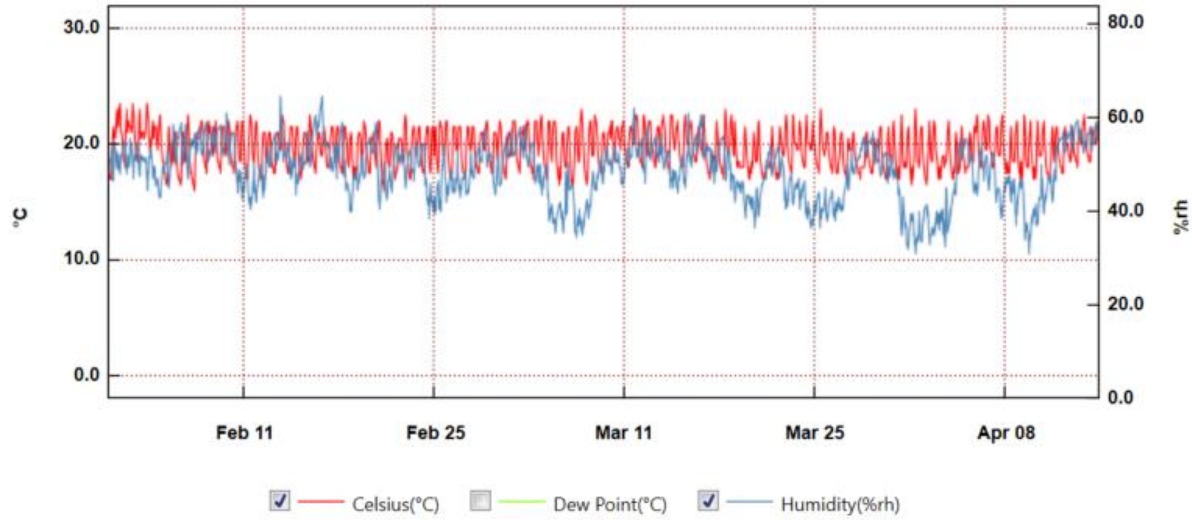


Figure A.30 Graph of living room temperature and relative humidity for household B-04 from 1 Feb 22 to 15 Apr 22, after the Boxergy Hero installation

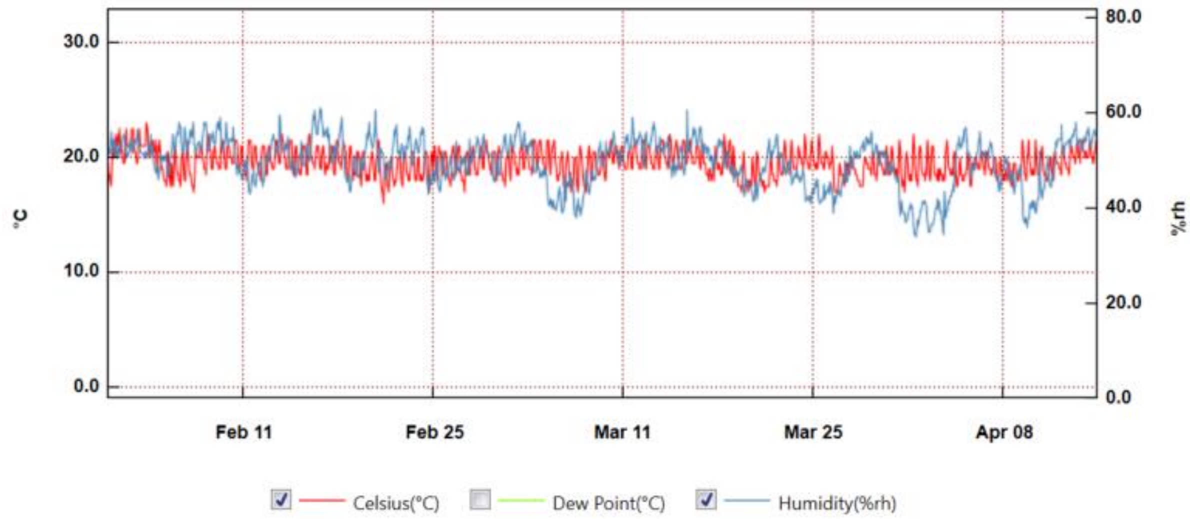


Figure A.31 Graph of bedroom temperature and relative humidity for household B-04 from 1 Feb 22 to 15 Apr 22, after the Boxergy Hero installation

After the heat pump for the Boxergy Hero system was operational, the living room and bedroom was less affected by variations in external temperature. The room temperature stayed within a narrower temperature range of 16 to 23.5˚C. There was a daily fall in temperature overnight and the room temperature quickly reached a comfortable temperature in the morning and remained above 19˚C for the rest of the day. There was little difference in the temperature and humidity between the living room and bedroom.

Estimates of the electricity consumption by the Vaillant aroTHERM plus heat pump for household B-04 are shown in table A.32. The data is derived from the Vaillant sensoAPP which provides an indication of consumption and may normally differ by up to 20% from the actual consumption. Data from February is not included as a full month of data was not available. The total consumption in December 2022 was particularly high at 23.65kWh/day.

This was due to a particularly cold period of weather with the month having 356.2 Degree Days. The total heat pump consumption was lower for household B-04 than for household B-03 for all the months where there was comparable data.

Data was also collected from the Vaillant sensoCOMFORT smart thermostat during visits. Environmental Yield data was used to estimate the Coefficient of Performance for a month. This was estimated to be 3.33 in September 2022.

Month	Heat Pump Space Heating (kWh/day)	Heat Pump Water Heating (kWh/day)	Heat Pump Total Consumption (kWh/day)	Percentage water heating (%)	Space heating consumption per Degree Day (kWh/DD)
Mar-22	11.87	2.39	14.26	16.7%	1.44
Apr-22	8.67	2.30	10.97	21.0%	1.18
May-22	4.56	1.29	5.85	22.0%	1.18
Jun-22	2.09	1.47	3.56	41.3%	0.85
Jul-22	0.71	1.13	1.84	61.4%	0.75
Aug-22	0.35	1.16	1.52	76.6%	0.69
Sep-22	1.40	1.17	2.57	45.5%	0.57
Oct-22	4.06	1.35	5.42	25.0%	1.34
Nov-22	8.90	0.97	9.87	9.8%	1.34
Dec-22	22.03	1.61	23.65	6.8%	1.92
Total	6.48	1.48	7.96	18.6%	1.38

Table A.32 Electricity consumption of the Vaillant aroTHERM plus heat pump with the Boxergy Hero system for household B-04. Data derived from the Vaillant sensoAPP.

11. Appendix 6 - Household C-01

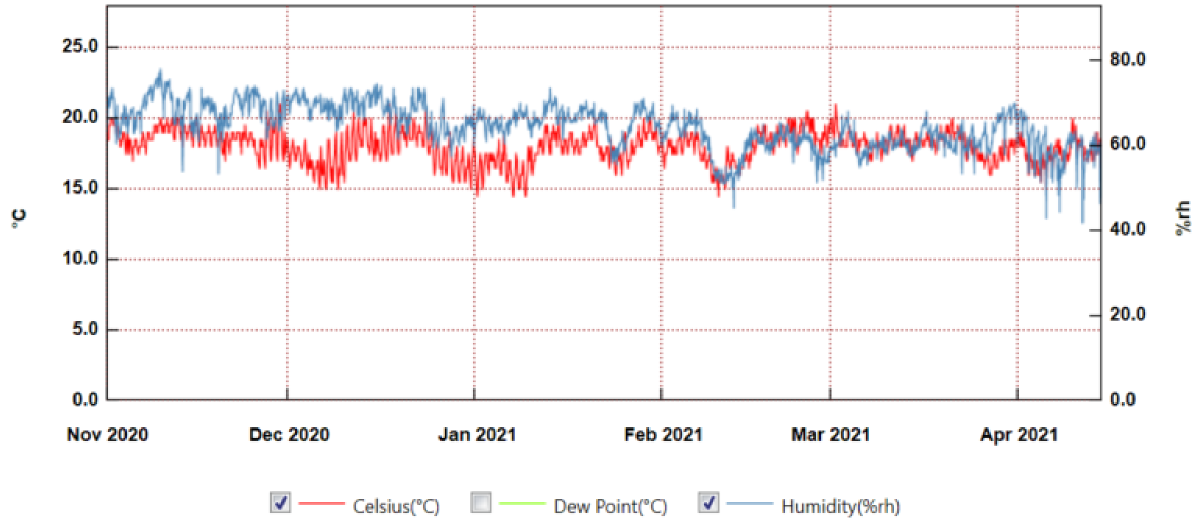


Figure A.33 Graph of bedroom temperature and relative humidity for household C-01 from 1 Nov 20 to 15 Apr 21, using infrared panel heaters

Household C-01 was a control for the project. The residents installed infrared heating panels in the rooms and did not use the storage heaters in the house. Figure A.33 shows the variation in temperature and relative humidity for the bedroom during the first heating season of the project, between 1 Nov 20 and 15 Apr 21. There was greater variation in the bedroom temperature over this analysis period than during the same dates the following year. Some of the broad dips in room temperature are likely to be due to periods of colder weather, such as in early to mid-February 2021.

A plot of the living room temperature and relative humidity for the first heating season is shown in figure A.34. The living room was rarely used and was usually unheated. As a result, the average temperature was considerably lower than for the bedroom.

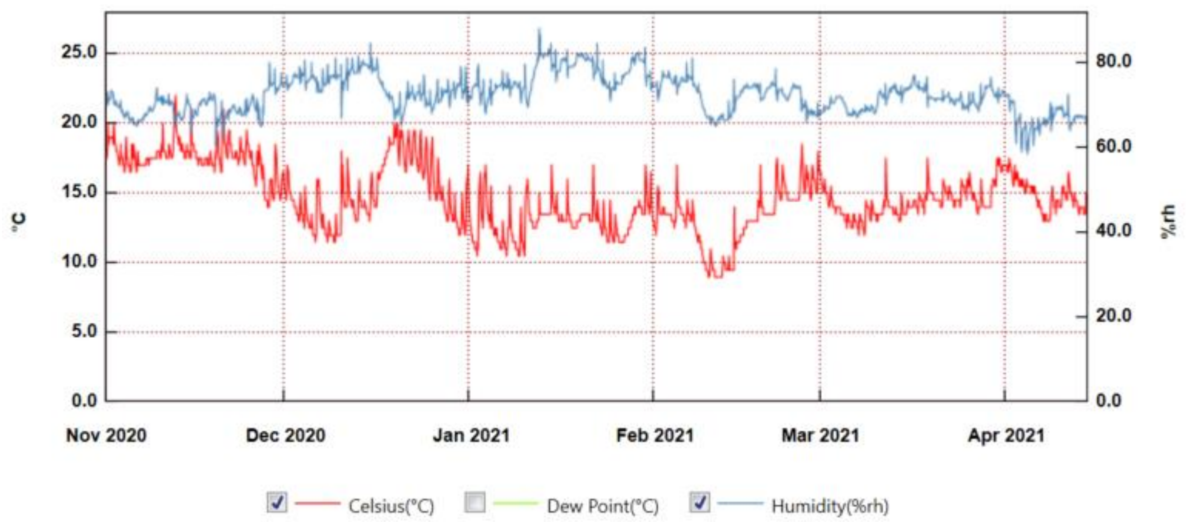


Figure A.34 Graph of living room temperature and relative humidity for household C-01 from 1 Nov 20 to 15 Apr 21, using infrared panel heaters

The living room temperature was colder during the first heating season, with an average temperature of 14.67˚C compared to 15.99˚C the following year. The temperature dropped to 9.0˚C on 10 Feb 21 at 04:00 during a period of particularly cold weather.

There were short periods with higher temperatures in the living room and these were likely to have occurred during a brief period when the living room was used and the heating turned on. For example, at 19:00 on 11 Feb 21, the living room temperature was 14.0˚C. From this time, the temperature rose, reaching a peak of 17.5˚C at 21:30 and fell back to 14.0˚C by 09:00 on 12 Feb 21 and remaining at that temperature for the rest of that day.

12. Appendix 7 - Household C-02

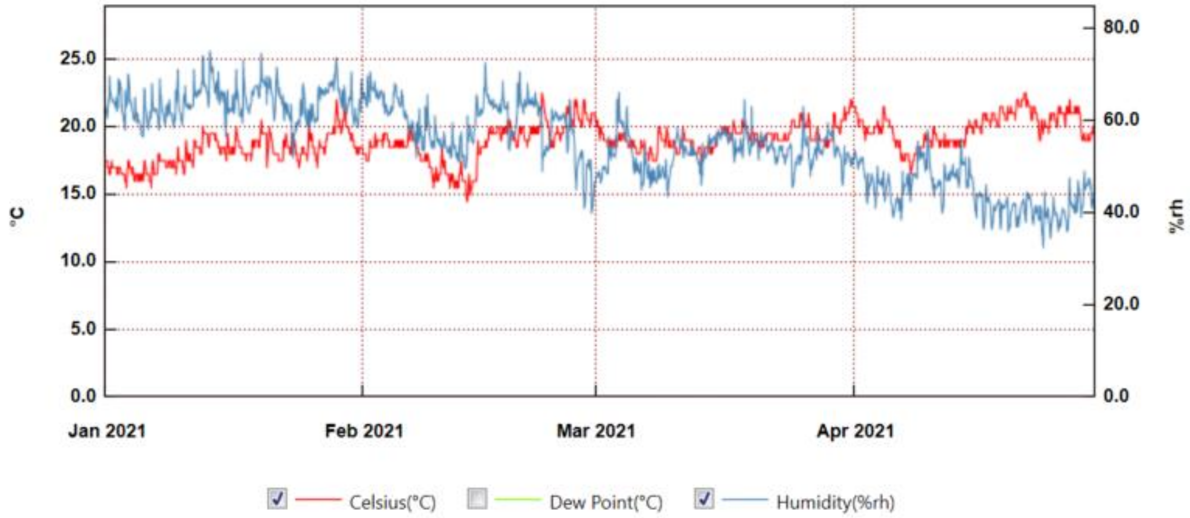


Figure A.35 Graph of bedroom temperature and relative humidity for household C-02 from 1 Jan 21 to 30 Apr 21, using traditional storage heaters

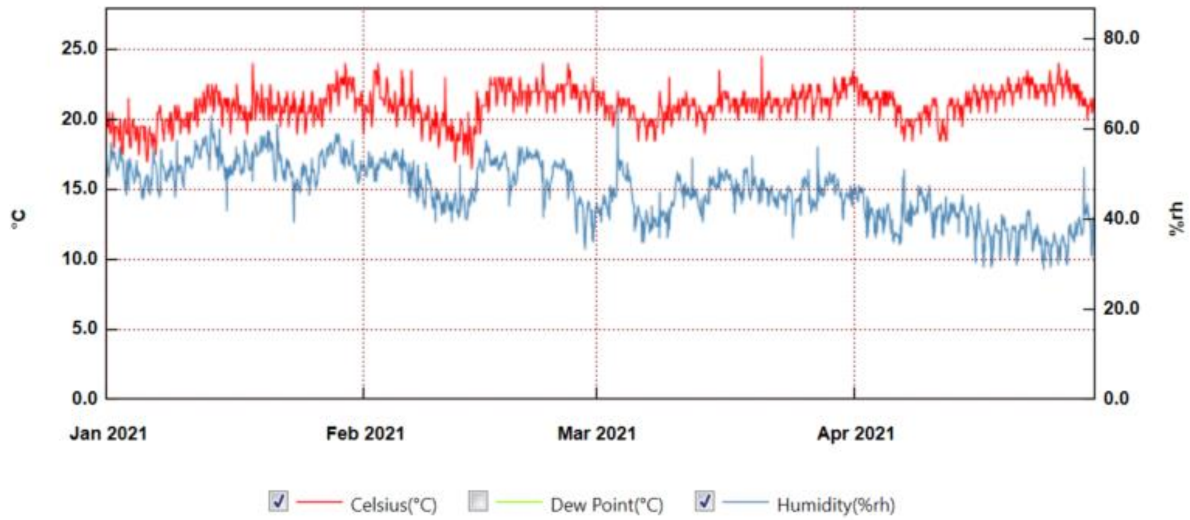


Figure A.36 Graph of living room temperature and relative humidity for household C-02 from 1 Jan 21 to 30 Apr 21, using traditional heaters

13. Appendix 8 - Household C-03

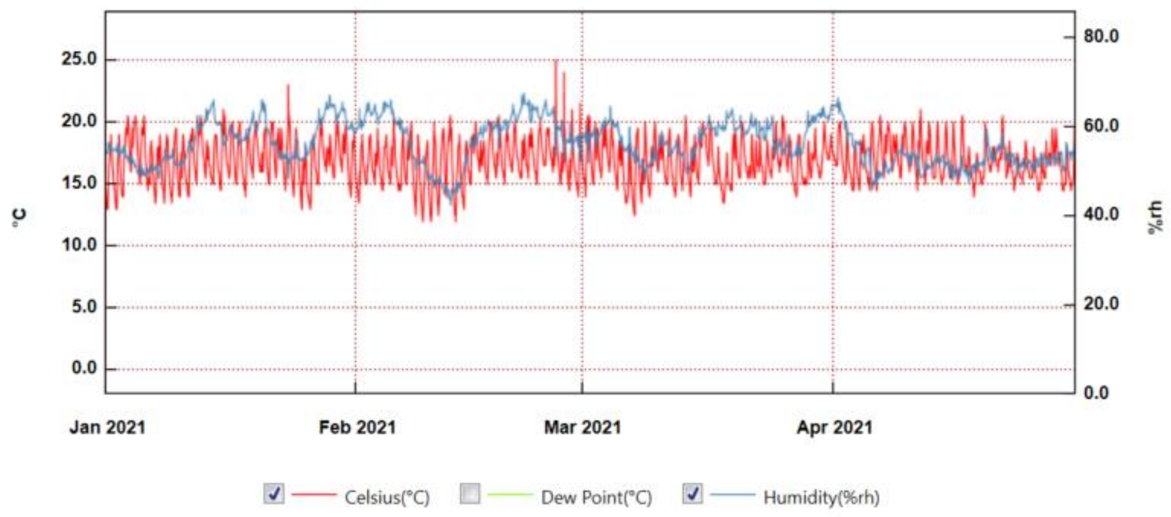


Figure A.38 Graph of bedroom temperature and relative humidity for household C-03 from 1 Jan 21 to 30 Apr 21, using a Daikin Altherma low temperature ASHP

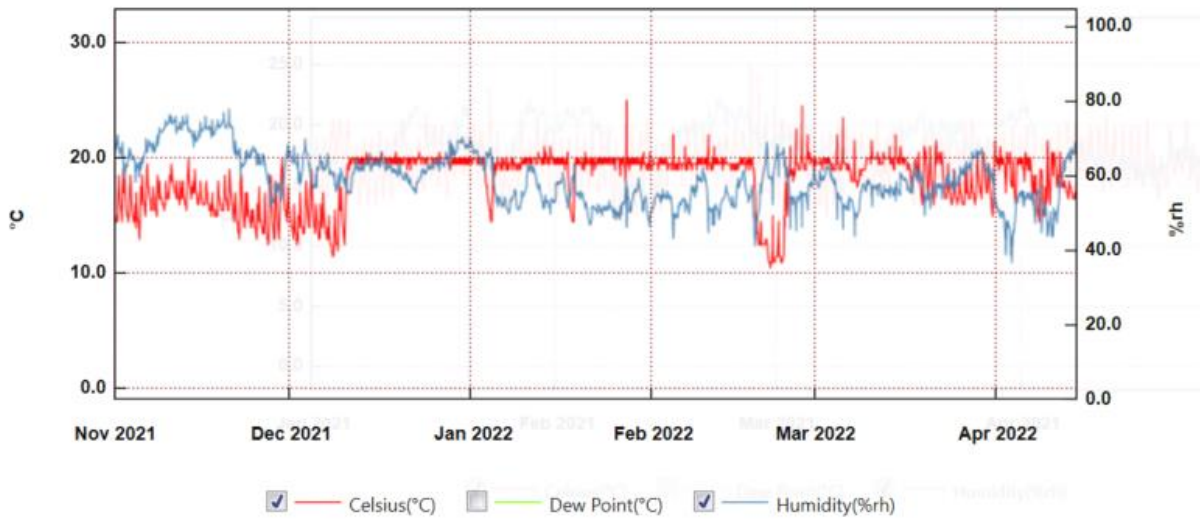


Figure A.39 Graph of bedroom temperature and relative humidity for household C-03 from 1 Nov 21 to 15 Apr 22, using a Daikin Altherma low temperature ASHP

Figures A.38 and A.39 show the bedroom temperature and relative humidity for household C-03 during the year 1 and year 2 monitoring periods. The temperature and humidity profiles of the graphs were similar to those for the living room for household C-03 during the same monitoring periods.

14. Appendix 9 - Household C-04

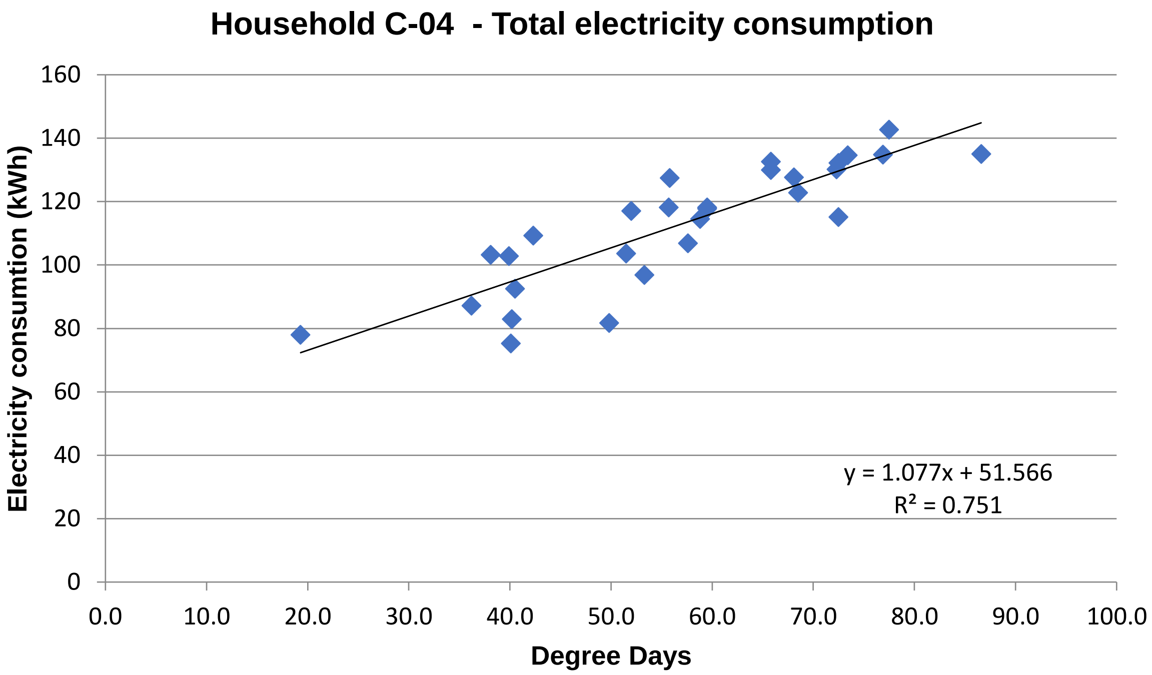


Figure A.40 Graph showing the variation in weekly total electricity consumption with Degree Days, from 13 Oct 21 to 4 May 22, with Daikin Altherma low temperature ASHP

Figure A.40 is a plot of weekly electricity consumption (from smart meter data) against Degree Days. This illustrates how the household electricity consumption is affected by external temperature. There is a general increase in electricity consumption as the number of Degree Days increases (with the external temperature becoming colder). There was limited scatter around the trend-line which suggests that the heating system was well controlled, maintaining a consistent temperature within the home. There will be some more general variation in consumption due to differences in appliance use on particular days.