TECHNICAL INNOVATION FUND

CP1139
Tesla Powerwall 2 batteries charged using off peak electricity
North Devon Homes

Technical Evaluation Report

Paul Rogers and Michael Hamer

April 2018

Background

About National Energy Action

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.

About the Technical Innovation Fund

NEA believes that there is huge potential for new technologies to provide solutions for some of the 4 million UK households currently living in fuel poverty, particularly those residing in properties which have traditionally been considered too difficult or expensive to improve through mandated fuel poverty and energy efficiency schemes. However, more robust monitoring and evaluation is needed to understand the application of these technologies and assess their suitability for inclusion in future schemes.

The Technical Innovation Fund (TIF) which was designed and administered by NEA, formed part of the larger £26.2m Health and Innovation Programme along with the Warm Zone Fund and Warm and Healthy Homes Fund.

TIF facilitated a number of trials to identify the suitability of a range of technologies in different household and property types and had two strands: a large measures programme to fund contributing towards the installation and evaluation of technologies up to a maximum £7,400 per household, and a smaller measures programme contributing up to the value of £1,000 per household. The fund launched in May 2015, with expressions of interest sought from local authorities, housing associations, community organisations and charities wishing to deliver projects in England and Wales.

Over 200 initial expressions of interest were received and NEA invited 75 organisations to submit full proposals. Applications were assessed by a Technical Oversight Group, chaired by Chris Underwood, Professor of Energy Modelling in the Mechanical and Construction Engineering Department at Northumbria University who is also a trustee of NEA. In total, 44 projects were awarded funding to trial 19 different types of technologies and around 70 products (although this number reduced slightly as some products proved not to be suitable and were withdrawn).

More than 2,100 households have received an intervention under this programme. Of course the amount of benefit varies depending on the household make up and the measures installed. In a small number of instances we removed the measures and took remedial action to ensure residents were not detrimentally affected.

Technical monitoring and evaluation

NEA has been working with grant recipients to monitor the application of these technologies and assess performance, as well as understand householder experiences and impacts.

A sample of households from each TIF project was selected for monitoring and evaluation purposes. Participation was entirely voluntary and householders were free to withdraw at any time. This involved the installation of various monitoring devices within the home which collected data for analysis by NEA's technical team. Some residents were also asked to take regular meter readings. In some instances, a control group of properties that had not received interventions under TIF were also recruited and monitored for comparison purposes.

The technical product evaluation was conducted alongside a social impact evaluation to inform our understanding of actual energy behaviour changes, perceived comfort levels and energy bill savings, as well as any other reported benefits. Householders were asked to complete a questionnaire both before and after the installation of the measures which captured resident demographic data including any health conditions. Small incentives in the form of shopping vouchers were offered to maintain engagement over the course of the evaluation period.

The HIP fund was principally designed to fund capital measures to be installed into fuel poor households. A small proportion of the funding enabled NEA to conduct limited research and monitoring of products installed, and was restricted to ensure that the majority of funds were spent on the products. All products included in the trials were deemed to offer costs savings and energy efficient solutions as proposed by the delivery partners. The research and monitoring aimed to provide insights to inform future programme design and interested parties of the applicability of the product to a fuel poor household. We recognise that due to the limited number of households involved in the monitoring exercises and the limited period we were able to monitor a product's performance, we may recommend that further research is needed to better understand the application of these products in a wider range of circumstances over a longer period of time.

The research was conducted according to NEA's ethics policy, which adopts best practice as recommended by the Social Research Association (SRA) Ethical Guidelines 2002.

An accompanying programme of training and outreach work was also delivered to 292 frontline workers to increase local skills and capacity.

Individual project reports are being compiled and will be made available publicly on NEA's website from September 2017, along with a full Technical Innovation Fund Impact Report.

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Executive summary

Project overview

The project was led by NEA and North Devon Homes Ltd and had the following aims:

- Install Tesla Powerwall 2 domestic battery systems in 8 socially rented homes in North Devon without solar PV where the batteries charge only from the electricity grid.
- Assess the performance of the 13.5kWh Tesla Powerwall 2 batteries when grid charging
- Assess levels of resident satisfaction with the technology
- Determine the battery performance over about a year and quantify the savings for the residents from the batteries
- Consider any challenges associated with deployment and operation of the technology when charging with time of use tariffs.

Context

There are about 42,074 households in North Devon and the proportion of fuel poor households is estimated to be 11.6%. According to the Non-gas map, 47.1% of properties in North Devon are off the gas grid. North Devon Homes Ltd is the main social landlord in the area and rents 3,221 homes. Out of these, 623 are off the gas grid and likely to be on Economy 7 electricity tariffs. About 7,000 households in North Devon have Economy 7 meters.

North Devon Homes has limited numbers of properties with solar PV, with only 114, primarily on new build properties heated by mains gas. The total number of domestic solar PV installations in North Devon which claim the feed-in tariff was 2,683 at the end of Dec 2018.

Domestic battery storage can be used to store excess electricity generated during the day by a solar PV system for later use in the evening. The majority of domestic batteries on the market have until recently been smaller 2 kWh Lithium-ion batteries.

Many domestic batteries are now able to also charge from the electricity grid. Households on well-known time of use tariffs – such as economy 7, can charge the battery at night when the tariff rate is cheap and supply power during the day when it is more expensive. This is suitable for households without solar PV as well as those with solar panels. For batteries with a higher capacity and greater power output, there is potential for the system to power the household through much of the peak rate period. The savings from a larger battery charged using off peak rate electricity can be greater than those from a small battery charged for free from solar PV. For a household with a high electricity consumption, a Tesla Powerwall 2 battery charging only at night using off peak electricity might save about £1 per day. In the future, when dynamic time of use tariffs become available, savings could be greater when coupled with smart charging and smart appliances.

The technology – *Tesla Powerwall 2 battery storage system*

The Tesla Powerwall 2 battery has a usable capacity of 13.5 kWh and dimensions of 1150 x 755 x 155 mm. It is IP67 rated and so can be fitted outside or inside a property. The battery can output up to 3.68 kW or 5 kW depending on the grid connection available at the site.

The energy management and communications for the battery is provided by the Tesla Gateway. This has dimensions of 240 x 243 x 130 mm and is connected to the household consumer unit and the Tesla Powerwall 2 battery. Although the Gateway can communicate by 3G mobile, it needs to be connected to the household WIFI router. This is usually done using TP Link power line adapters. The Gateway downloads system updates and provides Tesla with monitoring of the performance of the battery. It has a built-in hard drive so data is not lost during periods when the battery system goes offline. A newer version of the Gateway, the Backup Gateway 2 can now offer the additional function of allowing the battery to operate during power cuts.

Monitoring of the household consumption and battery performance is provided by the Tesla App which is available for Apple or Android phones. This provides details of the current state of charge of the battery as well as plotting graphs of the battery charge/discharge and household consumption for that day or the day before. The app can be used to manually set the times for peak rate and off-peak rate electricity periods – defining the grid charging times.

The project

Households were recruited by North Devon Homes Ltd (NDH) and NEA, targeting properties that were off the gas grid and unlikely to be connected in the future, had night storage heaters and were likely to be high electricity users. Households were contacted by letter and/or telephone and provided with information about the battery system and the project. Surveys were carried out at candidate properties to determine whether there were suitable locations for the Tesla battery and Gateway and cable runs between them and the consumer unit. The number and power rating of the night storage heaters was also recorded.

A total of 8 Tesla Powerwall 2 batteries were installed in homes in Witheridge, George Nympton, Kings Nympton and East Buckland between January and June 2018. Most of the batteries were operational from the end of March 2018. A limited number of batteries in the UK received the software update which allowed grid charging at this time. Batteries in this project were the first in the UK to receive this software, and charge only from the grid.

In addition to the 8 households with installations, there were 3 households with night storage heaters which acted as control properties. Monitoring equipment was fitted at sites from December 2017. Data on electricity consumption was obtained from bills, electricity suppliers and household utility meter readings. Interviews were carried out with the households where possible near the time of the installation and in January 2019. These assessed the satisfaction of the households with the Tesla battery and collected information on their patterns of electricity use.

Summary of findings

Resident satisfaction

- All the households interviewed thought the installation was neat and tidy, the battery was fitted in a suitable agreeable location and the installers were careful and respectful in the properties. They all found the battery easy to use.
- Out of the 7 households interviewed, 6 either agreed or strongly agreed that they had seen savings on their electricity payments. A single household disagreed after analysing their bills, which included a unit rate price rise from the supplier. When using standardized tariffs savings were also achieved with this household.

Issues which occurred during the project

- A household switched supplier before the battery was operational. This included switching from an Economy 7 tariff to a single rate tariff. As a result, the battery was not able to charge at a cheaper electricity cost rate and no savings were made. The issue could not be resolved during the duration of the project due to difficulties contacting and communicating with the household. NDH are pursuing this through their resident support mechanisms.
- There were 3 households where there was a large difference between the site import recorded by the battery system and from meter readings. This was because these installations did not record the consumption from the heating electrical circuit as accurately as the main electrical circuit. This problem could have been avoided if the installer had used a Y-splitter cable and they have agreed to resolve the issue. At 3 other sites, the difference between the consumption measured by the battery system and the utility meter was less than 1%.

Most households that received battery installations were high electricity consumers

- The Ofgem Typical Domestic Consumption Value (TDCV) for a high electricity consumer is 7,100 kWh/year for a household with a Profile 2 meter. 7 of the households that received installations had an annual consumption of between 7,402 and 13,952 kWh. The annual costs were between £950 and £1,676. Among these households, 4 contained residents who were at home during the day due to a chronic health condition.
- One household with a battery installation was a medium electricity consumer with an annual consumption of 5,868 kWh and cost of £733. The household consisted of 2 residents who worked full time and were not at home during the day on weekdays.

The battery was typically able to fully power appliances apart from the electric shower

- All 7 of the households interviewed with batteries had electric showers. These were rated at between 8.5 and 9.5 kW. The batteries with a G59 grid connection could supply up to 5 kW of the electricity requirement of the shower, with the rest coming from the grid.
- Other occasions where the battery could not fully power the household load included when there was use of several high consuming appliances, such as a cooker and supplementary heating or a washing machine. Such occasions were rare, particularly in summer.

There was a large drop in peak rate electricity consumption and increase in the percentage of off-peak use after the Tesla Powerwall 2 was operational

- For a high consuming household, the average peak rate consumption fell from 18.3 kWh/day to 4.8 kWh/day. The average percentage off peak consumption increased from 43.7% to 80.5%.
- The medium consuming household had an average peak rate consumption between 7.8 and 12.2 kWh/day before installation and in the range 0.5 to 1.2 kWh/day after. The percentage off peak consumption increased from 50.1% over the previous 2 years to between 91.1 and 96.9% between July 2018 and January 2019.
- A household with a smart meter had a monthly average peak rate consumption of between 9.4 and 11.2 kWh/day before the installation and an average monthly off-peak consumption in the range 36.4 to 79.4%
- After the battery was operational in March 2018, the average peak rate consumption dropped to between 0.84 and 4.65 kWh/day with the average percentage off-peak consumption between 84.3% and 96.4%. In April 2018, there were 18 days where the percentage off peak consumption was 99% or more.

The average battery discharge was high throughout the year for all but 1 household

- For the 7 high consuming households, the average monthly battery discharge was in the range 8.3 to 13.0 kWh/day over the monitoring period.
- For the medium consuming household, the average battery discharge was 2.86 kWh/day in June 2018 and increased to 9.47 kWh/day in January 2019 due to supplementary heating use.

Households saved an average of up to £1.21/day over the evaluation period

- For the high consuming households with batteries operational between April 2018 and January 2019, the total savings for households were between £323 and £368 **over the analysis period**. This equated to **average annual savings of up to £1.21/day or £440**.
- The medium consuming household had average monthly savings of £0.23 to £0.96/day over the analysis period of June 2018 to January 2019. The average saving over the full year was £0.54/day or £198/year
- These saving were much higher than in another study looking at smaller 2 kWh Maslow and PowerFlow Sundial batteries which charged only from solar PV. In that study, the annual savings were in the range £23 to £67/year

There was an increase in grid import due to inefficiencies in the battery

- There was an increase in household electricity consumption due to inefficiencies in the inverter and consumption by the battery system.
- For the households with batteries running from April 2018 until the end of January 2019, the extra site import due to the battery operation was between 437 kWh and 553 kWh.
- Savings due to charging at off peak rate and discharging at peak rate more than compensated for this increased consumption. However, for the household which switched from Economy 7, losses in the battery led to extra costs.

Conclusions and recommendations

- This project showed that substantial savings were achieved by installing Tesla Powerwall 2 batteries in homes without solar PV with the batteries charging only from the grid using an Economy 7 tariff.
- For a high electricity consumer, average savings were up to £1.21/day while a medium electricity consumer saved an average of £0.54/day. These savings are higher than for smaller batteries time shifting solar PV.
- Greater savings would be possible with the Tesla Powerwall 2 installations if they were at sites with pre-existing solar PV systems.
- The payback time of about 15 years for high consuming households is within the expected lifespan of the battery. A payback of over 30 years for the medium electricity consumer is difficult to justify on savings from tariff arbitrage alone.
- For medium and low electricity consumers, there is spare capacity available with a Tesla Powerwall 2 battery. This could be used to provide grid services once this is possible with the Tesla system. Income from grid services could improve the business case for installations at sites with lower electricity consumption.
- Other benefits are also available with the Tesla Powerwall 2 battery beyond electricity savings. The new Backup Gateway 2 will operate during power cuts, but costs an additional £1000 compared to the version tested in this project.
- The Tesla app can monitor household consumption and solar PV performance (if present). Use of the app can encourage savings through behaviour change and assist in detecting when faults in a solar PV system occur, which would lead to loss of income and increased electricity costs.
- Those developing a project with significant numbers of battery installations should allow sufficient time for the pre-installation phase. It may take 3 – 6 months for household recruitment and surveys before installations take place. Careful selection of the most appropriate households for installations is important. This will save time and money in the long run through reduced problems with installations and residents.
- It is important to check that the household selected has an internet connection and that the residents are willing for the battery to plug into their WIFI router.
- If a battery will be charging on Economy 7 (or another time of use tariff) where other high consuming appliances like night storage heaters will be running, it is important to check the household consumption will not exceed the supply limit for the property after adding the battery charging overnight.
- The Tesla Powerwall 2 is now able to reduce the charging rate for the battery if the household load approaches the supply limit. For this to occur the battery must accurately measure both the main electrical circuit and heating electrical circuit. If necessary, the installer should use a Y-splitter cable so current clamps can measure both electrical circuits.
- In rented accommodation there is a risk that the resident does not understand how the savings are achieved from grid charging. Good engagement is necessary with households provided with clear documentation on how the system works at the recruitment stage and installation. A handover pack with information about the system and its operation should be provided if a new resident moves in. Labels should be left on the battery and by the electricity meter. It is important to avoid the resident mistakenly switching from a time of use tariff to a single rate tariff.

1. Project overview

1.1 Introduction

Domestic battery storage can be used to store excess electricity generated during the day by a solar PV system for later use in the evening. The majority of domestic batteries on the market until recently were smaller 2 kWh Lithium-ion batteries. An earlier NEA trial looked at solar time shifting with 3 brands of batteries[1]. A 2kWh Maslow battery with a usable capacity of 1.6kWh discharged an average of 1.44kWh/day in July, but only 0.23kWh/day in January.

Most brands of batteries can now also charge off the grid and so batteries can provide savings to homes on time of use tariffs such as Economy 7. This would include homes without solar PV as well as those with a PV installation. The battery would charge during the cheaper night rate and supply electricity to the household during the more expensive day rate. For a home with solar PV, grid charging could be greater in winter and reduced or not used in summer[2]. For a home without a PV system the battery could be fully charged each day from the grid throughout the year if there is sufficient demand to discharge the battery during the peak rate period.

There are losses in the battery inverter and consumption by the battery management system. As a result, the round-trip efficiency for the battery charge/discharge cycle may be 90% or less. These losses become more important in applications where the battery is not operating with a solar PV system and all the power to charge the battery must be purchased from the grid. Despite these losses, the savings from a large battery charging from the grid are likely to be higher than for a small battery charging for free off solar PV.

The Tesla Powerwall 2 battery has a usable capacity of 13.5kWh and a maximum output of 5kW. This is a significantly higher specification than many batteries on the UK market. Although more expensive than other systems, the Tesla battery typically has a lower cost per kWh of storage. Savings for higher consuming households with a Tesla Powerwall 2 battery only grid charging from the grid could be about £1 per day.

1.2 Aims

The project was led by NEA and North Devon Homes Ltd and had the following aims;

- Install Tesla Powerwall 2 domestic battery systems in 8 socially rented homes in North Devon without solar PV where the batteries charge only from the electricity grid.
- Assess the performance of the 13.5kWh Tesla Powerwall 2 batteries when grid charging
- Assess levels of resident satisfaction with the technology
- Determine the battery performance over about a year and quantify the savings for the residents from the batteries
- Consider any challenges associated with deployment and operation of the technology when charging with time of use tariffs.

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[1] Paul Rogers & Michael Hamer, SunGain Battery Bank, Thurrock, (January 2019) http://www.nea.org.uk/wp-content/uploads/2019/01/CP775-TIF-REPORT-FINAL.pdf (Accessed 21 Jan 19)

[2] Battery Management, https://www.powerflowenergy.com/battery-storage/powerflow-portal/ (Accessed 21 Jan 19)

1.3 Context

There are about 42,074 households in North Devon and the proportion of fuel poor households is estimated to be 11.6%[3]. According to the Non-gas map, 47.1% of properties in North Devon are off the gas grid[4]. An Ofgem Insights paper on households with electric and other non-gas heating from 2015 noted that there were 1.6 million households in Great Britain using storage heaters[5].

North Devon Homes Ltd (NDH) is the main social landlord in North Devon and rents 3,221 homes at the time of writing. Out of these, 623 are off the gas grid and likely to be on Economy 7 electricity tariffs. A total of about 7,000 households in North Devon have Economy 7 meters[6].

NDH has limited numbers of properties with solar PV, with only 114, primarily on new build properties in Barnstaple heated by mains gas. In 2011, they surveyed their properties and planned an extensive programme of PV installation. However, large cuts were announced to the feed-in tariff during the development of this project and the installation programme did not go ahead as it was no longer considered financially viable. The total number of domestic solar PV installations in North Devon which claim the feed-in tariff was 2,683 at the end of December 2018.[7]

The feed-in tariff is scheduled to end for new installations at the end of March 2019. At present there is no financial incentive for to encourage installation of battery storage. Unlike solar PV, there is also currently no improvement in the SAP rating for Energy Performance Certificates (EPCs) following installation of battery storage.

1.4 Project timeline

This was the last of the Technical Innovation Fund (TIF) projects and the proposal was developed with North Devon Homes Ltd (NDH) following experience on projects with smaller batteries installed on homes with solar PV. The project was run in conjunction with NDH who had suitable off gas grid properties. No other TIF project had taken place in south west England.

The contract was signed in September 2017. Exeter based SunGift Energy was selected as the contractor in Autumn 2017[8]. They are an award-winning installer of solar PV and an experienced installer of Tesla Powerwall batteries.

Initial surveys were carried out from the beginning of December. These included staff from SunGift Energy and NEA. There was also consultation on some surveys with staff from NDH and their electrical contractor, James Electrics.

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[3] Sub-regional fuel poverty data 2018, Department of Business, Energy and Industrial Strategy (BEIS), https://www.gov.uk/government/statistics/sub-regional-fuel-poverty-data-2018 (Accessed 17 Jan 2019)

[4] The non-gas map, https://www.nongasmap.org.uk/ (Accessed 17 Jan 2019)

[5] Insights paper on households with electric and other non-gas heating (Ofgem, 2015) https://www.ofgem.gov.uk/ofgem-publications/98027/insightspaperonhouseholdswithelectricandothernon-gasheatingpdf (Accessed 21 Jan 19)

[6] Sub-national Electricity Consumption Statistics 2017, https://www.gov.uk/government/statistical-data-sets/regional-and-local-authority-electricity-consumption-statistics (Accessed 11 Feb 19)

[7] Sub-regional Feed-in Tariff Statistics, 20 Feb 2018, https://www.gov.uk/government/statistical-data-sets/sub-regional-feed-in-tariffs-confirmed-on-the-cfr-statistics (Accessed 22 Feb 2019)

[8] SunGift Energy https://www.sungiftsolar.co.uk/ (Accessed 17 Jan 2019)

The first batch of Tesla Powerwall 2 batteries were installed between mid-January and mid-February 2018. The last 2 batteries were installed in March and June 2018. When the project was initiated, the software was not available to allow Tesla Powerwall 2 batteries to charge off the grid. There were delays in the release of this software, but the batteries which had been installed were able to charge from the grid from late March 2018.

Monitoring equipment was fitted during either the survey, initial interview or the installation. It was possible to complete initial interviews with 6 of the households who had batteries. The monitoring equipment was collected, and the final interviews completed in January 2019. There were final interviews with 7 of the households who received batteries and the 3 control properties.

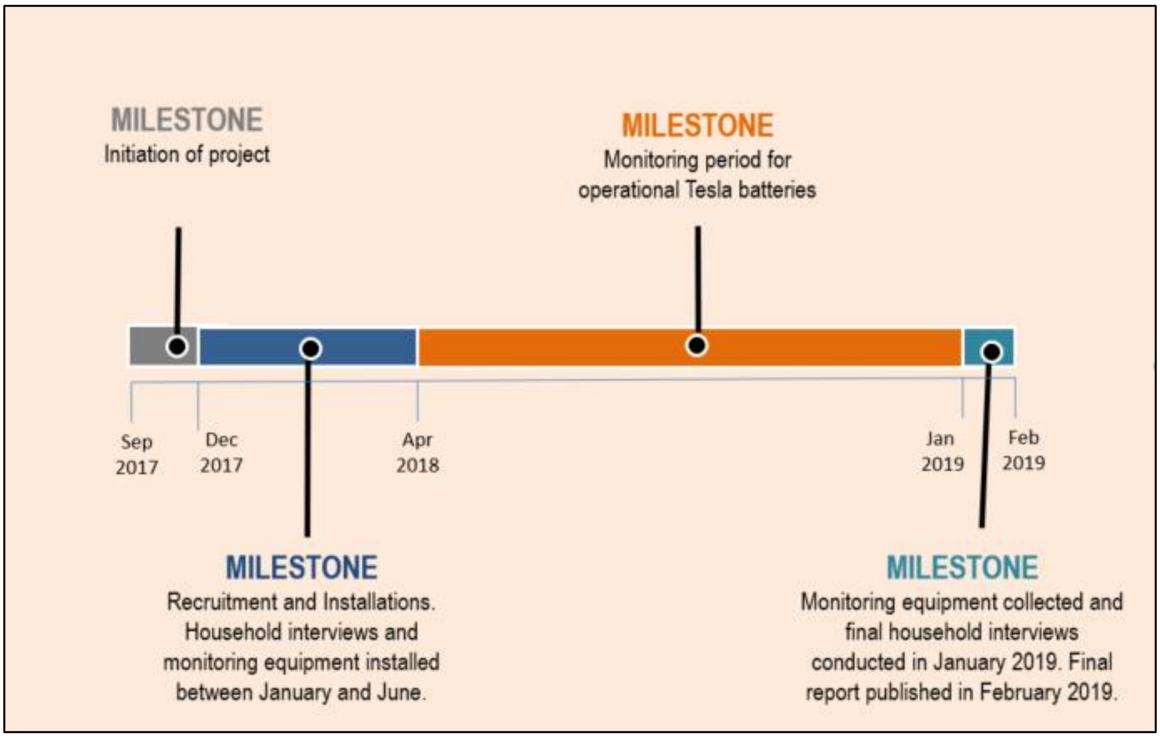


Figure 1.1 Project timeline

1.5 Attracting beneficiaries and establishing a monitored group

- NDH Ltd provided NEA with a list of their larger properties with electric storage heaters, which were unlikely to get a gas connection in future.
- A shortlist of properties was drawn up and these households were invited to have a Tesla battery. The criteria for selection included higher occupancy and/or at home during the day leading to higher electricity consumption.
- There were a number of suitable properties in Witheridge. As a result, this was the initial focus for recruitment and the first surveys.
- An information leaflet promoting the project is shown in Appendix 1 and this was sent out along with an introductory letter by North Devon Homes Ltd.
- A tenant liaison officer for NDH and a staff member from NEA phoned residents on the shortlist to see if they were willing to have a survey for the installation of a Tesla battery.
- Given that there were only 8 Tesla batteries to be installed, all of these were to be part of the monitored group.

- In some cases, households decided against having a battery. Reasons included them not wanting the battery in the only suitable location or an intrusive cable run between the battery and the consumer unit.
- It was not possible to fit the battery internally at 1 household. The only alternative location was on an external wall, narrowing a path and reducing access to the back door.
- Another site had 6 storage heaters and there were concerns the overnight consumption might at times be too high for the supply.
- Both these households became control properties for the study instead of having batteries.
- All monitored and control properties were provided with £50 in shopping vouchers during the final interview as an incentive for taking part in the study.
- There were difficulties finding a property that was suitable for the last battery installation based on the original criteria. A household with lower electricity consumption was invited to have the last battery and this was fitted in June. Here there were only 2 residents who both worked.

1.6 Factors affecting the planned evaluation methodology

Issue	Description and mitigation
Delayed project start	The contract for the project between NEA and NDH Ltd was signed in September 2017, but the majority of the batteries did not begin charging off the grid until late March 2018. This was primarily due to a delay in the release of the software update which enabled the Powerwall 2 battery to charge off the grid. Batteries in this project were the first Tesla Powerwall 2 batteries in the UK to use grid charging without solar
External installations	It was not possible to install batteries internally at 2 sites in Bishops Nympton. Since the external walls at these properties were highly visible, the option of fitting a wooden cover over the battery was considered. This would have hidden the battery, reducing the risk of theft or vandalism. However, any cover was considered to unacceptably reduce access to the properties. As a result, batteries were not fitted at these sites, but the households agreed to be control properties in the study. There was 1 household which had an external battery installation, but the site was less visible.
Delayed last installation	The household that originally agreed to have the last battery installation pulled out at the last minute. A further site was deemed unsuitable as there was a possibility that the overnight current might exceed the supply limit if all appliances were operational. In the end a household was recruited which had 2 residents and a lower household electricity consumption than at other sites.
Switch from Economy 7	During the project a household switched electricity supplier and also from Economy 7 to a single rate tariff. This may have been due to dissatisfaction with the running cost of the night storage heaters. NEA staff discovered this issue when contacting the new supplier. It was not possible to discuss with the resident the issue that the battery was no longer providing any benefit. This was despite numerous attempts at contact by phone, email, text and letter. It was not possible to complete a final interview as the resident was unavailable due to a health condition. In the study, for assessment purposes, the household was considered to be on an Economy 7 tariff throughout, with day rate 18p/kWh and night rate 7p/kWh.
Verv data loggers	As part of the monitoring regime, Verv data loggers were used to measure the charge/discharge of the battery every second. The loggers produced large volumes of data and there were challenges easily analysing the amount of data produced. 2 of the loggers did not upload data to the online portal that was set up. These had to be returned to the manufacturer to access the data. A fuse had blown in both these loggers and the extracted data had been corrupted.

2. Social evaluation and impacts

2.1 Details of properties

Location of the installations

Figure 2.1 Map showing the location of Tesla Powerwall 2 installation and controls in North Devon

Location	Total installations	Monitored group	Control properties
Witheridge	3	3	
George Nympton	2	2	
Kings Nympton	2	2	
East Buckland	1	1	
Bishops Nympton			2
Georgham			1
Total	**8**	**8**	**3**

Table 2.2 Locations of the Tesla battery installations and controls in North Devon

There was a total of 8 x Tesla Powerwall 2 battery installations in North Devon Homes properties. The locations are shown in figure 2.1 and table 2.2. There were 3 batteries installed in Witheridge, 2 in George Nympton, 2 in Kings Nympton and 1 in East Buckland.

It was not possible to install Tesla Powerwall 2 batteries at 2 sites in Bishops Nympton. These households were however willing to take part in the study as control properties. A further household living in private rented accommodation in Georgeham was also recruited as a control.

Build types and characteristics

Figure 2.3 a/b Examples of building types selected for deployment of Tesla Powerwall 2 batteries

Technical Reference Number	Dwelling Type	Floor area (m^2)	Wall Type	Heating Type	SAP Rating	Date of battery installation	Grid connection (kW)	Date of start of battery operation
T-01	Semi-detached house		Filled cavity	Storage heaters	56	24-Jan-18	5	23-Mar-18
T-03	End-terrace house	83	Filled cavity	Storage heaters	59	01-Feb-18	3.68	23-Mar-18
T-05	End-terrace house	100	Filled cavity	Storage heaters	56	23-Jan-18	3.68	22-Mar-18
T-06	Semi-detached house	90	Filled cavity	Storage heaters	57	16-Feb-18	5	04-Apr-18
T-07	Semi-detached house	88	Filled cavity	Storage heaters	60	12-Mar-18	5	13-Apr-18
T-09	Mid-terrace house		Filled cavity	Storage heaters	60	31-Jan-18	5	23-Mar-18
T-38	Semi-detached house	85	Filled cavity	Storage heaters	59	19-Feb-18	5	23-Mar-18
T-61	Semi-detached house	82	Filled cavity	Storage heaters	55	06-Jun-18	3.68	15-Jun-18
C-04	Semi-detached house	71	Filled cavity	Storage heaters	61			
C-11	Semi-detached house	70	Filled cavity	Storage heaters	62			
C-25	Semi-detached house	106	Filled cavity	Storage heaters	50			
Average		**86.1**			**57.7**			

Table 2.4 Details of properties where a Tesla Powerwall 2 battery was installed and control properties in the study

Figure 2.3 a/b shows examples of the styles of properties selected for the Tesla Powerwall 2 battery installations. All the households in the study were assigned a technical reference number to maintain their anonymity. These were based on the reference number for loggers used at each site. Table 2.4 provides details of the households which received batteries (T-01 to T-61) and the controls properties (C-04, C-11 and C-25). While the privately rented control property C-25 was in SAP band E, all the North Devon Homes properties which received the batteries along with the other 2 controls properties were in SAP band D.

All the properties in the study were in villages which were the off-gas grid and night storage heaters were provided as the primary form of space heating. Most of the storage heaters were older models with mechanical controls. Examples included the Dimplex XL18N[9] and Creda TSR18ACW[10], which had an input of 2.5kW.

Control property C-04 had 2 Dimplex Quantum high heat retention storage heaters along with a further 4 older model storage heaters and a panel heater. Household T-38 had their older

[9] Operating Instructions Dimplex Storage heater XLN manual https://www.dimplex.co.uk/sites/default/files/assets//XLN_XLSN_GDC_Operating_Instructions_Issue_1.pdf (Accessed 24 Jan 2019)
[10] Creda storage heater models, http://www.storageheaters.com/Creda-models.htm (Accessed 24 Jan 2019)

mechanically controlled storage heaters replaced in October 2018 with 2 Dimplex Quantum storage heaters and 3 Creda slimline storage heaters which all had digital controls.

The installer on the project, SunGift Energy made G59 grid applications to Western Power Distribution (WPD) for each of the battery installations. A network assessment was carried out by WPD and 5 of the G59 applications were successful. This allowed the Tesla Powerwall 2 batteries to discharge at up to their maximum rate of 5kW. The other batteries had standard G83 connections where the discharge was limited to 3.68kW.

The first 4 installations were in late January and early February 2018. A further 2 were in mid-February. The installation at household T-07 was delayed until mid-March due to difficulty gaining access to the property for surveys and the installation. The household who originally agreed to have the last battery pulled out on the day the installation had been planned. It was not possible to install a Tesla battery at a further site as WPD had concerns about the number of storage heaters and the potential overnight load. The last battery was finally installed in June 2018 at a property with 2 residents which had a lower electricity demand than the other sites. All the batteries were installed internally in utility rooms apart from household T-06 where the battery was fitted outside.

There were delays in the release of the software update which allowed the Tesla Powerwall 2 batteries to charge off the grid. This meant that it was not possible for most of the battery installations to start operating until late March/early April 2018. The last battery started operating correctly from mid-June 2018.

Details of monitored households

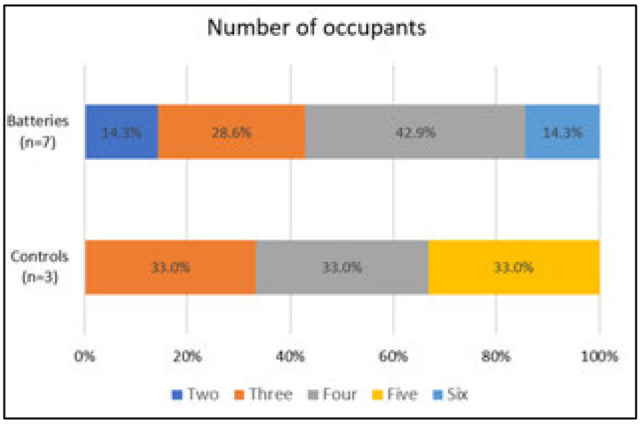


Figure 2.5 Number of occupants per household

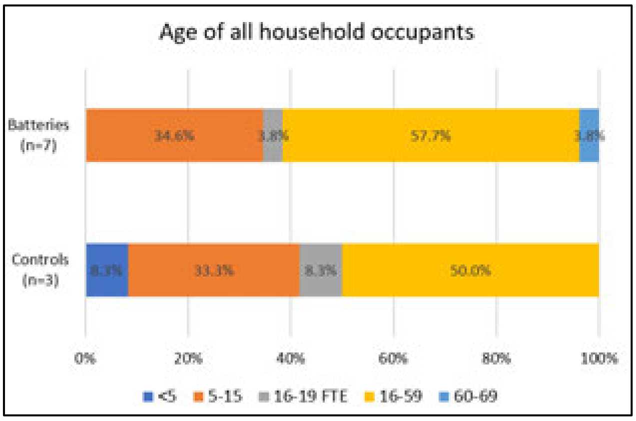
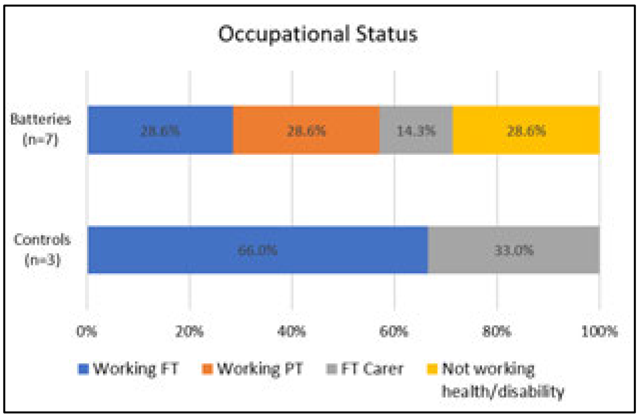


Figure 2.6 Age of all household occupants

Among the households that received batteries, figure 2.5 shows that 3 of the 7 households (42.9%) interviewed had 4 residents and 2 households had 3 members (28.6%). There was a single household that had 2 residents and another which had 6 residents. Out of the control properties, there were single households with 3, 4 and 5 members (33.3%).

There were 26 residents in the 7 households with batteries that were interviewed. Out of these, 15 were in the age bracket 16-59 years (57.7%) and 9 were between 5 and 15 years old (34.6%). There were 12 residents in the control properties and 6 were in the age bracket 16-59 years (50%), while 4 were between 5 and 15 years (33.3%).



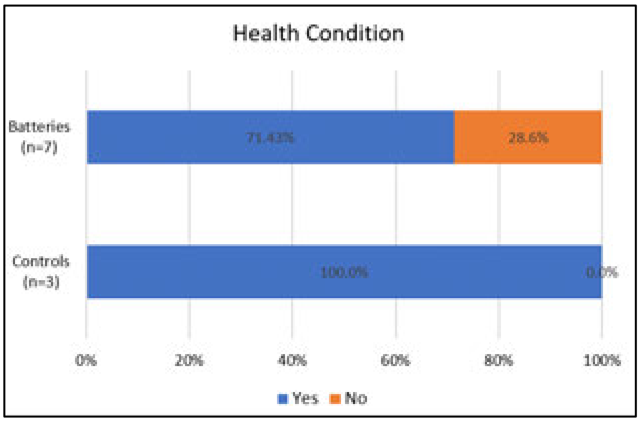


Figure 2.7 Occupational status of interviewee

Figure 2.8 Households where there is a health condition

Among the residents with batteries who were interviewed, there were 2 each (28.6%) who were working full-time, part-time or were not working due to a health condition or disability. For the control properties, 2 of the residents interviewed were working full-time while another was a full-time carer.

Among those with batteries, 5 out of the 7 households interviewed or 71.4%, had a household member with a health condition. All the control properties had a householder with a long-term medical condition or disability. All the households which had members with a medical condition noted that the condition was made worse by cold living conditions.

Among the health conditions noted by the residents in the project were: Adison's disease, angina, arthritis, asthma, diabetes, emphysema, fibromyalgia, heart condition, spinal myopathy and stress.

2.2 Affordability of energy bills

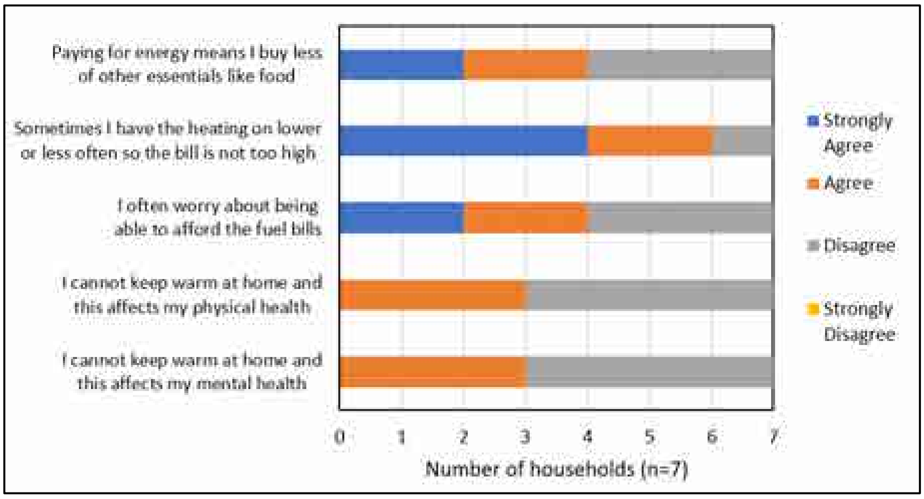


Figure 2.9 Chart illustrating the affordability of electricity bills for the households where batteries were installed

During the final interviews, households in the study were asked a series of questions relating to the affordability of their energy bills. There were 2 households who strongly agreed and a further 2 that agreed that paying for energy meant they bought less of other essentials like food. When asked if they had the heating on lower or less often so the bill was not too high, 4 of the 7 households strongly agreed and a further 2 agreed.

A total of 4 households worried about being able to afford their fuel bills. There were also 3 households who could not keep warm and it affected their physical and mental health.

Among the control properties, all 3 households had the heating on lower and worried about being able to afford the electricity bills. 2 of the control households bought fewer essentials like food as a result of their electricity bills.

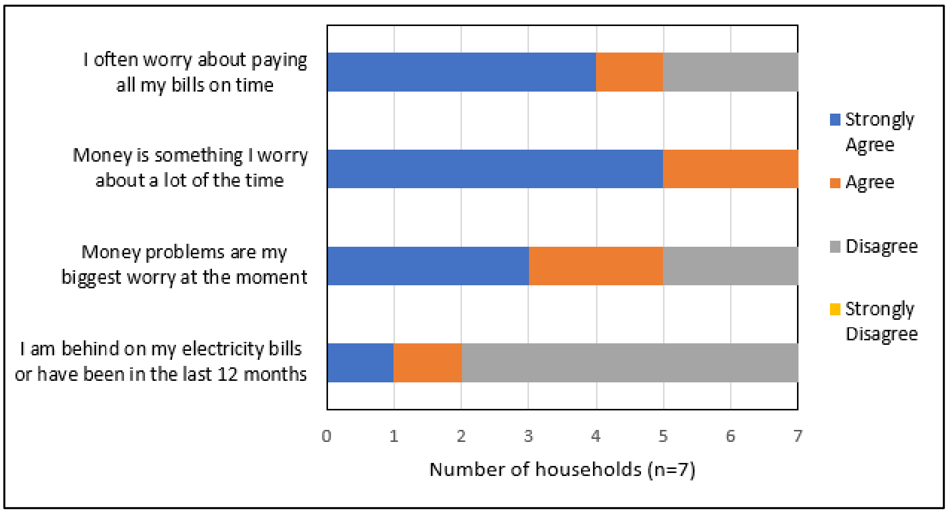


Figure 2.10 Chart illustrating money concerns for the households where batteries were installed

Further questions on household finance during the final interview (figure 2.10) showed that 5 out of the 7 households often worried about paying all their bills on time. All 7 of the households worried about money a lot of the time and for 5 of the households it was their biggest worry. Only 2 of the households noted they had been behind on their electricity bills in the last 12 months and they paid by Direct Debit or Quarterly Bill. Among the other households, 4 used pre-payment meters.

Out of the control households, 1 had been behind on their electricity bill, but this was primarily due to a billing dispute with the supplier. The other 2 households were on pre-payment meters. There were 2 households where concerns over money was their biggest worry. This was not the case with the remaining household where both adults worked full-time.

Heating and Insulation

The households where batteries were installed were off the gas grid and their primary method of heating was electric. Storage heaters were fitted at all the properties along with panel heaters, which were usually in the bedrooms (table 2.11).

Nearly all the households used supplementary heating. 3 of the households used an open fire or multifuel stove in the living room. These were used on weekday evenings and weekends during the winter. As a result, the living room storage heaters at households T-03 and T-05 were never used. The households using open fires or stoves in the living room felt it was necessary to keep the home warm in winter.

Household	Storage Heaters (off peak rate)	Panel Heaters (peak rate)	Supplementary Heating
T-01	3	2 (not used)	3 x oil radiators used 24 hrs per day in winter
T-03	5	1	Open fire in living room (storage heater never used)
T-05	4	2	Multi fuel stove in living room (storage heater never used)
T-06	3	3	Open fire in living room; fan heaters in evening
T-09	3		Occasional use of boost on storage heater or electric fire
T-38	4	1	Heaters replaced in October 18 - 2 x Dimplex Quantum
T-61	3	1	Oil filled radiator daily in winter; fan heater in bathroom

Table 2.11 Summary of methods of space heating in the properties which received Tesla Powerwall 2 batteries

Household T-01 used 3 x oil-filled electric radiators 24 hours a day during winter. Storage heaters were only used in the middle of winter. At the start of the project, household T-38 had older storage and panel heaters. The residents would use an electric room fire and a calor gas heater for supplementary heating in winter. In October 2018, the old heaters were replaced by new models, including 2 Dimplex Quantum high heat retention storage heaters. Since then the household had not used additional supplementary heating.

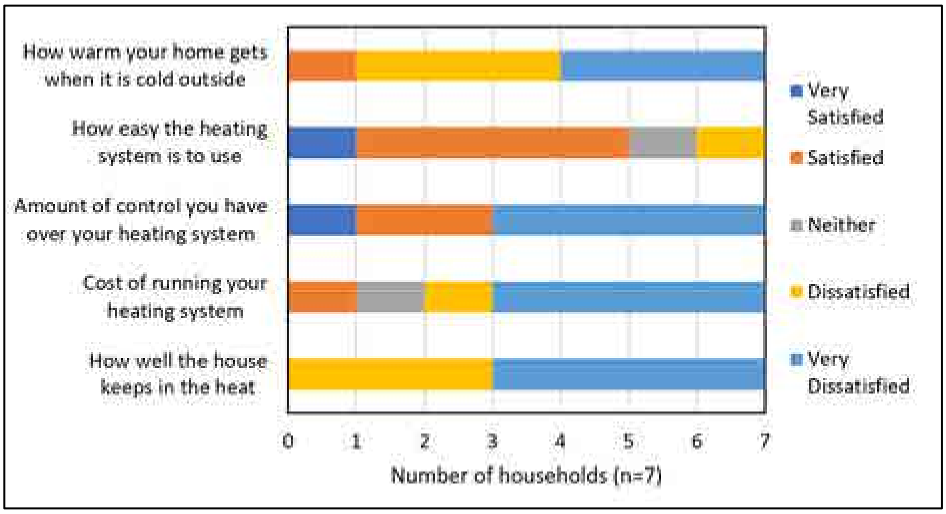


Figure 2.12 Chart illustrating satisfaction with heating and insulation at the time of the final interview

During the final interviews, households were asked about satisfaction with aspects of their heating and insulation. When asked how satisfied they were with the warmth of the home when it was cold outside, 3 households were dissatisfied and a further 3 households were very dissatisfied. The only household that was satisfied was T-38. When asked the same question at the start of the project, prior to the new storage heaters being installed, the resident said they were very dissatisfied.

There were 5 of the 7 households who were either very satisfied or satisfied with how easy the heating system was to use. This reflected the simplicity of the controls and experience using them[11]. Energy advisors have however commented that households often do not understand the controls on traditional storage heaters. Out of the 7 households interviewed, 4 were very

[11] Night storage heaters – a simple guide, https://www.cse.org.uk/downloads/advice-leaflets/energy-advice/insulation-and-heating/advice_leaflet_night_storage_heater.pdf (Accessed 28 Jan 19)

dissatisfied with the amount of control with the heating system. Household T-38 was satisfied with the level of control with their new storage heaters, but had been very dissatisfied with the control provided by the old storage heaters.

There were 4 households who were very dissatisfied with the cost of the heating system and a further household was dissatisfied (figure 2.12). Household T-38 was neither satisfied or dissatisfied at the time of the final interview, but had been very dissatisfied at the start of the project when they had the old storage heaters.

Household T-05 stated they were satisfied with the cost of the heating in the final interview, but noted they were very dissatisfied in the initial interview. For this household the storage heaters had not been upgraded. Since the cost of both heating and appliance use was included in the electricity bill, it is possible that a reduction in bills as a result of the Tesla battery may have also led to greater satisfaction with the cost of the electric heating.

When asked about how well the house kept in the heat, 4 households were very dissatisfied and 3 were dissatisfied. Generally, there were low levels of satisfaction with the electric storage heaters. Older storage heaters are known for poor levels of control and letting out heat in the morning, often when not needed. The level of heat that can be emitted in the evening may be limited at times when residents want to keep warm.

Household T-38 was more satisfied with their heating after new Dimplex Quantum high heat retention and modern Creda storage heaters were installed. Likewise, there was greater satisfaction with control property C-04 which had 2 Dimplex Quantum storage heaters along with several older heaters. In this case they were satisfied with how warm the house got, the ease of use of the heating system and the amount of control. They were however still dissatisfied with the cost of the heating system.

Old storage heaters in North Devon Homes properties will be replaced as part of their long term planned maintenance schedule. Where heaters break down and cannot be repaired, it would make sense to replace them with modern heaters. New heaters would be compliant with the EU Ecodesign directive, which ensures appliances follow certain design criteria to improve their energy efficiency. According to Lot 20 of the Ecodesign directive, solid fuel local space heaters or local space heaters which do not meet the regulations can no longer be manufactured after 1 January 2018[12]. For storage heaters, designs now have to include[13]:

- Electronic heat charge control with room and/or outdoor temperature feedback or controlled by the energy supplier
- Electronic room temperature control plus a week timer
- Fan assisted output

Other optional features include:

- The ability to control the heating remotely such as via a phone app
- Adaptive start control – heating initiates at the optimum time to achieve the set-point temperature at the desired time
- Open window sensing – heater shuts down if it detects a window has been opened

[12] Lot20 – Frequently Asked Questions, https://rointe.co.uk/lot20-questions/ (Accessed 28 Jan 19)
[13] Gaining compliance for storage heaters, http://www.lot20.co.uk/storage-heaters (Accessed 28 Jan 19)

2.3 Resident acceptance and satisfaction

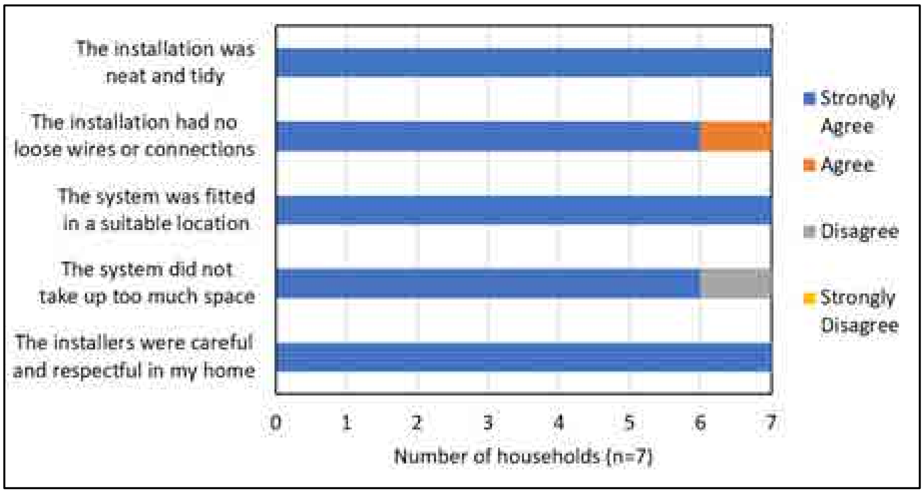


Figure 2.13 Satisfaction with the installation process

Households were asked about their satisfaction with the installation process during the final interviews. Figure 2.13 shows that all 7 of the households interviewed strongly agreed that the installation was neat and tidy and that the installers were careful and respectful in their home. There were 6 households who strongly agreed that there were no loose wires or connections and a further household, T-09 agreed with this statement. In this case, any less positive feelings might have been due to equipment that had been temporarily fitted as part of the NEA monitoring. All wiring for the installation had been fitted in plastic trunking by the installers. Overall these results reflect well on the installer. Household T-06 described them as professional and efficient, while household T-05 said they were very polite and tidy installers.

All the households strongly agreed that the battery was fitted in a suitable location. At 7 of the installations, the battery was fitted in indoors in a utility room, while the remaining battery was fitted on an outside wall. All but 1 household strongly agreed that the battery did not take up too much space. The household who disagreed commented that the battery took up a fair area of a wall and they had to move a cabinet. The battery dimensions are 1150mm x 755mm x 155mm.

Residents were asked their feelings about the installation process and on using the new battery. On a scale of 1 to 5, where 1 was negative and 5 was positive, figure 2.14(a) shows that all 7 households gave ratings of 5 on the installation and about use of the battery.

The households were also asked about the level of involvement that was required from them during the installation process and in using the battery (figure 2.14 b). Here on a scale of 1 to 5, a value of 1 represented being very passive and having to do little, while 5 reflected the resident being very actively involved. The average response from the households was 1.07 for the involvement of the residents using the battery and was 1.29 for their involvement with the installation process.

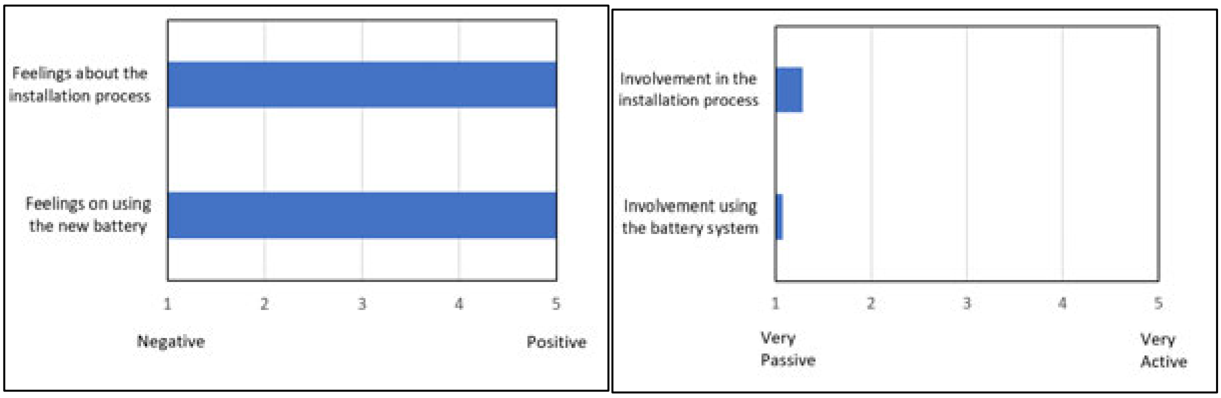


Figure 2.14 a/b Feelings and involvement with the installation process and use of the battery

2.4 Ease of use and reliability

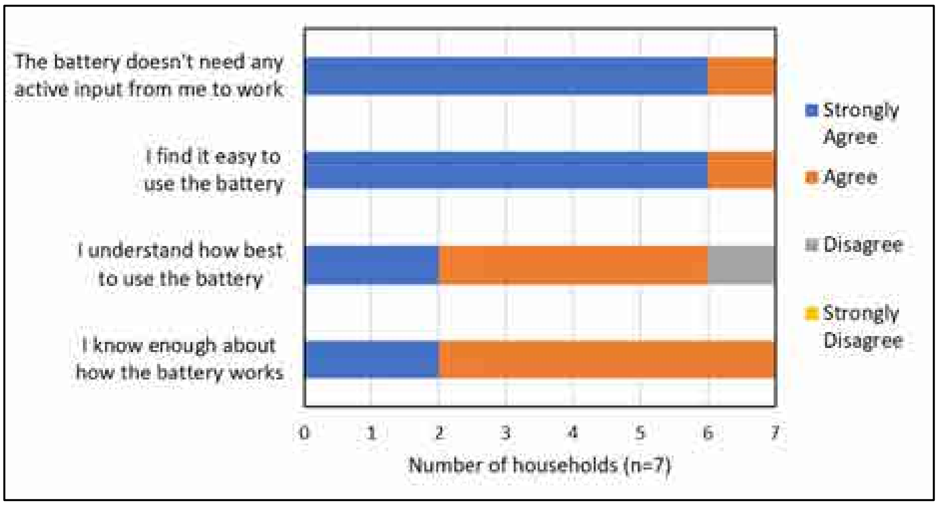


Figure 2.15 Ease of use and understanding of the battery system

Figures 2.15 shows there were 6 households who strongly agreed and a further household that agreed that the battery didn’t need any active input from them to work. The responses were the same when asked if the households found the battery easy to use.

All 7 households that were interviewed felt they knew enough about how the battery worked, with 2 households strongly agreeing with that statement. When asked if they understood how best to use the battery, 1 household disagreed. Most of the households understood that the battery was working in the background charging on cheap rate electricity overnight and supplying electricity to the home during the peak rate period during the day. There was not a detailed understanding of how it all worked however and that was reflected in household T-61 disagreeing that they best understood how to use the battery.

It was not possible to organise initial or final interviews with household T-07. Communication with this household was difficult and the resident missed appointments for surveys and the installation. After the battery was installed, the resident switched electricity supplier and also from an Economy 7 to a single rate tariff. The household was dissatisfied with their storage heaters which they found expensive to run and had stopped using them. As a result, switching away from Economy 7 seemed a logical thing to do for the resident. However, it is clear they did not understand that the battery could only save them money when there was a multi-rate tariff. There have been multiple attempts to engage with and visit this resident to address this problem. NDH are now working with the resident to support them in resolving the situation.

This illustrates the risks of installing a technology in a household where they do not engage with or understand the technology and communication with the household is far from straightforward. Experience suggests that more in-depth advice materials should be produced when recruiting households for installations and for the hand-over pack after the installation. Also, it should have been made even clearer to households that they should not switch from a multi-rate tariff.

While additional advice can help, not all households read advice leaflets and are available for visits during normal working hours. It is recommended that more time should also be allowed to recruit suitable households on further projects. It may also be advisable to screen out households who may be unable to engage with a project or new technology. There are risks when installing new technologies on a street by street basis. Should there be an issue, the household may later request the technology is removed

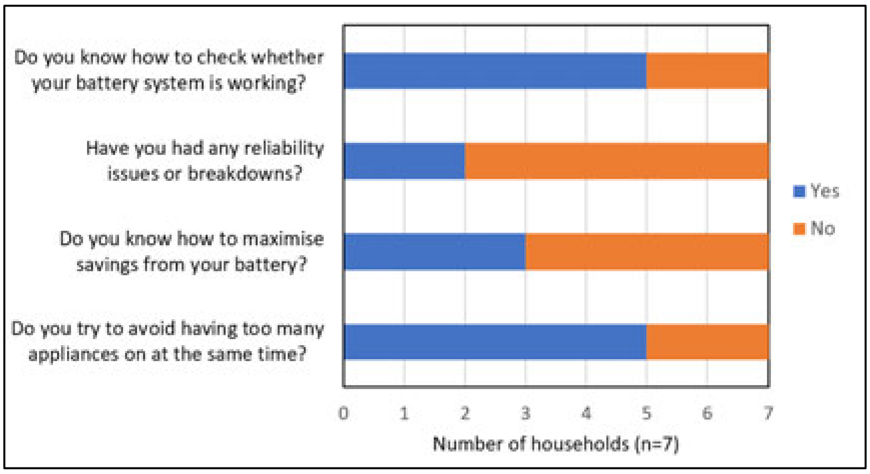


Figure 2.16 Reliability and understanding savings with the Tesla Powerwall system

At the time of the final interview, only 1 of the households had access to the Tesla phone app for their system. Since then, a further 5 of the households have been provided with advice on setting up the Tesla app on their phone. When asked if they knew how to check whether the battery system was working, figure 2.16 shows that 5 of the 7 households interviewed agreed. Without access to the phone app, this was by observing whether the lights were operating on the Tesla battery.

There were 2 households who noted reliability issues with the battery. Household T-09 had reported intermittent noise problems in the form of loud whirring noises every few days in early October 2018. Tesla technical support suggested this was may have been due fan noise from a bubble shedding routine which had been added to the control software a couple months earlier.

The Tesla Powerwall 2 is expected to produce up to 40dB of noise at 1 metre, with a similar noise level to a domestic refrigerator[14].

The final Tesla battery had an initial installation issue. The battery would fully charge overnight during the off-peak period and then fully discharge at maximum power as soon as the electricity switched to peak rate. This was resolved by the installer after a few days.

There were 4 of the 7 households interviewed who felt they did not know how to maximise the savings from the battery. There is a maximum limit to the amount of power the Tesla Powerwall 2 battery can provide which is either 3.68kW or 5kW, depending on the grid connection that was available at the site. If several appliances are running at the same time, only 3.68kW or 5kW of the total power consumption can be provided by the battery. The rest must be provided by electricity imported from the grid at the peak rate pricing. An appliance such as an electric shower may consume 9.5kW of electricity. In this case at least 4.5kW must be provided by the grid. The households were asked if they tried to avoid having too many appliances on at the same time. 5 of the households tried to limit the number of appliances on at the same time.

2.5 Perceived benefits

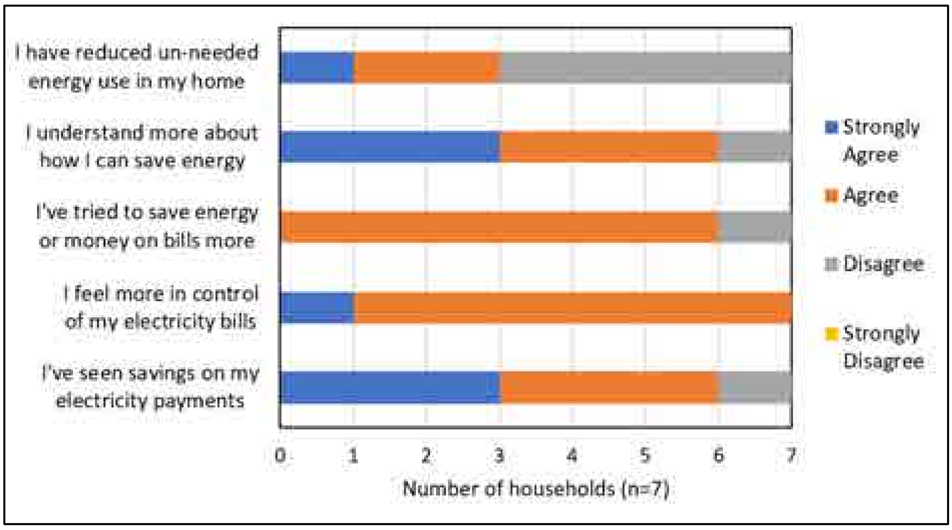


Figure 2.17 Perceived benefits from the project and Tesla battery

Figure 2.17 shows that 4 of the 7 households interviewed had not reduced unnecessary energy use in the home during the project. However, 3 households strongly agreed and a further 3 agreed that they understood more about how they could save energy. 6 of the 7 households tried to save energy or money on bills more.

Following the installation of the Tesla Powerwall 2 battery, 6 households agreed they felt more in control of their energy bills and a further household strongly agreed. There were 3 households who strongly agreed and a further 3 households who agreed that they had seen savings on the electricity payments. There was a single household that disagreed. They had analysed their

[14] Tesla Powerwall 2 datasheet, https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_GB.pdf (Accessed 28 Jan 19)

electricity payments since the battery was installed compared to a similar period the year before. They noted no savings on payments, but this was due to an overall increase in consumption and because their electricity supplier had increased the price per kWh during the last year. With the standardized figures of 18p/kWh for day rate and 7p/kWh for night rate used in the Technical Innovation Fund projects, the post installation period would have seen savings despite the increased consumption.

Further questions in the interview focused on benefits the household had experienced since the battery was fitted. Figure 2.18 shows 6 households said there was a reduction in energy bills, 5 felt they had more control of the electricity use and were saving energy in the home. 2 of the households noted an improvement to the quality of their home with the battery installations and a single household thought they were likely to be reducing their household effect on Climate Change. When questioned again on the impact of the battery on the cost of their bills, 6 households said they were cheaper and the same household mentioned earlier said they were about the same.

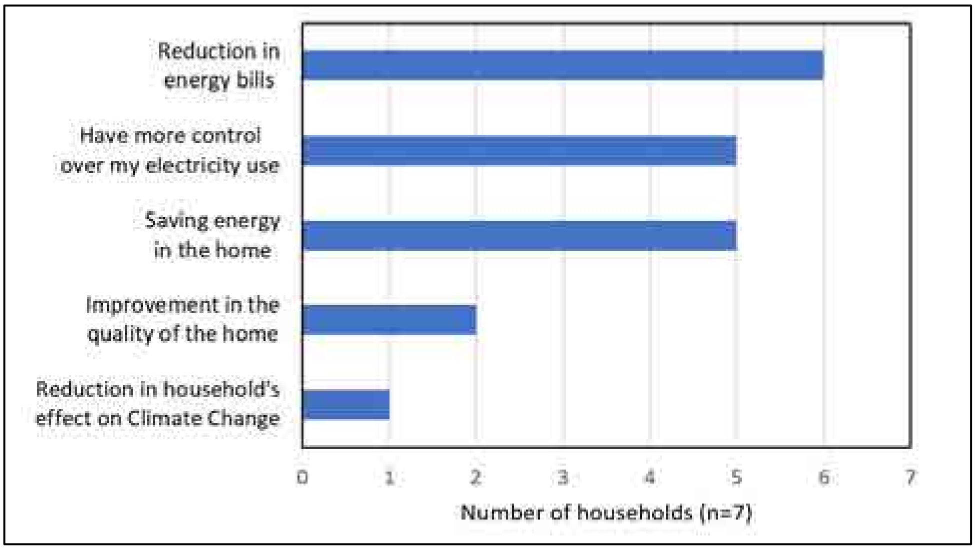


Figure 2.18 Benefits perceived by residents after installation of the Tesla battery system

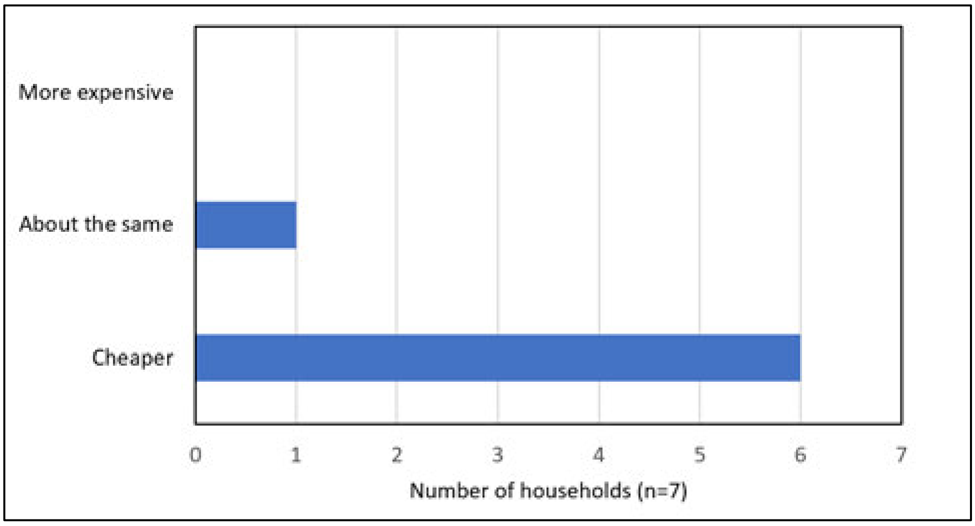


Figure 2.19 Impact of the battery on the cost of bills

3. Technical evaluation and results

3.1 Overview of technology

The lead acid battery was the first rechargeable battery and was invented in 1859 by Gaston Planté[15]. Maintenance free lead-acid batteries such as AGM (Absorbent Glass Mat) and gel batteries were available from the 1970s. The need for better rechargeable batteries for portable devices such as mobile phones accelerated battery development from the 1980s. Lithium is an attractive material for batteries due to its low weight. Due to the instability of metallic Lithium, rechargeable batteries were developed from the 1990s using non-metallic compounds with Lithium ions. There are various compositions of Lithium-ion battery. These include oxides of Lithium with other metals such as Cobalt, Nickel and Manganese as well as Lithium Iron Phosphate[16].

Lithium-ion batteries have a better energy density (Wh per litre) and specific energy (Wh per kg) than lead-acid batteries. All Lithium-ion batteries are 'deep cycle', usually taken to 80% depth of discharge (DoD) and have a longer lifespan than lead acid batteries. Lithium-ion batteries are currently more expensive than lead-acid batteries, but their costs have been falling as the technology develops and production increases.

Growth in the electric vehicle market has led to an increase in battery cell production and enabled batteries to be produced with larger capacities and at lower cost. Tesla built the Gigafactory 1 in Nevada which produces the Tesla Model 3 car, electric motors, car battery packs and the Powerwall and Powerpack energy storage systems[17] [18]. Battery production at Gigafactory 1 reached an annualized rate of about 20GWh by mid-2018, making it the world's highest volume battery plant.

Different battery chemistries have been used for the Tesla car and Tesla energy storage batteries. The cars use Lithium Nickel Cobalt Aluminium Oxide (NCA), where there are higher power outputs and typically weekly charging. A Lithium Nickel Manganese Cobalt Oxide (NMC) battery chemistry has been used for the energy storage products and these tend to experience daily charge and discharge cycles.

Tesla announced the first generation of the Powerwall domestic battery in April 2015 and the first installation in the UK took place in 2016.[19] The first generation of the Tesla Powerwall had a usable capacity of 6.4kWh and could supply up to 3.3kW of power. It used 18650 form factor cells which were also used in the Tesla Model S car.

[15] BU-201: How does the Lead Acid Battery Work?, Battery University http://batteryuniversity.com/learn/article/lead_based_batteries (Accessed 4 Feb 2019)
[16] BU-205: Types of Lithium-ion, Battery University https://batteryuniversity.com/index.php/learn/article/types_of_lithium_ion (Accessed 28 Jan 19)
[17] Tesla Gigafactory, https://www.tesla.com/en_GB/gigafactory (Accessed 4 Feb 19)
[18] Gigafactory 1, https://en.wikipedia.org/wiki/Gigafactory_1 (Accessed 4 Feb 19)
[19] Steven Morris, Welsh home installs UK's first Tesla Powerwall storage battery, The Guardian, 5 Feb 16, https://www.theguardian.com/environment/2016/feb/05/welsh-home-installs-uks-first-tesla-powerwall-storage-battery (Accessed 21 Jan 19)

3.2 Tesla Powerwall 2

Figure 3.1 Internal Tesla Powerwall 2 installation

Figure 3.2 External Tesla Powerwall 2 installation

Details of the Tesla Powerwall 2 battery were announced in October 2016. The usable battery capacity increased to 13.5kWh, but the system came in a smaller case. This was achieved partly by switching over to 21700 form factor battery cells which are also used in the Tesla Model 3 car. These have a better energy density than the 18650 form factor cells[20]. The battery capacity and power output of up to 5kW were both significantly higher than other domestic batteries on the UK market[21]. Batteries are currently treated as generation by Distribution Network Operators (DNOs) and this means a G59 grid connection is required if the battery is to discharge up to 5 kW. In some cases analysis of the local network shows that only a G83 connection is possible and the battery is restricted to an output of about 3.68 kW. The first UK installations of the second-generation battery took place in 2017. Although more expensive than many domestic batteries on the market, the Powerwall 2 typically has a lower cost per kWh of storage.

The Tesla Powerwall 2 battery has dimensions of 1150 x 755 x 155mm[22]. The battery unit must have a clearance of at least 50mm from the left side where there is an air intake, 150mm from the right side, where there is an air exhaust and 50mm from the top. The battery weighs 125kg; it can be floor or wall mounted and should not be installed more than 1.5m above the ground.

[20] Tesla Batteries 101 – Production Capacity, Uses, Chemistry, & Future Plans, https://cleantechnica.com/2017/12/02/tesla-batteries-101-production-capacity-uses-chemistry-future-plans/ (Accessed 8 Feb 19)

[21] Paul Rogers & Michael Hamer, SunGain Battery Bank, http://www.nea.org.uk/wp-content/uploads/2019/01/CP775-TIF-REPORT-FINAL.pdf (Accessed 4 Feb 19)

[22] Tesla Powerwall 2 AC data sheet, https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_GB.pdf (Accessed 4 Feb 19)

The battery can be fitted internally or externally. The battery and power electronics have an IP67 solids and liquids ingress rating while the wiring compartment is IP56 rated[23]. The optimum temperature range is between 0 and 30°C, but the system is capable of operating between -20°C and 50°C. The battery system closely monitors the cell temperatures to ensure optimum performance and longevity. An ideal battery temperature is maintained by a pump, fan and when too cold, heating. The Powerwall should not be fitted in locations with sustained low or high temperatures. This includes being fitted in direct sunlight which leads the temperature in the case to rise above ambient temperature.

Some noise is produced by this system, typically a gentle hum comparable to that from a refrigerator (<40dBA at 30°C at 1 metre away). Some additional noise has been noted periodically when the system runs a bubble shedding routine.

Since batteries charge and discharge as direct current (DC) and electricity used in the home is AC (alternating current) electricity, an inverter is required by the Tesla Powerwall 2 system to convert the electricity between AC and DC (figure 3.3). There are inefficiencies in the power going to and from the battery due to energy losses in the inverter and battery. The round-trip efficiency is typically of the order of 90%, but can be lower with some systems

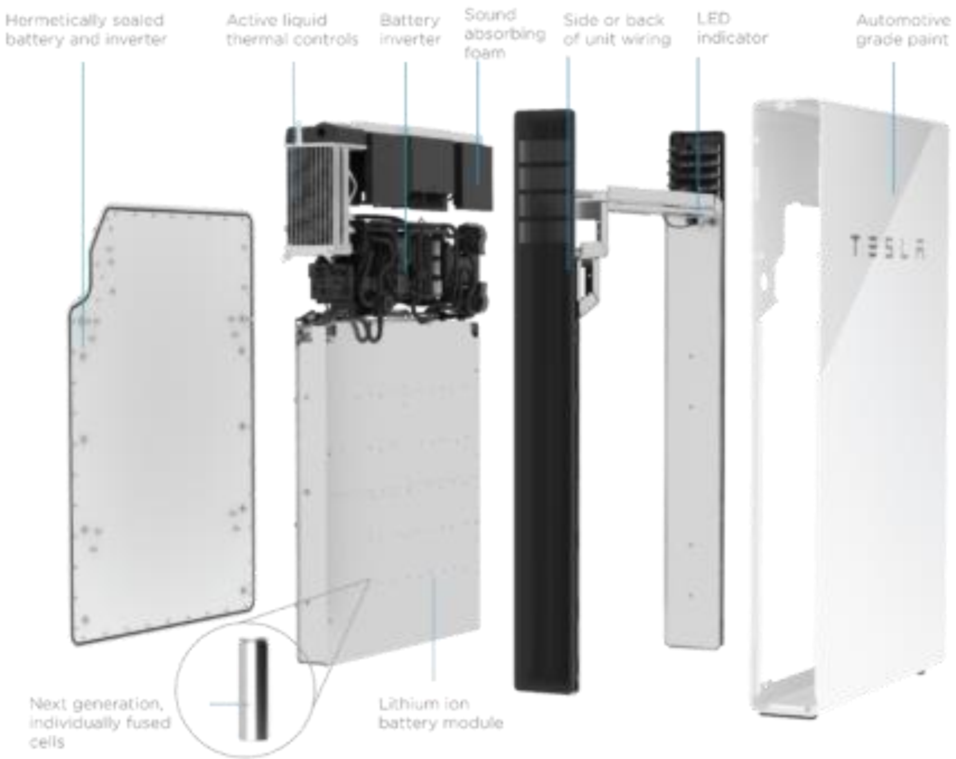


Figure 3.3 Inside the Tesla Powerwall 2 battery unit[24]

[23] IP Rating Chart, http://www.dsmt.com/resources/ip-rating-chart/ (Accessed 4 Feb 19)

[24] Everything you need to know about the Tesla Powerwall 2 (2019 Edition) https://cleantechnica.com/2019/01/19/everything-you-need-to-know-about-the-powerwall-2-2019-edition/ (Accessed 5 Feb 19)

The other main part of the Tesla Powerwall system is the Gateway[25]. It is wall mounted and has dimensions of 240 x 243 x 130mm. The Gateway and the main Powerwall unit are both connected to the consumer unit (distribution board). The Gateway provides energy management and monitoring functions for the Powerwall system. It has an AC meter with an accuracy of ±1% and a single Gateway which can support up to 10 AC coupled Powerwalls. It communicates directly with the Powerwall, transmitting performance data back to Tesla and allowing the household to monitor their energy using the Tesla app. The Gateway can access the internet either with an Ethernet cable directly connected to the broadband router (or via TP Links/power line adapters), WI-FI or 3G mobile (if the signal is strong enough). The Gateway has a built-in hard drive which continues to record data during short periods offline.

Updates to the Powerwall operating system software are downloaded by the Gateway. At the time of release, the Powerwall 2 was only able to charge from solar PV. The ability for grid charging came in a software update to the Gateway and Tesla app. There was initially a soft launch to this update in Spring 2018, with selected installations taking part. Installations in this project were part of the soft launch and were the first Tesla Powerwall 2 batteries in the UK to charge only from the grid using time of use tariffs. Subsequently, the ability to charge from the grid was available to new installations from commissioning. A CT clamp is used to measure the household electricity supply. For sites with Economy 7 and peak and off-peak meter tails such as with this project, it may be necessary to use a Y-splitter cable to connect 2 CT clamps. This ensures both the peak and off-peak supplies are measured by the system.

An alternative to the standard Gateway used in this project is the Backup Gateway 2 which was released in the UK in March 2019. This new version of the Gateway allows the battery to operate during power cuts. It controls the connection to the grid, automatically detecting power outages and provides a near seamless transition to backup power, islanding the household from the grid.

Figure 3.4 Tesla Powerwall 2 battery with the new Powerwall Backup Gateway 2[26]

[25] Powerwall Gateway data sheet https://www.tesla.com/sites/default/files/pdfs/powerwall/Gateway_Datasheet_en.pdf (Accessed 4 Feb 19)

[26] Tesla unveils its Gateway upgrade for Powerewall 2 battery, https://reneweconomy.com.au/tesla-unveils-its-gateway-upgrade-for-powerwall-2-battery-84845/ , 19 Nov 18 (Accessed 4 Feb 19)

The Backup Gateway 2 looks like a mini version of the Powerwall 2 battery as shown in figure 3.4, and has dimensions of 584 x 380 x 127mm. The mains incoming power is connected through the Backup Gateway 2. It is possible to wire up the system so that some circuits (e.g. cooker) are on a non-backup circuit and would not be powered during an outage. Monitoring of the household consumption is improved with the Backup Gateway 2, with an accuracy of ±0.2%.

At the time of writing, Tesla was advertising a price of £6,200 for the Powerwall 2 and £650 for the standard Gateway. The price of the Backup Gateway 2 was £1700. Typical installation costs for a system with a standard Gateway may range between £950 and £2,800. Installation with the Backup Gateway 2 is more complex may be more expensive than with the standard Gateway. All prices include VAT at 20%. If the battery was installed with a new solar PV system, VAT would be charged at 5% and when installed as part of a new build property, the VAT rate is 0%.

The Tesla Powerwall 2 comes with a 10-year warranty[27] which guarantees the system with be free from defects for 10 years following the initial installation date. Where the battery has been used for solar self-consumption and backup, the battery is guaranteed to retain 80% of the initial 13.5kWh usable capacity after 10 years for unlimited numbers of cycles. This covers grid charging with time of use tariffs as well as solar charging. For other applications such as charging from a wind turbine or the battery being used for grid services, the guarantee is limited to 10 years or an aggregate throughput of 37.8MWh.

3.3 Technological monitoring

(a) (b) (c) (d)

Figure 3.5 Images from the Tesla app

The Tesla app is available for Apple or Android devices. Users need to initially set up an account on the Tesla website with a user name and password. After providing Tesla (or their installer) with the Tesla account user name and the serial number for their Gateway unit, it is possible to view the battery's performance when logging on to the Tesla app.

[27] Tesla Powerwall Warranty (European Warranty Region), 9 Jun 17, https://www.tesla.com/sites/default/files/pdfs/powerwall/powerwall_2_ac_warranty_europe_1-5_english.pdf (Accessed 5 Feb 19)

The home screen shows the state of charge of the battery (figure 3.5 a). It also provides options for seeing more details of the power flow and energy usage, the performance (level of self-consumption) or to customise the time-based control. Figure 3.5 b shows the live power flows between the Powerwall and the home, the grid and if present solar PV.

Energy usage data can be viewed by pressing the graph icon (3 lines) at the top right of the power flow screen. The app can show a plot of today's or yesterday's energy use (figure 3.5 c). It can also plot bar charts for days over the last week, weeks over the last month or months over the last year. Below these charts are values of data. Figure 3.5 d shows the electricity which the household consumed and the amount going to and from the Powerwall (charge/discharge). It also includes values of electricity consumed from the grid and any that was exported to the grid. These can be displayed for the whole day, peak rate or off-peak rate periods.

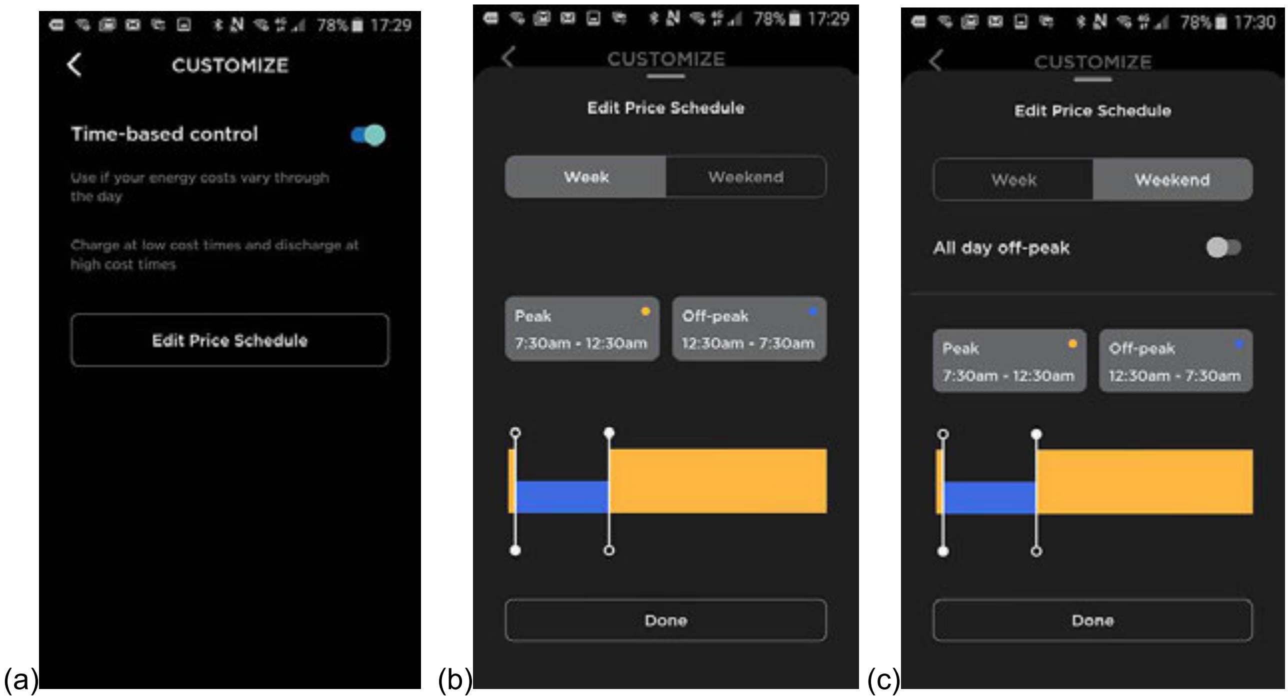


Figure 3.6 Customizing the Tesla app for time-based control

The Tesla app offers the opportunity to select time-based control and edit the price schedule with times of peak and off peak electricity as shown in figure 3.6. Different settings can be made for the price schedule during the week and at weekends. This allows for special deals like all day off-peak electricity during the weekend. The example shown was for a household whose electricity was supplied by British Gas where off-peak electricity was between 12.30am and 7.30am GMT (Greenwich Mean Time). A time switch determined the change from peak to off peak electricity and this operated on GMT. As a result of switching from GMT to BST (British Summer Time), the off-peak times for this households were 01:30am to 8.30am between March and October and so the times on the Tesla app needed altering. The times for off-peak and whether it changed with the switch from GMT to BST varied with household and electricity supplier. This will be discussed further in section 3.4.

Daily performance data was only available from the app for the current day or the day before. Tesla records detailed data from each battery system down to a per minute level. This is more accurate than the values shown on the Tesla app. To assist the project, Tesla provided daily values for the battery import and export, site import and household load (with the householder consent). There is currently no means for users to download such data.

Supplementary monitoring was also carried out at each site by NEA. This included the following:

- Regular electricity meter readings recorded by residents and from past billing
- Half-hourly smart meter data where available
- Tiny Tag View 2 or Lascar EL-USB-ACT current clamps on the household meter tails
- Lascar EasyLog EL-USB-2 temperature and humidity loggers in the living room

A summary of the data collected at each site is shown in table 3.7.

Technical Reference Number	Meter readings	Smart meter readings	USB-2 Temperature logger	Current clamp on mains supply	Verv data logger	Notes
T-01	Limited	N	Y	Y	Y	Verv not connected to internet
T-03	Y	N	Y	Y	Y	
T-05	Y	N	Y	Y	Y	Verv fitted on meter tail
T-06	Y	N	Y	Y	Y	
T-07		Limited	Y	Y	N	
T-09		Y	Y	Y	Y	
T-38	Y	N	N	Y	N	No temperature logger
T-61	Y	N	Y	Y	N	2 x temperature loggers
C-04	Y	N	Y	Y	N	
C-11	Y	N	Y	Y	N	
C-25	Limited	N	Y	Y	N	

Table 3.7 Monitoring that was available at each of the sites in the study

Many of the loggers recorded data for only part of the study as there wasn't the opportunity to swap the loggers over before their batteries ran out. Figure 3.8(a) shows a Lascar EL-USB-ACT current clamp and a Lascar EL-USB-2 temperature and humidity logger. The temperature and humidity loggers were set to record data every 20 minutes and their batteries typically lasted about 8 months. The Lascar EL-USB-ACT current clamps were able to record instantaneous values of current every 5 minutes for the whole duration of the study. The Tiny Tag View 2 current clamps recorded the current every 15 minutes and the batteries typically lasted for 11 months. Current clamps were fitted on both the peak and off-peak tails of the household electricity meter.

(a) 

(b) 

Figure 3.8 Lascar EL-USB-ACT current clamp
Lascar EL-USB2 temperature and humidity logger
Verv data logger with current clamp

The Verv data loggers are mains powered and also used a current clamp as shown in figure 3.8(b). They recorded power, current, voltage and frequency every second. As a result of the high sample rate and measuring real power rather than just current, the accuracy of these loggers was significantly better than the Lascar ACT and Tiny Tag View 2 loggers. About a year of data could be recorded in the built-in memory of the Verv logger, but it could also be uploaded to the internet. Where these loggers were used, they were intended to record the charge and discharge of the battery. The current clamp was typically fitted by the installer in the consumer unit where the live and neutral of the battery cable had been separated. There was a site where this did not occur, and the logger was fitted over a mains meter tail. There were technical issues with 2 of the Verv loggers and the data from these sites was corrupted.

3.4 Economy 7 and night storage heaters

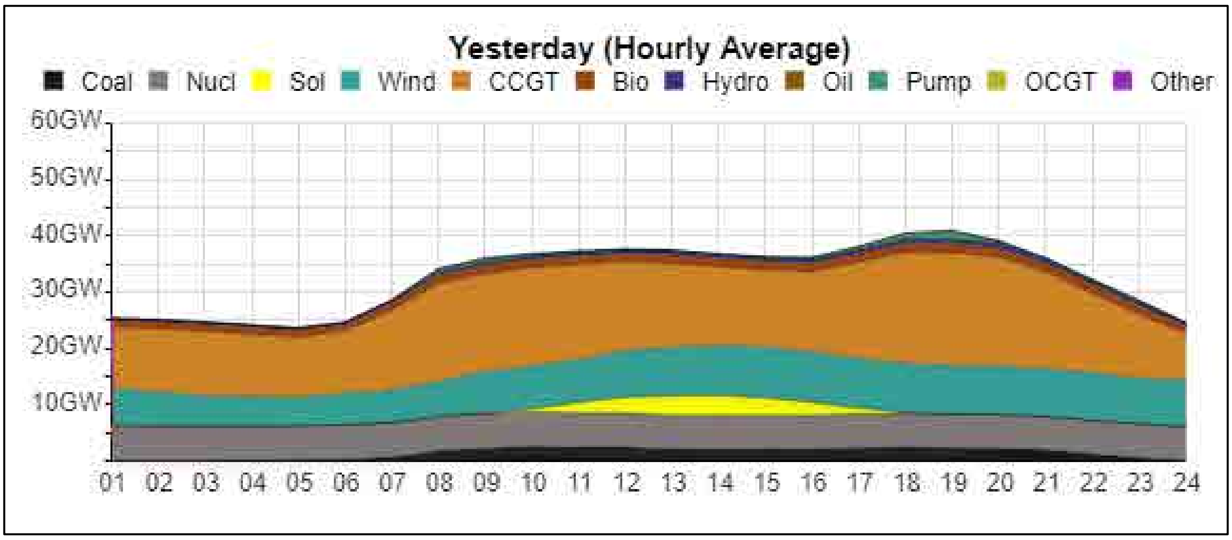


Figure 3.9 UK electricity demand and output on 7 Feb 2019[28]

UK Electricity consumption is lower at night than during the day and this has meant that thermal power plants have traditionally been turned down during this period and run less efficiently. Offering cheaper tariffs overnight has been a method to increase demand and allow these thermal power stations to run more efficiently. Off peak tariffs have been used for space and water heating, which has been particularly beneficial for homes which do not have gas central heating.

The heating elements in a night storage heater warm a bank of ceramic blocks overnight during the period of cheaper rate electricity. These blocks retain the heat which is gradually emitted during the rest of the day. Older storage heaters have 2 controls (figure 3.10 (a))[29 30]. You can alter the Input, which varies the amount of power the elements receive and the heat that is stored. The Output dial can be used to open and close vents which regulate the rate at which heat is released. By closing the vents, it is possible to retain more of the heat later into the day, however a lot of heat is still lost during the day leaving the unit relatively cool by the evening.

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[28] http://gridwatch.co.uk/ (Accessed 8 Feb 19)

[29] Night storage heaters – A simple guide, https://www.cse.org.uk/downloads/advice-leaflets/energy-advice/insulation-and-heating/advice_leaflet_night_storage_heater.pdf (Accessed 8 Feb 19)

[30] Getting the most from Economy 7, http://www.nea.org.uk/wp-content/uploads/2019/02/Getting-the-most-from-Economy-7-PRINT.pdf (Accessed 8 Feb 19)

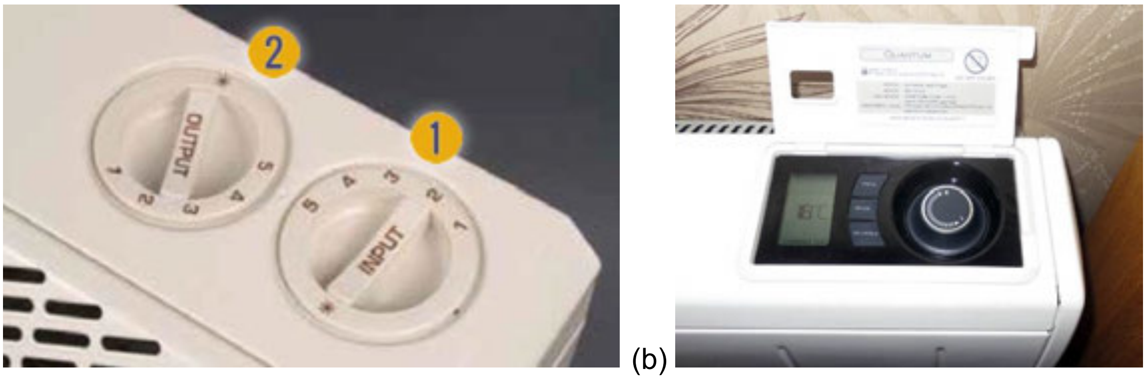
(a) (b)


Figure 3.10 (a) manual controls for an older storage heater (b) electronic control for a Dimplex Quantum Storage Heater

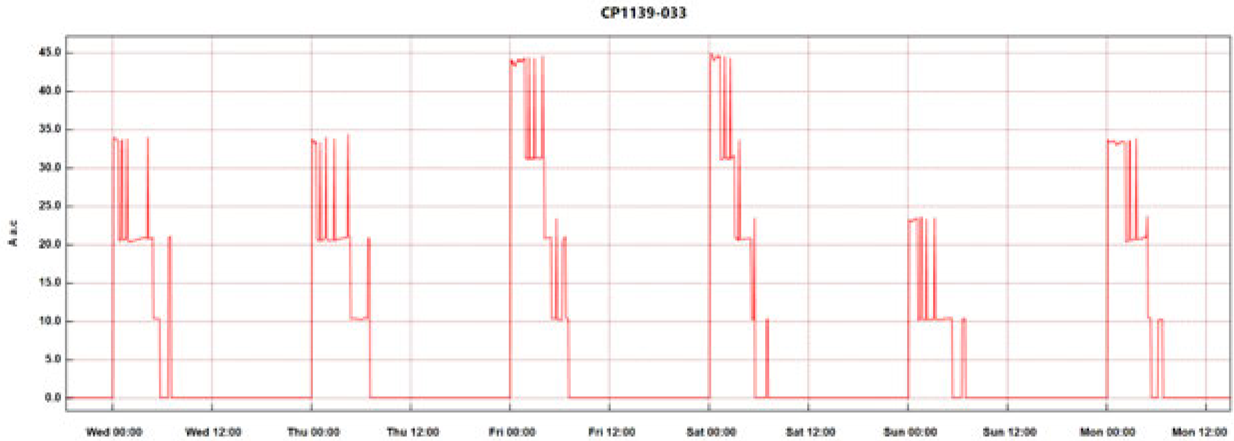


Figure 3.11 Off peak electricity consumption (in amps) for household T-03 between 12 Dec 17 and 18 Dec 17

The off-peak electricity consumption for household T-03 in December 2017 is shown in figure 3.11 with consumption from both water heating and night storage heaters. The maximum demand was dependant on the number of storage heaters turned on and the level of the input setting. The immersion heater initially ran for about an hour with short power bursts to maintain temperature.

Electric heaters manufactured after 1 Jan 18 must meet Lot 20 of the EU EcoDesign Directive. For storage heaters, designs now have to include[31]:

- Electronic heat charge control with room and/or outdoor temperature feedback or controlled by the energy supplier
- Electronic room temperature control plus a week timer
- Fan assisted output

The Dimplex Quantum storage heater meets the Lot 20 standard, having electronic controls (figure 3.10 (b)), and a fan. It is also a high heat retention system where only a small amount of heat is released from natural convection and radiation from the storage heater case. The majority of the heat is released when the household requires it by the fan in the unit distributing heat through the outlet grille[32].

[31] Gaining compliance for storage heaters, http://www.lot20.co.uk/storage-heaters (Accessed 28 Jan 19)
[32] Dimplex Quantum Operating Instructions, https://www.dimplex.co.uk/sites/default/files/assets//Quantum_Operating_Instructions_Issue_5_Series_D.pdf (Accessed 8 Feb 19)

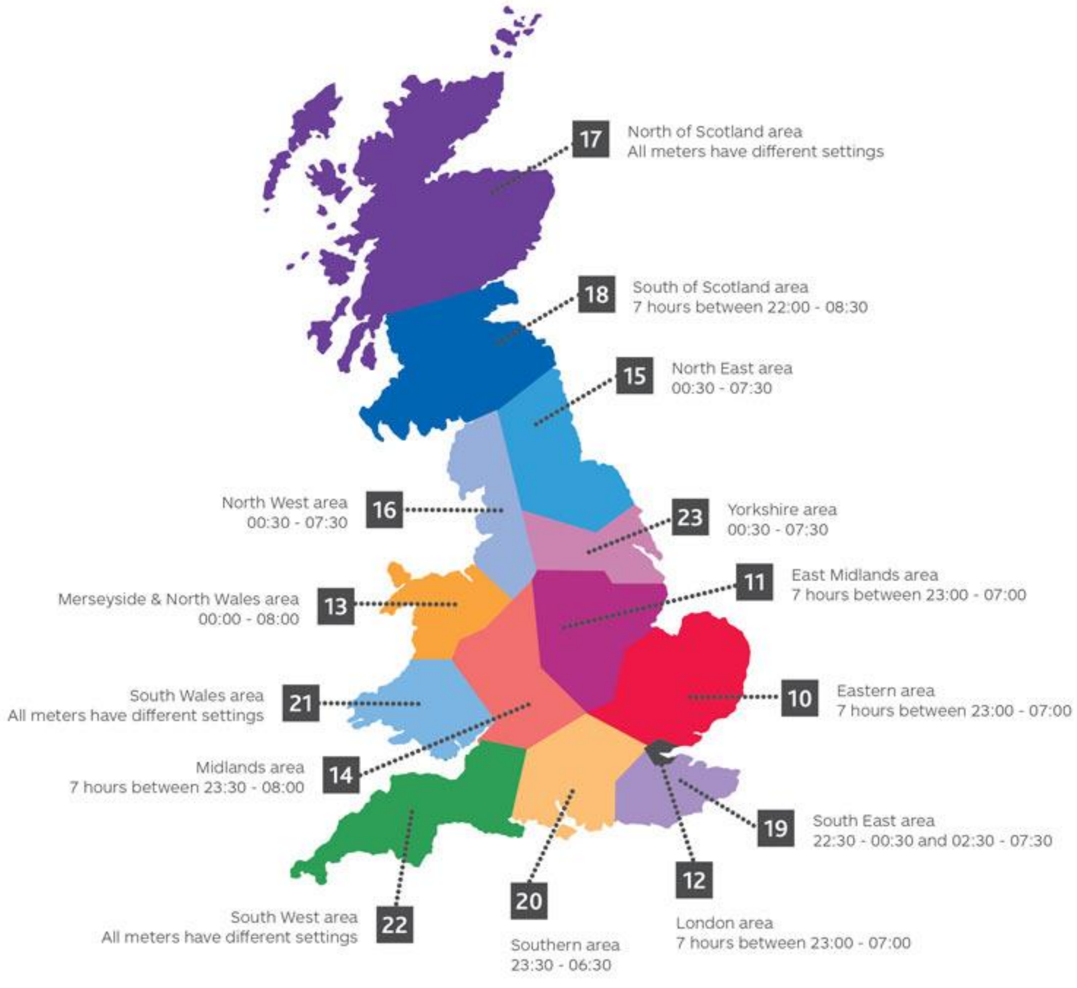


Figure 3.12 Typical times for off-peak electricity in different parts of the country[33]

The Economy 7 off-peak tariff was available from 1978 and provides 7 hours of cheaper rate electricity overnight[34]. Different areas of the country and suppliers can have different times for the off-peak electricity (figure 3.12). In the past, network engineers may also have staggered the times of off-peak electricity for households in a district to avoid all the off-peak loads coming on at the same time. The off-peak times for a particular account can usually be determined from a label on the meter, a recent bill or contacting the energy supplier.

Radio teleswitches have been used to switch between peak and off-peak rates. These detect information transmitted via the 198 kHz Radio 4 long-wave signal. The switching between peak and off-peak may occur within the meter in more modern systems and also keep with clock time. The meters have a Standard Settlement Configuration (SSC) code and this determines the times when the supply switches from peak to off-peak[35]

[33] Frequently asked questions – What are the Economy 7 peak and off-peak periods? https://customerservices.npower.com/app/answers/detail/a_id/179/~/what-are-the-economy-7-peak-and-off-peak-periods%3F (Accessed 8 Feb 19)

[34] Economy 7, https://en.wikipedia.org/wiki/Economy_7 (Accessed 8 Feb 19)

[35] Guidance Note: Radio Teleswitch – Standard Settlement Configuration Mapping, https://www.elexon.co.uk/wp-content/uploads/2016/02/Radio_Teleswitch_Standard_Settlement_v1.0.pdf (Access 8 Feb 19)

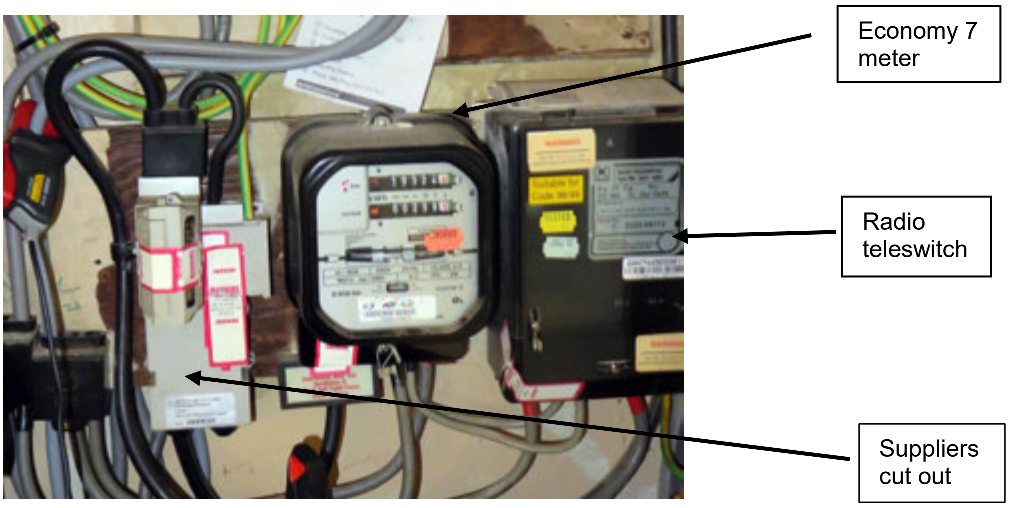


Figure 3.13 Economy 7 meter with radio teleswitch

The time for the off-peak rate, may alter by an hour as the clocks go forward or back between Greenwich Meant Time (GMT) and British Summer Time (BST). A British Gas customer had their off-peak rate between 00:30 and 07:30 GMT, but between March and October, the times were 01:30 to 08:30. A Utilita customer on the project had the time of off-peak electricity between 00:00 and 07:00 throughout the year as the SMETS1 smart meter was set to local time. As a customer switches supplier or the meter is replaced, the time for Economy 7 off-peak may change.

Ofgem noted in 2017 that out of a total of 28 million domestic customers, 4 million of these were on Profile Class 2 electricity meters[36]. The majority of these were Economy 7, with others such as Economy 10 (where there is 10 hours of off-peak electricity) or separate peak and off-peak meters also included. They analysed the distribution of Typical Domestic Consumption Values (TDCVs) for Profile 2 meter customers. The median average annual consumption was 4,200 kWh/year and this level of consumption was classed as a medium user. Low users were those with a consumption of 2500 kWh/year, at or below the 25th percentile of consumers. A high electricity user had an annual consumption of 7,100 kWh/year or more. This corresponded to households who were at or above the 75th percentile of the range in consumption.

Sub-national electricity consumption figures, based on data from 2016, show that the median consumption for Economy 7 households was 3,995kWh in the UK. The South West was the region with the highest mean consumption per Economy 7 meter (6,381 kWh mean and 5,320 kWh median)[37]. In North Devon the median electricity consumption for households with Economy 7 meters was 5,575kWh[38]. BEIS have also produced estimates of the electricity consumption at a postcode level using 2015 data based on averages of the consumption for postcodes with 6 or more meters[39].

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[36] Typical Domestic Consumption Values for gas and electricity (Ofgem, 2017) https://www.ofgem.gov.uk/system/files/docs/2017/08/tdcvs_2017_open_letter.pdf (Accessed 8 Feb 19)

[37] Sub-National Electricity and Gas Consumption Statistics, (BEIS, 2016), p.15, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/678653/Sub-national_electricity_and_gas_consumption_summary_report_2016.pdf (Accessed 11 Feb 19)

[38] Sub-national electricity consumption statistics 2017, https://www.gov.uk/government/statistical-data-sets/regional-and-local-authority-electricity-consumption-statistics (Accessed 11 Feb 19)

[39] https://www.gov.uk/government/statistics/postcode-level-electricity-estimates-2015-experimental (Accessed 12 Feb 19)

3.5 Control households

Household C-04

There were 5 residents in Household C-04, with 2 parents working full-time and 2 school aged children. The property was semi-detached and had night storage heaters. Creda TSR storage heaters were fitted in 2012. The storage heaters in the Living Room and Kitchen were replaced by Dimplex Quantum high heat retention models in October 2017, leaving 4 remaining Creda storage heaters. The loft insulation was also improved at around the same time.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
13-Sep-12	21-Sep-13	373	3604	5316	9.66	14.25	23.91	59.60%
21-Sep-13	06-Sep-14	350	4602	6288	13.15	17.97	31.11	57.74%
06-Sep-14	29-Aug-15	357	3984	7671	11.16	21.49	32.65	65.82%
29-Aug-15	20-Sep-16	388	4043	8044	10.42	20.73	31.15	66.55%
20-Sep-16	10-Sep-17	355	3859	6568	10.87	18.50	29.37	62.99%
10-Sep-17	28-Sep-18	383	3873	8534	10.11	22.28	32.39	68.78%

Table 3.14 Peak and off-peak consumption for control household C-04

Table 3.14 shows approximately yearly electricity consumption data for household C-04. The average total consumption ranged from 23.9 kWh/day to 32.7 kWh/day. This corresponds to annual total consumption figures of 8,729 to 11,916 kWh/year and costs of £999 to £1,282 using standardized rates of 18p/kWh for peak rate and 7p/kWh for off peak.. For comparison, the Ofgem Typical Domestic Consumption Value (TDCV) for a high energy user on a Profile 2 meter is 7,100 kWh/year as discussed in the previous section. The percentage of off-peak usage for these figures were in the range 57.7% to 68.8%. Between 2014 and 2018, the peak rate consumption was in a narrow range of 10.1 to 11.2 kWh/day.

The off-peak consumption rose from an average of 18.5 kWh/day for Sept 16/17 to 22.3 kWh/day for Sept 17/18. Looking at Degree Day data for Exeter Airport[40], the number of degree days per day for Sept 16/17 was 5.27 compared to 5.21 in Sept 17/18. This suggests the higher average consumption for Sept 17/18 was not necessarily due to a year with colder weather. It might alternatively have been due to the household taking greater thermal comfort after the new Dimplex Quantum storage heaters were installed.

The household noted they were satisfied with how warm the home got when it was warm outside and the amount of control with the heating system. They were happy with the Dimplex Quantums, but less so with the older storage heaters. No supplementary heating was used.

A plot of the current consumed by the heating electrical circuit in household C-04 for 3 days in February 2018 is shown in figure 3.15 (a). The initial consumption at about midnight was between 50 and 60A on the nights shown. The consumption fell as the storage heaters became hotter. Figure 3.15 (b) shows the consumption on the main household circuit for the same days. Typically, the consumption was under 13A, although there were occasional periods where the current was between 13 and 24A. This may have been when high power or multiple appliances were used.

[40] Degree Day data for EGTE Exeter Airport, https://www.degreedays.net/ (Accessed 11 Feb 19)

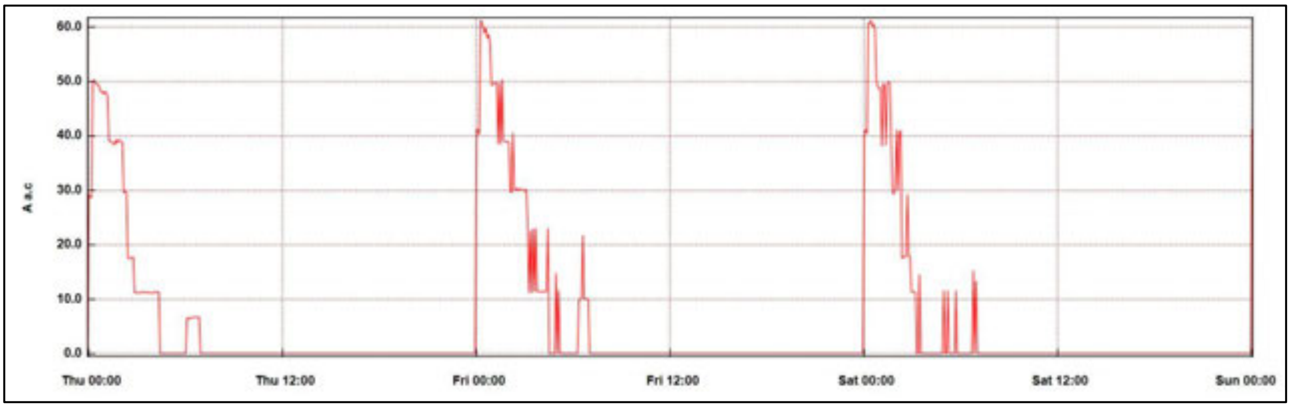

Figure 3.15 (a) Consumption on heating electrical circuit for control household C-04 between 15 Feb 18 and 18 Feb 18

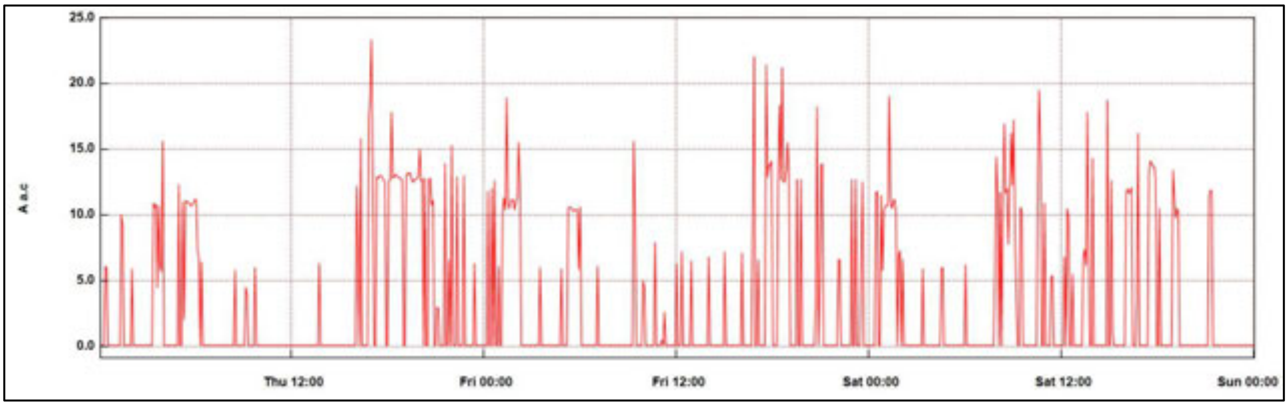

Figure 3.15 (b) Consumption on main household circuit for control household C-04 between 15 Feb 18 and 18 Feb 18

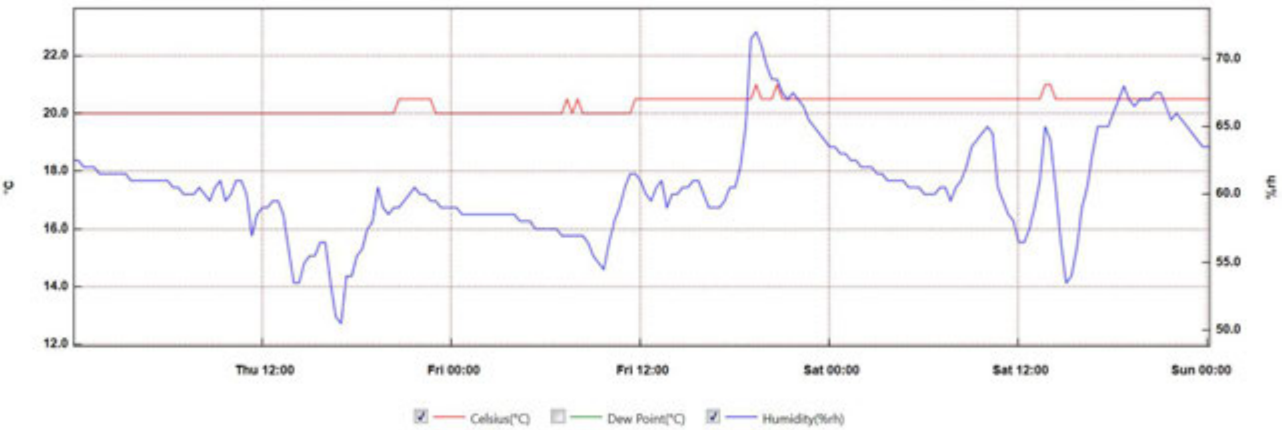

Figure 3.16 Living room temperature and relative humidity for control household C-04 between 15 Feb 18 and 18 Feb 18

Figure 3.16 shows the temperature and humidity in the living room for household C-04 between 15 Feb 18 and 18 Feb 18. It is apparent that the Dimplex Quantum storage heaters maintained the room at a steady 20°C, with an increase to 20.5°C on the Friday, possibly after being turned up.

Consumption on the heating electrical circuit in July 2018 is shown in figure 3.17. The storage heaters were not being used at that time and the consumption was due to the 3kW immersion heater on the hot water cylinder. From midnight, the electric immersion ran for just over 1 hour and then there was a periodic short burst of power to maintain the water at the desired temperature.

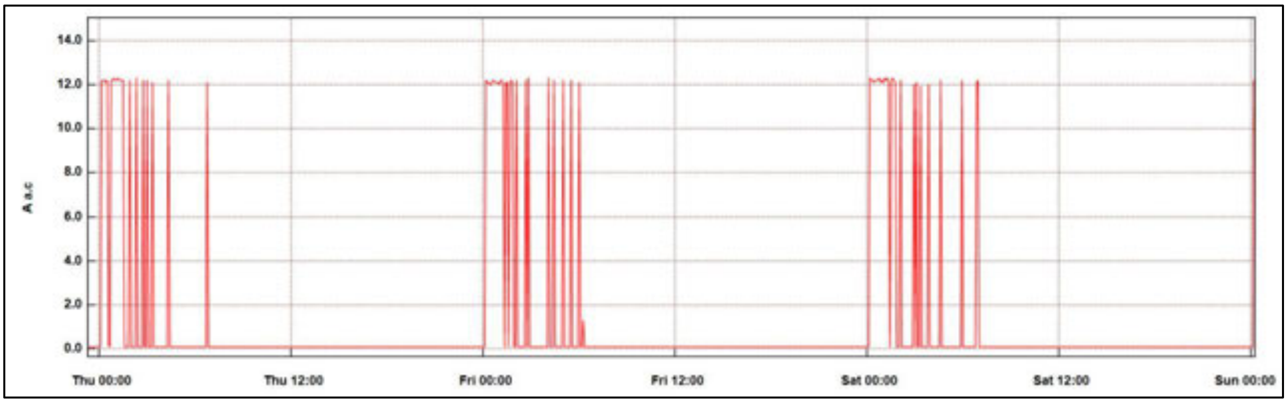

Figure 3.17 Consumption on heating electrical circuit for control household C-04 between 5 Jul 18 and 8 Jul 18

The household had an electric hob and oven which were used daily in the evening along with a microwave. There was a washing machine that was used twice a day – once during the day and once overnight. The tumble drier also tended to be used overnight. These are likely to be the main cause of the overnight consumption on the main household circuit which are charged at the cheaper rate during the off-peak period. There was also a fridge and chest freezer which contributed to the baseload electricity consumption.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
14-Dec-17	01-Feb-18	49	699	1871	14.27	38.18	52.45	72.80%
01-Feb-18	25-Mar-18	52	702	2176	13.50	41.85	55.35	75.61%
25-Mar-18	19-Apr-18	25	254	750	10.16	30.00	40.16	74.70%
19-Apr-18	21-May-18	32	280	441	8.75	13.78	22.53	61.17%
21-May-18	24-Jun-18	34	258	441	7.59	12.97	20.56	63.09%
24-Jun-18	20-Jul-18	26	145	202	5.58	7.77	13.35	58.21%
20-Jul-18	26-Aug-18	37	262	311	7.08	8.41	15.49	54.28%
26-Aug-18	28-Sep-18	33	254	344	7.70	10.42	18.12	57.53%
28-Sep-18	02-Nov-18	35	335	644	9.57	18.40	27.97	65.78%
02-Nov-18	15-Dec-18	43	498	1264	11.58	29.40	40.98	71.74%
15-Dec-18	10-Jan-19	26	301	844	11.59	32.46	44.05	73.69%

Table 3.18 Peak and off-peak consumption for control household C-04

Table 3.18 shows approximately monthly electricity consumption data for household C-04. The peak rate consumption ranged from 14.3 kWh/day in late Dec 17 and Jan 18, which included the Christmas holidays, to 5.6 kWh/day in Jul 18. The off-peak rate consumption was at its highest at 41.9 kWh/day in Feb/Mar 18 during a period of particularly cold weather[41]. This decreased to 7.8 kWh/day in Jul 18.

During the periods with colder weather when all the storage heaters were routinely used, the percentage of off-peak consumption was between 71.7% and 75.6%. Even during the summer, the percentage of off-peak consumption was still 54.3%. This was most likely due to the household running their washing machine as well as the electric immersion heater overnight.

[41] 2018 Great Britain and Ireland cold wave, Wikipedia, https://en.wikipedia.org/wiki/2018_Great_Britain_and_Ireland_cold_wave (Accessed 11 Feb 19)

Household C-11

Control household C-11 lived in a similar property to household C-04. There were 4 household members, with 1 adult not working due to a health condition/disability and the other being a full-time carer for their partner and a pre-school child. The property only had older storage and panel heaters. Normally the household only used the storage heater in the living room, which was likely to be a 3.4kW model. In 2018, the living room storage heater was used consistently up to mid-March and for periods of about a week in late March and early April. In the Autumn they had the heater on from late October onwards. However, it broke down in December 2018 and they subsequently used the 1.7kW Creda TSR12ACW storage heater in the hall.

Figure 3.19(a) shows the consumption on the heating electrical circuit for household C-11. The overnight peak of up to 13A was considerably lower than for household C-04. This was because C-11 only used the storage heater in the living room, while C-04 used all the storage heaters in the house. Household C-11 had a bath, but no shower and the immersion heater was typically left on 24 hours a day. There was a need for water throughout the day and at short notice.

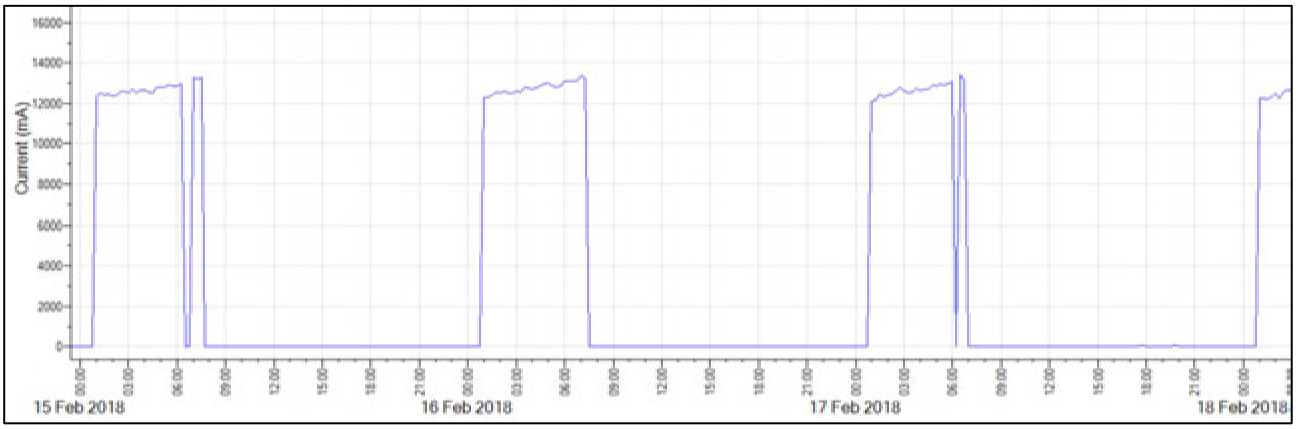

Figure 3.19 (a) Consumption on heating electrical circuit for control household C-11 between 15 Feb 18 and 18 Feb 18

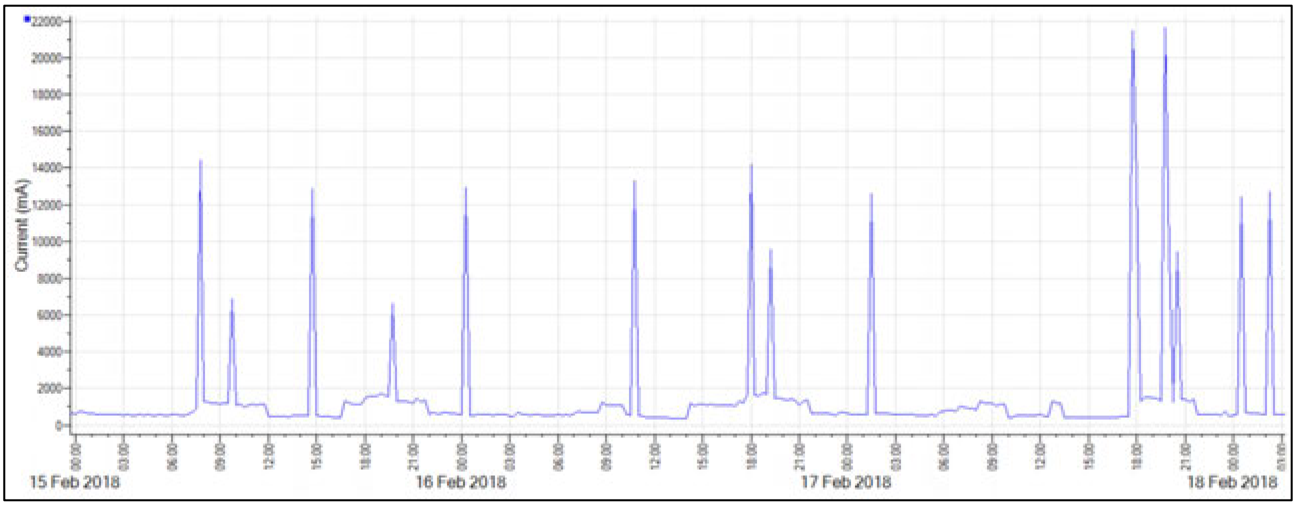

Figure 3.19 (b) Consumption on main household circuit for control household C-11 between 15 Feb 18 and 18 Feb 18

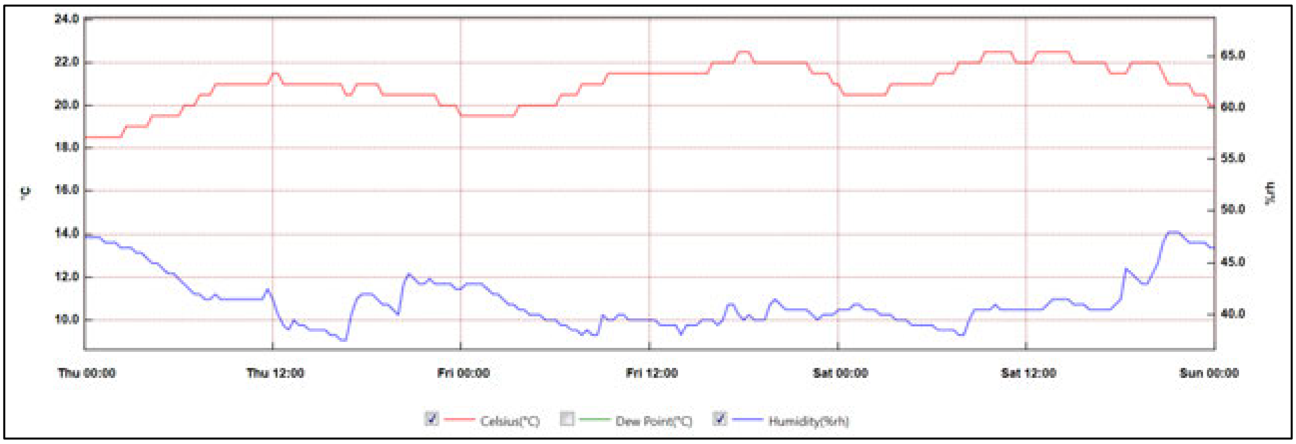

Figure 3.20 Living room temperature and relative humidity for control household C-11 between 15 Feb 18 and 18 Feb 18

There was less consumption on the main household circuit for household C-11 in mid-February (figure 3.19(b)) compared to household C-04 over the same period (figure 3.15(b)). Household C-11 used the washing machine 3-4 times per week instead of twice a day for household C-04. There was a single fridge-freezer and a TV was regularly used during the day. These along with a Sky+ box were likely to have contributed to the baseload consumption, while peaks may have been caused by use of a kettle, the microwave or the electric cooker.

Figure 3.20 shows a plot of temperature and relative humidity in the living room for household C-11 on the same days in February 2018 as the electricity consumption profiles. The temperature ranged from 18.5°C to 22.5°C between 15 Feb and 18 Feb 18. Although the temperature in the living room was comfortable over this period, there was poorer temperature control with the older storage heater compared to the Dimplex Quantum in household C-04. It should be noted that although the living room temperature was comfortable, rooms in the rest of the house were likely to be cold as the other heaters were not being used.

Table 3.21 shows approximately monthly electricity consumption data for household C-11. In colder weather, the average off-peak consumption was normally in the range 15.2 to 20.6 kWh/day. There was particularly low off-peak consumption between Dec 18 and Jan 19 of 2.34 kWh/day and the peak rate consumption was higher than usual at 15.3 kWh/day. This was due to the living room storage heater breaking down. Normally in colder weather, the percentage of off-peak consumption was between 60 and 70%.

In summer, the peak rate consumption was between 6 and 8.3 kWh/day, while the off-peak consumption fell to between 1.7 and 2.3 kWh/day. This meant that outside the heating season, the percentage of off-peak consumption was typically between 17.3 and 22.4%. Using the meter readings between Dec 17 and Dec 18, the total annual consumption was 6,547 kWh/year. This was above the median electricity consumption of 5,575kWh/year for households in North Devon with Economy 7 meters, but comparable to the mean of 6,632 kWh/year.[42] The percentage of off-peak consumption over the year was 51.6%. The annual cost was £807 using standardized rates for Economy 7.

[42] Sub-national electricity consumption statistics 2017, https://www.gov.uk/government/statistical-data-sets/regional-and-local-authority-electricity-consumption-statistics (Accessed 11 Feb 19)

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
17-Aug-17	22-Sep-17	36	284	82	7.89	2.28	10.17	22.40%
22-Sep-17	01-Nov-17	40	420	89	10.50	2.23	12.73	17.49%
01-Nov-17	15-Nov-17	14	186	69	13.29	4.93	18.21	27.06%
15-Nov-17	21-Dec-17	36	398	740	11.06	20.56	31.61	65.03%
21-Dec-17	22-Jan-18	32	334	611	10.44	19.09	29.53	64.66%
22-Jan-18	22-Feb-18	31	296	585	9.55	18.87	28.42	66.40%
22-Feb-18	26-Mar-18	32	319	486	9.97	15.19	25.16	60.37%
26-Mar-18	16-Jul-18	112	819	409	7.31	3.65	10.96	33.31%
16-Jul-18	16-Aug-18	31	186	52	6.00	1.68	7.68	21.85%
16-Aug-18	19-Sep-18	34	283	59	8.32	1.74	10.06	17.25%
19-Sep-18	26-Oct-18	37	348	181	9.41	4.89	14.30	34.22%
26-Oct-18	21-Nov-18	26	213	487	8.19	18.73	26.92	69.57%
21-Nov-18	24-Dec-18	33	396	537	12.00	16.27	28.27	57.56%
24-Dec-18	11-Jan-19	18	275	42	15.27	2.34	17.62	13.31%
21-Dec-17	24-Dec-18	368	3194	3407	8.68	9.26	17.94	51.61%

Table 3.21 Peak and off-peak consumption for control household C-11

Assessment of the performance of individual battery systems

Household T-01

The number or residents in household T-01 at the time of the final interview was 3, with 2 children in full time education and an adult working part time. In the year before the start of the project, between 30 Nov 16 and 1 Dec 17, the annual electricity consumption was 11,910 kWh, which equates to £1,571 with a standardized Economy 7 tariff. The percentage of off-peak consumption was 43.7% (table 3.22). In previous years this was 38.8 and 51%. The mean annual consumption for domestic electricity meters in the same postcode was 9,327 kWh using 2015 data.[43]

For a Profile 2 electricity meter, Ofgem classed a household with a Typical Domestic Consumption Value (TDCV) of 7,100kWh/year as a high electricity consumer[44]. This corresponds to the 75th percentile in the distribution of meter consumption values. A household with a consumption of 11,000 kWh/year (below household T-01) is in the 90th percentile of meter consumption values. This means that only 10% of Profile 2 electricity meters have a higher annual consumption.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
21-Oct-14	30-Oct-15	374	7602	4815	20.33	12.87	33.20	38.78%
30-Oct-15	30-Nov-16	397	7073	7353	17.82	18.52	36.34	50.97%
30-Nov-16	01-Dec-17	366	6705	5205	18.32	14.22	32.54	43.70%

Table 3.22 Electricity consumption of Household T-01 from electricity meter readings before battery installation.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
30-Nov-16	02-Mar-17	92	2506	2053	27.24	22.32	49.55	45.03%
02-Mar-17	14-May-17	73	1570	1200	21.51	16.44	37.95	43.32%
14-May-17	15-Aug-17	93	985	617	10.59	6.63	17.23	38.51%
15-Aug-17	01-Dec-17	108	1644	1335	15.22	12.37	27.59	44.82%
01-Dec-17	04-Apr-18	124	3223	3161	25.99	25.49	51.48	49.51%
04-Apr-18	18-Jan-19	289	1399	5783	4.84	20.01	24.85	80.52%

Table 3.23 Electricity consumption of Household T-01 from electricity meter readings.

Table 3.23 shows the approximately quarterly electricity consumption prior to the start of the project. The average daily consumption for the winter quarters was 49.6 and 51.5 kWh/day. In both these winter quarters, the peak rate consumption was greater than the off-peak consumption. The summer quarter from May-Aug 17 had a total daily consumption of 17.2 kWh/day, which was about a third of the winter time daily consumption. The percentage of off-peak consumption was between 38.5 and 49.5% for the periods between Nov 16 and Apr 18 in table 3.23.

The Tesla Powerwall 2 battery was fitted on 24 Jan 18 and was operational from 23 Mar 18 once the update to the Tesla software was available which allowed grid charging. There were limited

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[43] Postcode level electricity estimates 2015 (experimental) https://www.gov.uk/government/statistics/postcode-level-electricity-estimates-2015-experimental (Accessed 12 Feb 19)

[44] Typical Domestic Consumption Values for gas and electricity (Ofgem, 22 June 17) https://www.ofgem.gov.uk/system/files/docs/2017/08/tdcvs_2017_open_letter.pdf (Accessed 8 Feb 19)

meter readings available for this household as the meter was hard to read and the energy company did not appear to regularly record meter readings when the pre-payment meter was topped up. Between 4 Apr 18 and 18 Jan 19, 80.5% of the consumption was off peak. The previous period with highest off peak consumption was 30 Oct 15 to 30 Nov 16, with 51% off peak consumption. The average peak rate consumption between 4 Apr 18 and 18 Jan 19 had decreased to 4.84 kWh/day. This was less than half that of the next lowest value of 10.59 kWh/day in the summer quarter between 14 May 17 and 15 Aug 17.

The average off-peak consumption between 4 Apr 18 and 18 Jan 19 was 20.0 kWh/day. This was lower than for winter quarters in 2016/17 and 2017/18, but higher than the spring, summer and autumn quarters for 2017. The average total consumption of 24.9 kWh/day was lower than for the annual values in table 3.22. The cold period of mid-January to April with high electricity consumption was not included in the post installation consumption and the average value was lower as a result.

The property had 3 older Dimplex storage heaters downstairs. These were only used during the coldest periods in the middle of winter. There were 2 panel heaters upstairs that were never used. Instead the household used 3 thermostatically controlled oil filled electric radiators 24 hours a day during winter. 2 of the radiators were rated at 1,500W with the other at 2,500W.

The household had a higher than average baseload electricity consumption. There was a large American style fridge-freezer and similar models have an annual consumption of about 400 to 450 kWh/year. There was also a reptile tank with a 75W heat lamp operating permanantly and a large fish tank with a pump that was continuously operating.

The cooker had an electric hob and oven and was used after 6pm on 5 days and for Sunday lunch. The washing machine was used daily during peak rate times in the morning or evening. The tumble drier was used in the evening about 4 times per week. The residents used appliances when they were needed rather than scheduling them during the off peak period. The household had an electric shower and there were typically 14 showers per week and 5 baths.

The Tesla Powerwall 2 battery was fitted on the main household electrical circuit. Figure 3.24 shows the electrical consumption on this circuit before and after the battery was turned on.

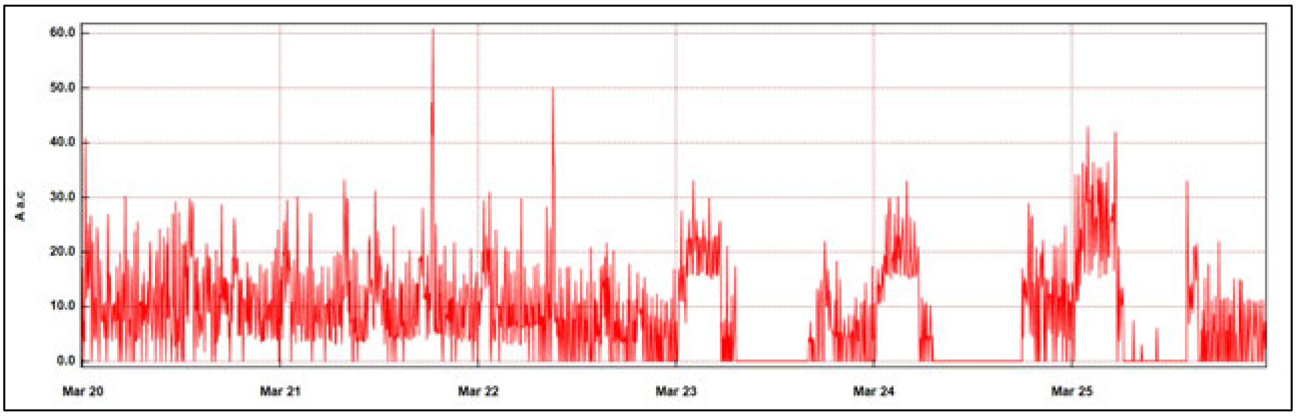


Figure 3.24 Consumption on main household electrical circuit for household T-01 between 20 Mar 18 and 26 Mar 18

Lower priced electricity was available on both the main and heating electrical circuits during the off peak period. There are however parts of the country where off peak electricity is only available on the heating circuit.

Prior to operation of the battery there were high levels of consumption both day and night due to use of the 3 oil-filled radiators. The peaks of about 50 and 60A were likely to be due to the electric shower. Once the Tesla Powerwall 2 battery started to operate, there was a clear drop in electricity consumption during the day.

On 23 Mar 18, the battery provided all the daytime consumption until 16:05 and the same happened on 24 Mar 18 until 18:00. The battery fitted at household T-01 had a grid connection which allowed it to provide up to 5kW of power. On 25 Mar 18, the battery became depleted at 14:00. For most of the time before that, the battery supplied all the power to the household. However, there were some times when the household demand exceeded 5kW and extra power was required from the grid. At 08:30 an additional 3.1A was required and at 10:20 a further 6.1A was provided by the grid.

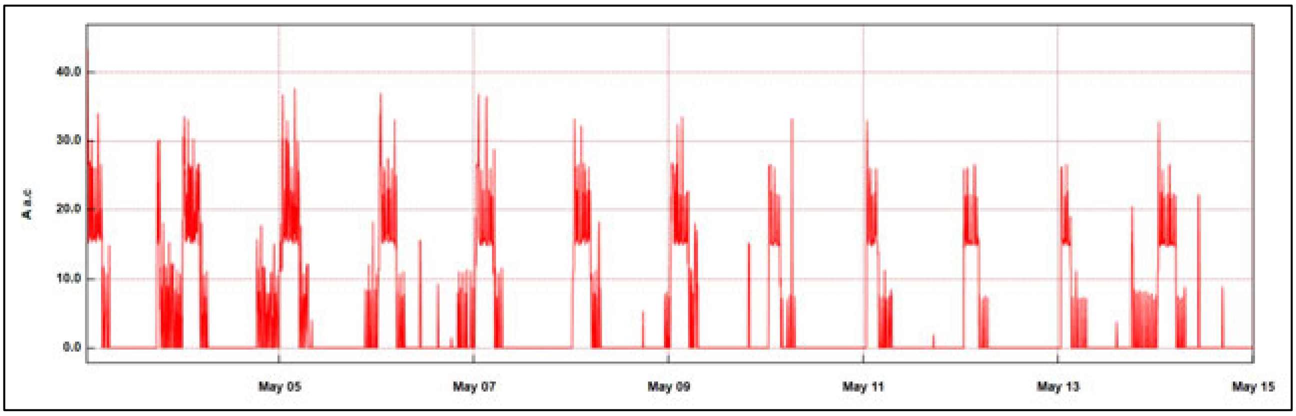
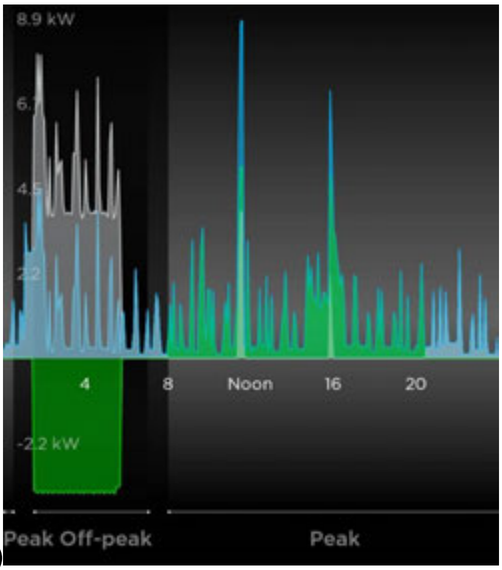


Figure 3.25 Consumption on main household electrical circuit for household T-01 between 3 May 18 and 15 May 18

(a)


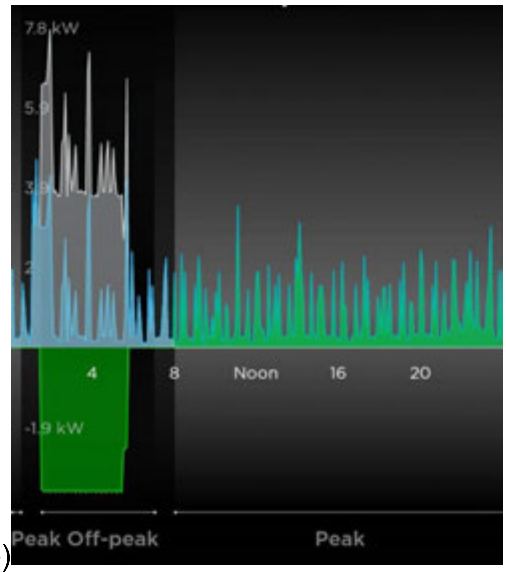
(b)


Figure 3.26(a) Tesla App screenshot for T-01 on 6 May 18

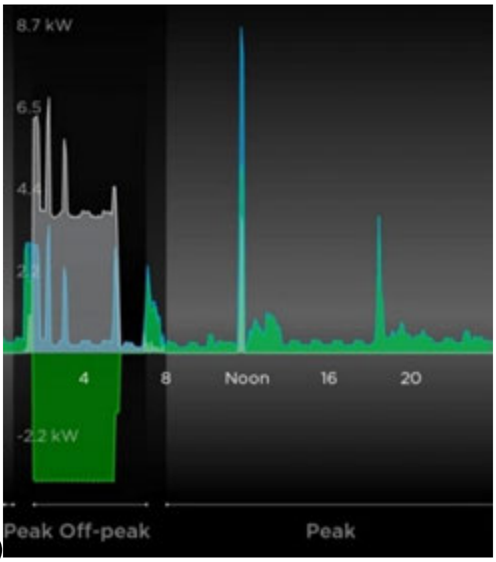
Figure 3.26(b) Tesla App screenshot for T-01 on 7 May 18

Figure 3.25 shows consumption on the main household electrical circuit in early May 2018. At the begining of the month, the battery was typically becoming depleted part way through the day. For example on 3 May and 4 May 18, the battery was fully discharged by 18:00 and 18:30 respectively. Later in the month, the battery was able to regularly power the household throughout the peak rate period apart from during times when the load exceeded 5kW.

Figure 3.26 (a) and (b) shows screen shots from the Tesla app. On 6 May 18, the battery became depleted at 20:00. Prior to that at near noon and 16:00, there were spikes in demand of 7 to 9 kW due to use of the electric shower. The Tesla battery provided 5 kW and the remaining power was imported from the grid, as shown by the 2 spikes in demand in the middle of the day on 6 May in figure 3.25. It is apparent from figure 3.26 (b) that the battery was able to supply power to household T-01 on 7 May 18 throughout the day. The household demand did not exceed 5 kW during this period and so no additional power was required from the grid before the battery recharged overnight. This can be seen in figure 3.25, where there were no additional consumption peaks on 7 May during the peak rate period.

There was a reduction in electricity demand for household T-01 during the summer, primarily because supplementary heating was no longer being used. The battery was typically able to power household T-01 throughout the peak rate period on summer days apart from times when the electric shower was used (figure 3.27 (a)). During the winter, the 3 oil filled electric radiators were left on throughout the day. Figure 3.27 (b) shows a screenshot from the Tesla app on a typical winter day. In this case the battery was fully depleted by 14:15.

(a)



(b)

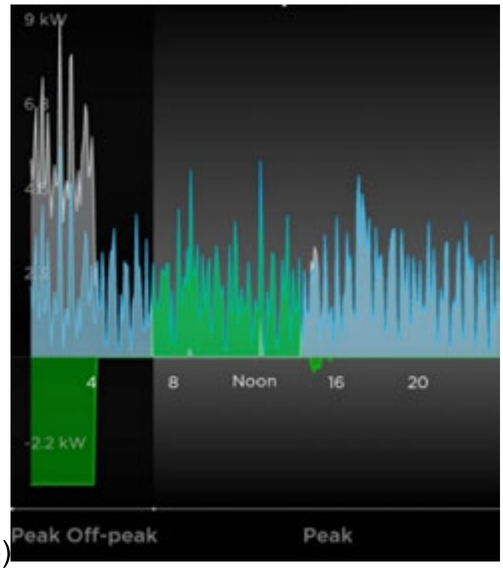


Figure 3.27(a) Tesla App screenshot for T-01 on 8 Jun 18

Figure 3.27(b) Tesla App screenshot for T-01 on 5 Jan 19

Monthly performance of the Tesla battery and electricity consumption for household T-01 as measured by the battery system is shown in table 3.28. Note that the battery imported more than it exported primarily due to inefficiencies in the inverter. This is illustrated by the battery round trip efficiency which ranged from 78.2 to 90.7%. As a resut, the site import was also greater than the household load due to the losses in the charge and discharge of the battery. The annual household consumption therefore increased due to installation of the battery, but savings were made because the battery imported the electricity during the cheaper off-peak rate. Between 1 Apr 18 and 31 Jan 19, the household load measured by the system was 7,267 kWh, while the site import was 7,788 kWh. The household consumption therefore increased by 521 kWh during this period due to inefficiencies in the charge/discharge of the battery. The cost of the extra import was £36.47, but overall there were savings due to increasing the amount of off peak rate consumption.

The total electricity consumption between 4 Apr 18 and 18 Jan 19 from meter readings in table 3.23 was 7182 kWh. The site import determined from the Tesla data for these dates was 7168 kWh. The difference was within the margin of error for the meter readings as the times they were taken differed. The error in the site import was about 0.2%.

The site import was above 1000 kWh/month in April, November, December and January. For these months the Tesla battery fully charged and discharged most days. This was indicated by the average battery export being 12.75 to 12.95 kWh/day out of a maximum of 13.5 kWh.

In June, July and August, the site import was under 500 kWh/month, which was less than half the values in April and November to January. Between June and October, the average battery export was 8.5 to 9.4kWh/day. This along with the screenshots shown earlier indicate that the battery was able to supply household T-01 throughout the day for most days in this period as it did not fully discharge.

The savings per month were calculated by multiplying the battery export by the peak rate tariff and subtracting the battery import multiplied by the off peak tariff. This took into account the inefficiencies of the charge discharge process. For the Technical Innovation Fund (TIF) projects standard tariff rates have been used for all installations on all projects. The rates for Economy 7 were 18p/kWh for peak rate and 7p/kWh for off peak rate.

For the months when the battery was fully discharging every day (Apr 18 and Nov 18 -Jan 19), the savings were £1.27 - £1.28 per day using the standard tariff rates. In the summer, when the battery was able to regularly power the home throughout the day and the battery did not fully discharge, the savings were between £0.77 and £0.94 per day. The total estimated savings between 1 Apr 18 and 31 Jan 19 were £328

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
01-Apr-18	01-May-18	388.47	445.73	1175.22	1115.97	12.95	14.86	39.17	37.20	87.2%	£1.29
01-May-18	01-Jun-18	341.84	376.86	611.37	574.49	11.03	12.16	19.72	18.53	90.7%	£1.13
01-Jun-18	01-Jul-18	271.69	322.82	446.87	399.30	9.06	10.76	14.90	13.31	84.2%	£0.88
01-Jul-18	01-Aug-18	290.23	327.98	443.08	403.70	9.36	10.58	14.29	13.02	88.5%	£0.94
01-Aug-18	01-Sep-18	262.46	332.38	455.27	391.73	8.47	10.72	14.69	12.64	79.0%	£0.77
01-Sep-18	01-Oct-18	259.56	331.75	558.97	494.24	8.65	11.06	18.63	16.47	78.2%	£0.78
01-Oct-18	01-Nov-18	353.75	434.69	764.64	706.79	11.41	14.02	24.67	22.80	81.4%	£1.07
01-Nov-18	01-Dec-18	384.90	436.39	1063.27	1014.09	12.83	14.55	35.44	33.80	88.2%	£1.29
01-Dec-18	01-Jan-19	398.27	460.98	1064.79	1011.69	12.85	14.87	34.35	32.64	86.4%	£1.27
01-Jan-19	31-Jan-19	382.38	430.68	1204.18	1154.88	12.75	14.36	40.14	38.50	88.8%	£1.29
Total		**3333.5**	**3900.3**	**7787.7**	**7266.9**						

Table 3.28 Battery performance and household consumption measured by the Tesla battery system for T-01

Household T-03

There were 2 adults in household T-03 and 2 school aged childen. 1 of the adults was working part time while the other had a chronic health condition and was unable to work. The annual electricity consumption from 18 Dec 16 to 18 Dec 17 was 13,952 kWh, with an average electricity consumption of 38.2 kWh/day as shown in table 3.29. The annual cost with standardized rates was £1,676. It should be noted that an annual consumption of 14,000 kWh is at the 95th percentile of the distribution of values for electricity consumption among Profile 2 electricity meters[45]. The mean electricity consumption in 2015 among all households in the same postcode was 8,451 kWh[46]. Between 18 Dec 16 and 18 Dec 17, the percentage off-peak consumption was 54.5%. The previous year, it was only marginally higher at 55.5%.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
30-Nov-15	18-Dec-16	384	5688	7083	14.81	18.45	33.26	55.46%
18-Dec-16	18-Dec-17	365	6355	7597	17.41	20.81	38.22	54.45%

Table 3.29 Electricity consumption of Household T-03 before battery installation from electricity meter readings.

Table 3.30 shows approximately monthly consumption values before (shaded lighter) and after the battery was operational on 23 Mar 18. The average daily consumption in Jan 18 to Mar 18 was in the range 55 to 63 kWh/day. The percentage off peak use was 66.4% to 70.3%, which was higher than the rest of the year due to use of the night storage heaters. In the first few days after the battery became operational, the average peak rate consumption fell from 18.7 kWh/day to 5.9 kWh/day while the percentage of off-peak consumption increased from 70.3% to 89%.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
02-Jan-18	01-Feb-18	30	554.7	1094	18.49	36.47	54.96	66.36%
01-Feb-18	26-Feb-18	25	544.3	1106	21.77	44.24	66.01	67.02%
26-Feb-18	21-Mar-18	23	430	1018	18.70	44.26	62.96	70.30%
23-Mar-18	01-Apr-18	9	53	430	5.89	47.78	53.67	89.03%
01-Apr-18	01-May-18	30	213	1167	7.10	38.90	46.00	84.57%
01-May-18	29-May-18	28	109	601	3.89	21.46	25.36	84.65%
29-May-18	02-Jul-18	34	95	635	2.79	18.68	21.47	86.99%
02-Jul-18	28-Jul-18	26	51	374	1.96	14.38	16.35	88.00%
28-Jul-18	27-Aug-18	30	128	665	4.27	22.17	26.43	83.86%
27-Aug-18	19-Sep-18	23	105	475	4.57	20.65	25.22	81.90%
19-Sep-18	15-Oct-18	26	96	590	3.69	22.69	26.38	86.01%
15-Oct-18	25-Nov-18	41	174	1625	4.24	39.63	43.88	90.33%
25-Nov-18	15-Dec-18	20	101	932	5.05	46.60	51.65	90.22%
15-Dec-18	10-Jan-19	26	152	1312	5.83	50.45	56.28	89.64%
10-Jan-19	31-Jan-19	21	85	1122	4.07	53.45	57.51	92.93%

Table 3.30 Electricity consumption of Household T-03 from electricity meter readings.

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45 Typical Domestic Consumption Values for gas and electricity (Ofgem, 22 June 17) https://www.ofgem.gov.uk/system/files/docs/2017/08/tdcvs_2017_open_letter.pdf (Accessed 8 Feb 19)

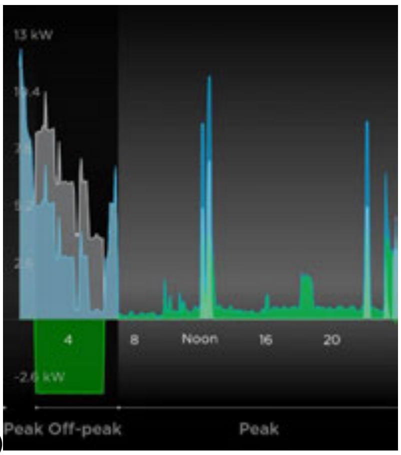
46 Postcode level electricity estimates 2015 (experimental) https://www.gov.uk/government/statistics/postcode-level-electricity-estimates-2015-experimental (Accessed 12 Feb 19)

During the period of monitoring, the percentage of off peak consumption ranged from 81.9% to 92.9%, significantly greater than the annual and monthly percentages before the battery was operational. In Jan 18, before the battery was running, the average peak rate consumption was 18.5 kWh/day. This decreased to 4.1 kWh/day in Jan 19 with the battery operational. The percentage off-peak consumption had increased from 66.4% to 92.9% for the same months.

The household used storage heaters in the dining room and stairwell on a daily basis between September and April. The living room was heated by an open fire during the winter. 2 smaller storage heaters in the bedrooms were only used on the coldest days. The household typically used their dish washer, washing machine and/or tumble drier overnight. To avoid possible issues of the household demand being too close to the supply rating, the battery off peak period was set to 2am. This was a couple hours later than the start of Economy 7 in winter and an hour later in summer. This ensured the peaks in heating demand had been passed by the time the battery started charging.

Figure 3.31 (a) shows an image from the Tesla app on 26 Dec 18, with a sharp drop in electrical heating demand between midnight and 2 am after which the battery starts to charge. There were peaks in household demand at about noon and 10pm of 9 to 11 kW due to use of the electric shower. There were typically 15 showers a week and 2 baths. The battery was only able to supply up to about 4 kW of the household demand from the battery (figure 3.31 (b)), with the additional power supplied by the grid. There are peaks of 1 - 2 kW at 10am and 4pm shown on the Tesla app image. The Verv data logger with monitoring every second shows that these and other peaks were up to 3 kW. These were most likely due to a kettle running for a couple minutes.

During January 2019, Tesla updated their system to allow a variable rate of battery charging. The system monitors the household load and can reduce the battery charge rate if the household consumption approaches a set limit.

(a)


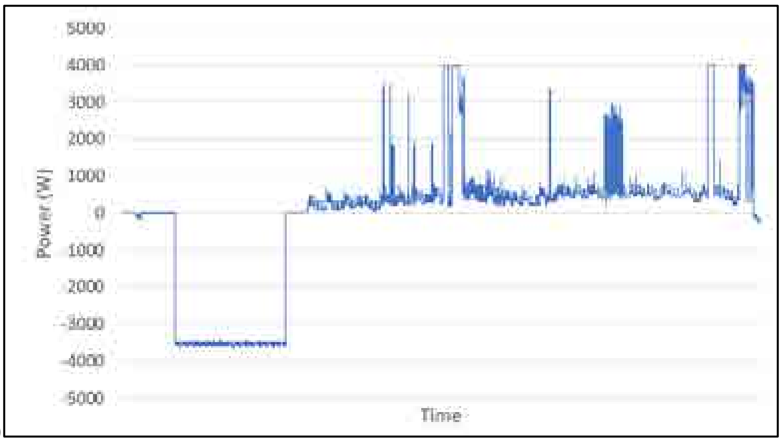
(b)


Figure 3.31 (a) Tesla App screenshot for T-03 on 26 Dec 18 showing power against time

Figure 3.31 (b) Plot of battery charge / discharge for T-03 on 26 Dec 18 measured by a Verv data logger

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
01-Apr-18	01-May-18	387.06	461.36	1314.23	1247.43	12.90	15.38	43.81	41.58	83.9%	£1.25
01-May-18	01-Jun-18	398.19	441.65	772.19	725.54	12.84	14.25	24.91	23.40	90.2%	£1.31
01-Jun-18	01-Jul-18	354.40	414.73	645.07	588.54	11.81	13.82	21.50	19.62	85.5%	£1.16
01-Jul-18	01-Aug-18	369.10	416.46	651.89	601.82	11.91	13.43	21.03	19.41	88.6%	£1.20
01-Aug-18	01-Sep-18	335.85	384.20	704.33	653.33	10.83	12.39	22.72	21.08	87.4%	£1.08
01-Sep-18	01-Oct-18	342.98	389.96	732.12	682.13	11.43	13.00	24.40	22.74	88.0%	£1.15
01-Oct-18	01-Nov-18	366.46	416.92	1060.38	1007.16	11.82	13.45	34.21	32.49	87.9%	£1.19
01-Nov-18	01-Dec-18	377.48	426.87	1438.20	1386.18	12.58	14.23	47.94	46.21	88.4%	£1.27
01-Dec-18	01-Jan-19	383.88	460.33	1666.31	1593.21	12.38	14.85	53.75	51.39	83.4%	£1.19
01-Jan-19	31-Jan-19	377.68	429.54	1721.25	1667.72	12.59	14.32	57.38	55.59	87.9%	£1.26
Total		**3693.1**	**4242.0**	**10706.0**	**10153.1**						

Table 3.32 Battery performance and household consumption measured by the Tesla battery system for T-03

Table 3.32 shows the battery performance and household electricity consumption recorded by the Tesla battery system. Between 1 Apr 18 and 31 Jan 19, the Tesla system measured the site import to be 10,706 kWh. This compares with 10,807 kWh measured between these dates by meter readings, which equates to an error of less than 1%.

The monthly site import was higher than for household T-01 in all the months studied and the difference was as high as 601 kWh in Dec 18. A factor in this was that the residents at household T-03 did not go on holiday during the study period and someone was usually in the house.

The household load was 10,153 kWh between 1 Apr 18 and 31 Jan 19 and so the losses from the charge/discharge cycles of the battery caused an increase in site import of 553 kWh. This compares to 521 kWh for household T-01 between the same dates.

The average battery export ranged from 10.83 kWh/day in Aug 18 to 12.9 kWh/day in Apr 18. As a result of the peak rate household demand being large throughout the year, the battery was likely to discharge all or most of its usable capacity. This meant the average savings from the battery were close to the maximum throughout the year. These ranged from £1.08/day in Aug 18 to £1.31/day in May 18 using the standard tariff rates of 18p/kWh peak rate and 7p/kWh off peak rate. Overall, between 1 Apr 18 and 31 Jan 19, the total savings were £367.81.

Household T-05

There were 4 adults living at household T-05, with 1 resident not working due to a chronic health condition. The electricity consumption between 7 Mar 17 and 8 Mar 18 for household T-05 was 7,402 kWh with an electricity cost of £950. The annual consumption was significantly lower than the amount for households T-01 and T-03, but household T-05 is still classed as a high electricity user according to the Ofgem Typical Daily Consumption Values (TCDVs). In the year, before the battery was operational, the percentage of off-peak consumption was 47%.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
14-Jun-15	06-Jun-16	358	4541	3776	12.68	10.55	23.23	45.40%
06-Jun-16	19-Apr-17	317	4033	3138	12.72	9.90	22.62	43.76%
07-Mar-17	08-Mar-18	366	3923	3479	10.72	9.51	20.22	47.00%

Table 3.33 Electricity consumption of Household T-05 from electricity meter readings prior to battery operation.

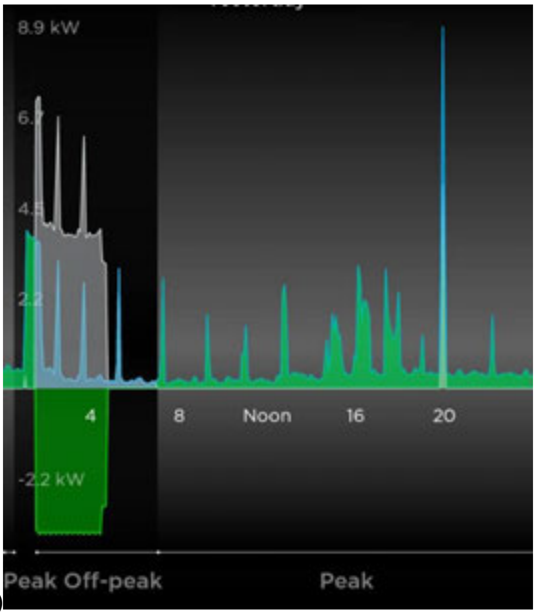
Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
07-Apr-18	06-May-18	29	86	470	2.97	16.21	19.17	84.53%
06-May-18	02-Jun-18	27	31	504	1.15	18.67	19.81	94.21%
02-Jun-18	05-Jul-18	33	48	571	1.45	17.30	18.76	92.25%
05-Jul-18	01-Aug-18	27	33	469	1.22	17.37	18.59	93.43%
01-Aug-18	01-Sep-18	31	38	617	1.22	19.91	21.12	94.24%
01-Sep-18	26-Sep-18	25	23	388	0.93	15.52	16.45	94.34%
26-Sep-18	24-Oct-18	28	49	540	1.75	19.29	21.04	91.68%
24-Oct-18	18-Nov-18	25	72	527	2.88	21.08	23.96	87.98%
18-Nov-18	19-Dec-18	31	114	801	3.68	25.84	29.52	87.55%
19-Dec-18	10-Jan-19	22	65	517	2.95	23.52	26.47	88.85%
10-Jan-19	31-Jan-19	21	106	407	5.04	19.40	24.44	79.39%

Table 3.34 Electricity consumption of Household T-05 from electricity meter readings after battery was running.

Table 3.34 shows approximately monthly meter readings for household T-05. The percentage of off-peak consumption with the battery ranged from 79.4% to 94.3%. As would be expected, after the battery was operational, the average peak rate consumption decreased. This ranged from 0.93 kWh/day to 5.04 kWh/day between Apr 18 and Jan 19 compared to an average of 10.72 kWh/day over the previous year. The off-peak consumption was 9.5 kWh/day over the previous year and this increased to between 15.5 and 25.8 kWh/day over the months after the battery was operational.

The household had a multifuel stove in the living room which they used daily on winter evenings. Their use of storage and panel heaters was more limited as a result. The storage heaters in the living room and on the landing were used during colder winter periods. A bedroom panel heater was used nightly in winter, but other heaters were rarely if ever used.

There was an 8.5kW electric shower and during a typical week there would be 12 showers and 6 baths. The washing machine was used every morning and the tumble drier was used in the evening during the winter, with clothes dried outside in summer. The household did not have a dishwasher, but there was a fridge-freezer and a separate freezer (estimated annual consumption of 217 kWh/year). The electric cooker had a hob and fan assisted oven which were used daily.

(a) 

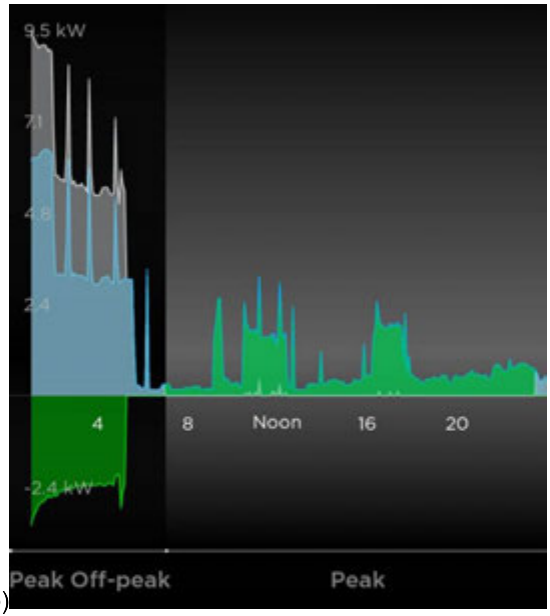
(b) 

Figure 3.35(a) Tesla App screenshot for T-05 on 7 May 18

Figure 3.35(b) Tesla App screenshot for T-05 on 23 Dec 18

Figure 3.35 (a) shows an example of a screenshot from the Tesla app on a spring day when no heating was required. The immersion heater for the hot water cylinder ran for about an hour overnight, followed by a further 3 short heating periods to maintain the water temperature. The battery charged at a fairly constant rate of about 3.7kW between about 01:00 and 05:00 and was able to supply power to the household from 07:00 until the next day. There was a shower at 20:00 and the electricity demand rose to 8.9 kW. Only a proportion of this power could be supplied by the battery (about 3.7kW), with the rest imported from the grid. At other times during the day the electricity demand was below 3.7kW and the battery could supply all the power required.

Figure 3.35 (b) illustrates the battery charge/discharge and household consumption on 23 Dec 18. Due to the colder weather, a 2.5kW Creda TSR18ACW storage heater was likely to be running overnight as well as the immersion for the hot water cylinder. The Tesla battery showed a variable rate of charging overnight and similar behaviour was noted with this battery from the end of May 2018. Such variable charging has been seen in the past with batteries located in a warmer environment and it is less efficient to charge rapidly[47]. This installation was fitted in a cooler utility room and so was unlikely to be overheated. The cause of the variable charging was therefore unclear. The battery supplied all the power to the household until the battery was depleted at about 23:30. The peak of up to 3 kW at about noon may have been due to the washing machine and from 16:00 to 18:00 may have been from cooking. During Dec 18 and Jan 19, there were days when the battery was fully discharged by mid evening and others when it was able to provide power throughout the day.

Table 3.36 shows battery performance and electricity consumption for household T-05 as measured by the Tesla battery system. Between 7 Apr 18 and 10 Jan 19, the household electricity import measured by the utility meter was 5,964 kWh. The battery system measured the household import as 5,926 kWh, which corresponds to an error of less than 1%.

[47] Personal Communication, Chris Penders, Powerwall Account Manager, Tesla UK, 8 Aug 18

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
01-Apr-18	01-May-18	272.29	310.36	563.40	522.80	9.08	10.35	18.78	17.43	87.7%	£0.91
01-May-18	01-Jun-18	332.43	366.25	600.18	563.55	10.72	11.81	19.36	18.18	90.8%	£1.10
01-Jun-18	01-Jul-18	317.24	361.90	572.24	525.05	10.57	12.06	19.07	17.50	87.7%	£1.06
01-Jul-18	01-Aug-18	340.36	379.45	565.82	523.93	10.98	12.24	18.25	16.90	89.7%	£1.12
01-Aug-18	01-Sep-18	327.59	371.20	559.31	512.61	10.57	11.97	18.04	16.54	88.3%	£1.06
01-Sep-18	01-Oct-18	335.78	380.23	590.22	543.26	11.19	12.67	19.67	18.11	88.3%	£1.13
01-Oct-18	01-Nov-18	362.98	407.32	676.83	633.15	11.71	13.14	21.83	20.42	89.1%	£1.19
01-Nov-18	01-Dec-18	366.15	411.94	749.52	699.26	12.21	13.73	24.98	23.31	88.9%	£1.24
01-Dec-18	01-Jan-19	355.84	407.00	905.78	855.77	11.48	13.13	29.22	27.61	87.4%	£1.15
01-Jan-19	29-Jan-19	316.25	364.59	691.06	640.66	11.29	13.02	24.68	22.88	86.7%	£1.12
Total		3326.9	3760.2	6474.4	6020.0						

Table 3.36 Battery performance and household consumption measured by the Tesla battery system for T-05

Between 1 Apr 18 and 29 Jan 19, the household import was 6,474 kWh while the household load was 6,020 kWh. The difference of 454 kWh was due to losses in the inverter and self-consumption of the battery. The average load was more consistent throughout the year for household T-05 than for T-01 or T-02. It ranged from 16.5 kWh/day in Aug 18 to 27 kWh/day in Dec 18. For comparison the average loads were 12.6 – 38.5 kWh/day for T-01 and 19.4 to 55.6 kWh/day for T-03.

The average battery export was typically in the range 10.6 to 12.2 kWh/day. In Apr 18, the export was lower at 9.1 kWh/day. In Apr 18, the average savings were £0.91/day, but for other months they were between £1.06 and £1.24 kWh/day. The total savings from Apr 18 to Jan 19 were £336.

Household T-06

Household T-06 lived in a semi-detached property which was built in 1947. There were 2 adults working full time and 4 school-aged children. As a result, there was typically limited consumption between 08:00 and 16:00 on school days. Table 3.37 shows household electricity consumption before the Tesla Powerwall 2 battery was fitted. In the previous year, the average daily consumption was 36.2 kWh/day, which equates to an annual consumption of 13,224 kWh. This shows that household T-06 was a particularly high electricity consumer, along with households T-01 and T-03. The annual cost of the electricity was £1,417 using a standardized Economy 7 tariff.

Over periods of about a year, the percentage off peak consumption was between 56.2% and 66.6%. Table 3.38 shows that in the first 3 months of 2018, before the battery was operational, the percentage off peak consumption was in the range 69.4% to 71.7%. This was higher than the annual average due to off-peak charging of the storage heaters during the winter.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
05-Dec-14	24-Dec-15	384	5459	10870	14.22	28.31	42.52	66.57%
24-Dec-15	22-Dec-16	364	4786	6134	13.15	16.85	30.00	56.17%
22-Dec-16	08-Jan-18	382	4674	9166	12.24	23.99	36.23	66.23%

Table 3.37 Electricity consumption of Household T-06 from electricity meter readings.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
08-Jan-18	01-Feb-18	24	405	918	16.88	38.25	55.13	69.39%
01-Feb-18	09-Mar-18	36	661	1725	18.36	47.92	66.28	72.30%
09-Mar-18	04-Apr-18	26	398	1007	15.31	38.73	54.04	71.67%
04-Apr-18	07-May-18	33	95	1188	2.88	36.00	38.88	92.60%
07-May-18	02-Jun-18	26	67	481	2.58	18.50	21.08	87.77%
02-Jun-18	01-Jul-18	29	57	524	1.97	18.07	20.03	90.19%
01-Jul-18	28-Aug-18	58	159	1077	2.74	18.57	21.31	87.14%
28-Aug-18	28-Sep-18	31	108	601	3.48	19.39	22.87	84.77%
28-Sep-18	27-Oct-18	29	113	622	3.90	21.45	25.34	84.63%
27-Oct-18	26-Nov-18	30	161	1183	5.37	39.43	44.80	88.02%
26-Nov-18	29-Dec-18	33	223	1411	6.76	42.76	49.52	86.35%
29-Dec-18	01-Feb-19	34	305	1716	8.97	50.47	59.44	84.91%

Table 3.38 Electricity consumption of Household T-06 from electricity meter readings.

The percentage off-peak consumption increased from 71.7% in March 18 to 92.6% in April 18 once the battery was running. The average peak rate consumption decreased from 15.31 kWh/day to 2.9 kWh/day. There was also a small decrease in the off-peak consumption between these months from 38.7 to 36.0 kWh/day. Although the battery was now charging overnight, there was less consumption from the storage heaters as the weather became warmer, which accounted for the small decrease. Over the period of testing, the monthly average peak rate consumption was between 1.97 and 8.97 kWh/day compared to 18.4 kWh/day in Feb 18 before the battery was operational.

A table summarising the battery performance and household consumption data recorded by the Tesla system is shown in table 3.39. The battery system measured the site import to be 8,725 kWh between 4 Apr 18 and 31 Jan 19. However, the grid import recorded by the utility meter was 10,091 kWh between 4 Apr 19 and 1 Feb 19. The reason for this significant difference was due to the installer initially fitting the battery current clamp only around the main household electrical circuit. In Jul 18 the installer returned and fitted a Y-splitter cable which enabled the system to measure the consumption of both the main and heating circuits. Between 20 Aug 18 and 1 Feb 19, the grid consumption based on meter readings was 6,668 kWh compared to 6,502 kWh measured by the Tesla system on 20 Aug 18 to 31 Jan 19. The difference in these values was 2.5% which can be partially explained an extra day of consumption with the utility meter reading.

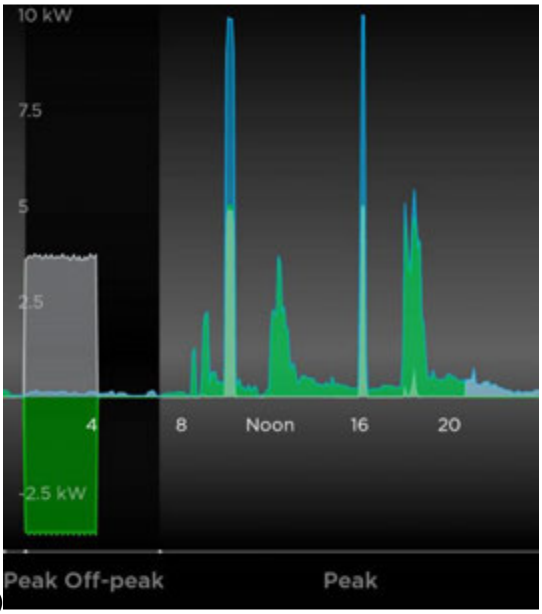
Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
04-Apr-18	01-May-18	225.01	272.82	419.30	369.34	8.33	10.10	15.53	13.68	82.5%	£0.79
01-May-18	01-Jun-18	283.37	311.10	450.24	420.21	9.14	10.04	14.52	13.56	91.1%	£0.94
01-Jun-18	01-Jul-18	270.32	315.12	442.74	399.83	9.01	10.50	14.76	13.33	85.8%	£0.89
01-Jul-18	01-Aug-18	313.59	362.87	506.97	455.10	10.12	11.71	16.35	14.68	86.4%	£1.00
01-Aug-18	01-Sep-18	366.12	422.21	705.28	646.94	11.81	13.62	22.75	20.87	86.7%	£1.17
01-Sep-18	01-Oct-18	350.64	401.48	675.07	621.75	11.69	13.38	22.50	20.73	87.3%	£1.17
01-Oct-18	01-Nov-18	359.16	415.49	863.54	804.70	11.59	13.40	27.86	25.96	86.4%	£1.15
01-Nov-18	01-Dec-18	373.37	428.32	1348.56	1291.21	12.45	14.28	44.95	43.04	87.2%	£1.24
01-Dec-18	01-Jan-19	353.79	431.87	1545.77	1469.16	11.41	13.93	49.86	47.39	81.9%	£1.08
01-Jan-19	31-Jan-19	375.81	431.24	1767.80	1710.94	12.53	14.37	58.93	57.03	87.1%	£1.25
Total		**3271.2**	**3792.5**	**8725.3**	**8189.2**						

Table 3.39 Battery performance and household consumption measured by the Tesla battery system for T-06

The savings ranged from £0.79/day when the average battery export was at its lowest (8.3 kWh/day) to £1.25/day in Jan 19 when the battery capacity was fully used most days. Over the period between 4 Apr 18 and 31 Jan 19, the total savings were £323.

In order to accurately measure the household consumption, it is important that the current clamp measures both the main and heating electrical circuits. This is also important if the battery is to vary the rate of charging should the total household demand approach the supply limit.

The site import in table 3.39 went up significantly from Aug 18 once all the water heating demand and was recorded by the Tesla system. Use of the storage heaters from Nov 18 caused a further large increase in site import, reaching 1768 kWh during Jan 19.

(a)


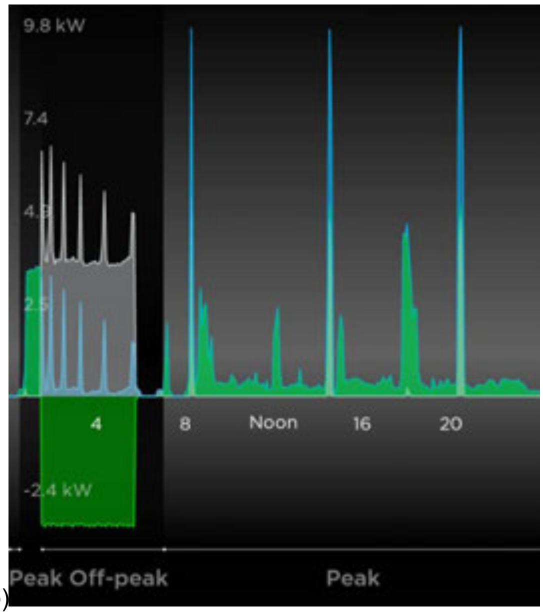
(b)


Figure 3.40(a) Tesla App screenshot for T-06 on 14 Apr 18

Figure 3.40(b) Tesla App screenshot for T-06 on 21 Jul 18

Figure 3.40(a) shows a screenshot from the Tesla app for household T-06 on 14 Apr 18. Apart from the battery charging overnight, there was only the baseload electricity consumption of appliances like fridges. On 21 Jul 18 after the Y-splitter cable was fitted, the characteristic consumption pattern of the immersion heater was apparent overnight, with about an hour of heating on full power followed by short bursts to maintain the temperature.

Electricity consumption peaks of about 10 kW due to the electric shower can be seen in both Figure 3.40 (a) and (b). The battery was able to provide about 5 kW of this power due having a G59 grid connection. When the Tesla Powerwall 2 battery is permitted to export 5 kW, a charged battery is typically able to fully power the household apart from when running an electric shower or multiple appliances.

With 6 residents, household T-06 had a high water heating demand. During an average week, the household would have about 30 showers and 3 baths. They alternated between using the immersion heater overnight and the boost during the day. During the project they bought a dishwasher which now runs every evening and has reduced hot water demand from the cylinder.

The washing machine is used daily during the day and the tumble drier is used daily in winter in the morning or at night. The electric cooker is used daily between 16:30 and 19:00. There is a fridge-freezer as well as a smaller separate fridge and freezer.

The property has draughty windows and doors. An open fire is used in the living room on winter evenings and weekends. The storage heaters in the dining room and hall are used between October and March, with a further heater in the living room only used on the coldest winter days. There are panel heaters in the 3 bedrooms which are used in the evening for about 15 – 30 mins.

(a) (b)

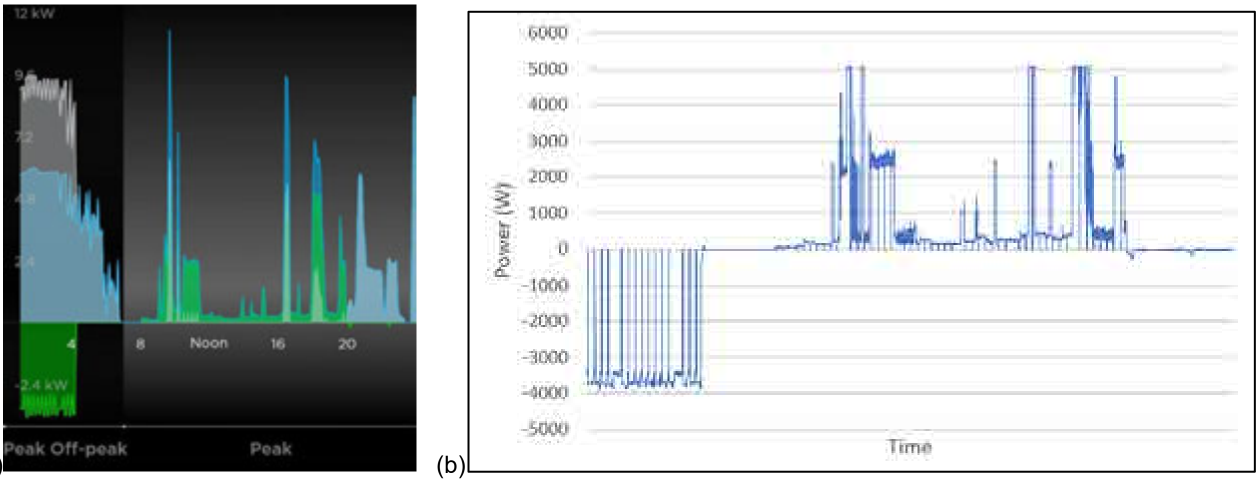


Figure 3.41 (a) Tesla App screenshot for T-06 on 4 Jan 19 showing power against time

Figure 3.41 (b) Plot of battery charge / discharge for T-06 on 4 Jan 19 measured by a Verv data logger

The Tesla app screenshot in figure 3.41(a) for 4 Jan 19 includes the overnight consumption from the storage heaters. It is likely the 3.4 kW Dimplex CXL24N in the Hall and the 2.25 kW Creda TSR18MW in the Dining room were running and caused the broad overnight consumption peak.

Figure 3.41 (b) shows a plot of charge and discharge of the battery on the same day using data recorded every second by a Verv data logger. Overnight the battery was typically charging at 3.45 to 3.68 kW. However periodically, the charging stopped for about a minute. There were at least 3 showers during the day and the Verv data plot shows the battery provided up to 5 kW. The battery became depleted at 20:00 and there was no further discharge after that time on the Verv data plot.

The consumption pattern of household T-06 was characterised by a number of high peaks in consumption on most days, typically caused by the electric shower. However other peaks were caused by secondary heating and cooking. Between 09:00 and 16:00 during the week, the consumption was typically lower when residents were at work and school. At weekends and during holidays, there tended to be more strong peaks in consumption during the day

Household T-07

The installation with household T-07 proved problematic. The resident was very difficult to contact by phone and was often out when visits had been agreed and confirmed in writing. This happened for the initial survey and the first attempt to install the battery. It was also not possible to organise a visit for the initial or final interview.

It was discovered that the household had switched electricity supplier on 5 Apr 18 before the battery started charging and discharging on 13 Apr 18. During this process, the new supplier fitted a new smart meter and switched the household from Economy 7 to a single rate tariff. It is likely the resident had been concerned about the high cost of running the night storage heaters.

Due to the switch from Economy 7, there was no benefit to the household from the battery charging overnight and discharging during the day as the cost of the electricity did not vary during the 24 hour period. Also, there were losses during the charge/discharge cycle, so the battery was increasing the consumption (and cost) to the household.

Details of the project had been explained to the household and the operation with Economy 7 was described in the leaflet in Appendix 2 that was provided during household recruitment. Numerous attempts were made to contact the resident after this issue was discovered by NEA staff in Aug 18. An external energy advisor was scheduled to visit in Dec 18, but the resident was again absent. Letters were sent by NEA staff offering advice in December and January while trying to arrange the visit for the final interview. No response was received, and the resident was unavailable at the time of other visits due to health issues. Further attempts will be made to contact this resident and if necessary, the battery may be removed and reinstalled elsewhere.

Prior to the battery running, between 1 Apr 17 and 31 Mar 18, the electricity consumption of household T-07 was 8,949 kWh. Using standardized tariffs of 18p/kWh for peak and 7p/kWh for off peak, the cost was £1,437 with 17.7% off peak. If the consumption had been charged at a single rate standardized tariff of 16p/kWh, the cost would have been £1,432.

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
14-Apr-18	01-May-18	206.20	245.92	422.94	381.90	12.13	14.47	24.88	22.46	83.8%	£1.17
01-May-18	01-Jun-18	378.73	412.27	546.24	510.52	12.22	13.30	17.62	16.47	91.9%	£1.27
01-Jun-18	01-Jul-18	368.46	417.41	605.61	554.77	12.28	13.91	20.19	18.49	88.3%	£1.24
01-Jul-18	01-Aug-18	359.89	401.59	586.08	542.72	11.61	12.95	18.91	17.51	89.6%	£1.18
01-Aug-18	01-Sep-18	374.92	424.57	648.25	596.80	12.09	13.70	20.91	19.25	88.3%	£1.22
01-Sep-18	01-Oct-18	369.08	412.82	763.14	717.56	12.30	13.76	25.44	23.92	89.4%	£1.25
01-Oct-18	01-Nov-18	381.95	430.55	1003.22	952.87	12.32	13.89	32.36	30.74	88.7%	£1.25
01-Nov-18	01-Dec-18	355.32	401.76	860.39	812.40	11.84	13.39	28.68	27.08	88.4%	£1.19
01-Dec-18	01-Jan-19	369.51	431.82	891.49	844.94	11.92	13.93	28.76	27.26	85.6%	£1.17
01-Jan-19	31-Jan-19	359.59	408.68	829.11	779.03	11.99	13.62	27.64	25.97	88.0%	£1.20
Total		**3523.6**	**3987.4**	**7156.5**	**6693.5**						

Table 3.42 Battery performance and household consumption measured by the Tesla battery system for T-07

Table 3.42 shows the battery performance and household electricity consumption for T-07 after the battery became operational on 14 Apr 18. The site import until 31 Jan 19 was 7,156 kWh while the household load was 6,693 kWh which meant the household consumed 463 kWh **extra** energy due to the battery. As the battery was on a single rate tariff and only charging from the grid, the extra cost of the battery running was £74.08, assuming a single tariff rate of 16p/kWh.

The household load ranged from 16.5 kWh/day in May 18 to 30.7 kWh/day in Oct 18. Figure 3.43 (a) shows a Tesla app screenshot with the household consumption on 13 Aug 18. In early August, there was a typically a high baseload consumption of 400 – 600W. There were several sharp peaks in consumption overnight which may have been due to water heating. There were larger peaks of about 3.6 kW at 18:00 (perhaps due to cooking) and at 22:45. On 13 Aug 18, the battery was able to fully power the household through what had been the day-time peak period. The battery had a G59 grid connection and so was able to provide up to 5 kW of power.

Figure 3.43 (b) shows a Tesla app screenshot for 23 Dec 18. It is apparent there was no storage heater consumption recorded overnight by the Tesla battery system. The daytime consumption was higher than on 13 Aug 18 and the battery became depleted at 18:30. There was a peak of about 3.6 kW at 15:15 and another wider one at about 10:00. The site import that day was 20.4 kWh. In Dec 18, the daily site import ranged between 8.5 kWh and 50.7 kWh.

It is possible to assess the savings the battery would have provided if the household had remained on the Economy 7 tariff with the standard tariff rates for Economy 7. Table 3.42 shows the daily average savings would have ranged from £1.17 kWh/day in Apr and Dec 18 to £1.27 kWh/day in May 18. Over the period of operation of the battery, between 14 Apr 18 and 31 Jan 19, the savings would have been £355 (rather than £74 extra as described earlier).

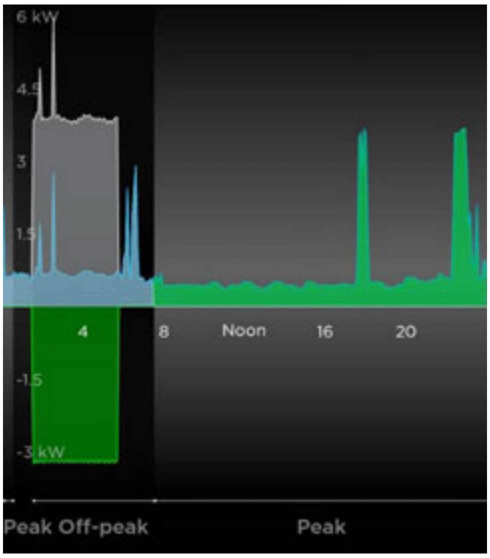


Figure 3.43(a) Tesla App screenshot for T-07 on 13 Aug 18

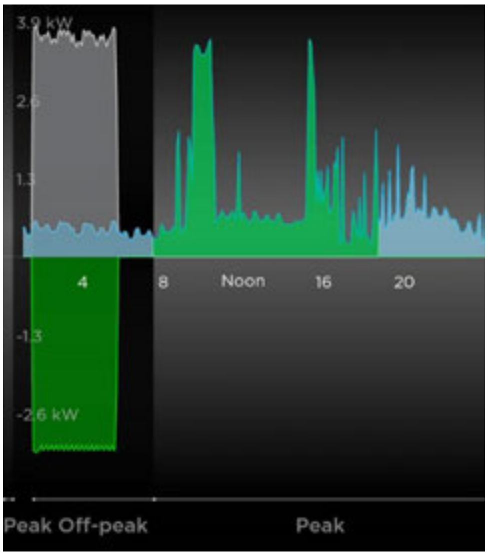


Figure 3.43(b) Tesla App screenshot for T-07 on 23 Dec 18

Household T-09

Out of the 3 residents in household T-09, 2 were adults over 35 years, with 1 not working due a chronic health condition and the other a full-time carer. The other resident was a young adult in full time education. The residents did not take any holidays during the project.

The household had a smart meter fitted in May 17. Table 3.44 shows the household electricity consumption from Jun 17 until the battery was operational on 23 Mar 18. The average daily peak rate consumption was in a tight range of 9.4 kWh/day in Aug 17 to 11.2 kWh/day in Dec 17. There was much greater variation in the off-peak consumption from 5.95 kWh/day in Jul 17 to 41.4 kWh/day in Mar 18. This was due to use of the storage heaters, with the highest consumption taking place during a period of particularly cold weather[48]. The percentage of off-peak consumption was between 36.4% in Jul 17 and 79.5% in Mar 18. The total consumption from 1 Jun 17 to 1 Jun 18 was 10,888 kWh, which included 70 days with the battery running.

Start date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
01-Jun-17	01-Jul-17	30	325.97	199.29	10.87	6.64	17.51	37.94%
01-Jul-17	01-Aug-17	31	322.72	184.38	10.41	5.95	16.36	36.36%
01-Aug-17	01-Sep-17	31	292.79	188.39	9.44	6.08	15.52	39.15%
01-Sep-17	01-Oct-17	30	290.73	320.35	9.69	10.68	20.37	52.42%
01-Oct-17	01-Nov-17	31	305.52	508.08	9.86	16.39	26.25	62.45%
01-Nov-17	01-Dec-17	30	291.29	694.06	9.71	23.14	32.84	70.44%
01-Dec-17	01-Jan-18	31	346.91	1016.45	11.19	32.79	43.98	74.55%
01-Jan-18	01-Feb-18	31	336.45	986.77	10.85	31.83	42.68	74.57%
01-Feb-18	01-Mar-18	28	312.03	959.63	11.14	34.27	45.42	75.46%
01-Mar-18	22-Mar-18	21	223.77	869.85	10.66	41.42	52.08	79.54%

Table 3.44 Electricity consumption of Household T-09 before the Tesla battery was operational using smart meter data.

Start date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
01-Apr-18	01-May-18	30	37.56	1004.80	1.25	33.49	34.75	96.40%
01-May-18	01-Jun-18	31	26.17	602.24	0.84	19.43	20.27	95.84%
01-Jun-18	01-Jul-18	30	25.90	457.30	0.86	15.24	16.11	94.64%
01-Jul-18	01-Aug-18	31	55.66	461.37	1.80	14.88	16.68	89.24%
01-Aug-18	01-Sep-18	31	88.87	495.32	2.87	15.98	18.84	84.79%
01-Sep-18	01-Oct-18	30	100.71	541.71	3.36	18.06	21.41	84.32%
01-Oct-18	01-Nov-18	31	94.39	796.89	3.04	25.71	28.75	89.41%
01-Nov-18	01-Dec-18	30	106.44	1041.40	3.55	34.71	38.26	90.73%
01-Dec-18	01-Jan-19	31	139.98	1050.32	4.52	33.88	38.40	88.24%
01-Jan-19	01-Feb-19	31	144.01	1279.36	4.65	41.27	45.91	89.88%

Table 3.45 Electricity consumption of Household T-09 before the Tesla battery was operational using smart meter data.

The consumption for household T-09 after the battery was running is shown in table 3.45. The average peak rate daily consumption had dropped from 9.4 – 11.2 kWh/day to between 0.84 and 4.65 kWh/day. The lowest average daily value for off-peak consumption was 14.9 kWh/day, which had increased from 5.95 kWh/day prior to operation of the battery.

[48] 2018 Great Britain and Ireland cold wave https://en.wikipedia.org/wiki/2018_Great_Britain_and_Ireland_cold_wave (Accessed 25 Feb 19)

The highest average for the off-peak consumption during the period the battery was tested was 41.3 kWh/day in Jan 19. This was comparable to the consumption during the cold weather period in Mar 18 when there was extra storage heater use. The average monthly percentage of off-peak consumption with the battery was between 84.3% and 96.4%. In April 18, there were 18 days when the percentage of off-peak consumption was 99% or more.

Figure 3.46 shows a plot of half hourly meter readings averaged for the months of January 2018 and January 2019. This illustrated a comparable winter period before and after the battery was operational.

There were high levels of consumption overnight, with the consumption up to about 1kWh greater for the half hourly periods in Jan 19, due to charging of the battery. There was a noticeable reduction in the day time consumption through most of the day in Jan 19 compared to Jan 18. After 19:30, the average half hourly consumption in Jan 19 was comparable to Jan 18 as a result of the battery becoming depleted.

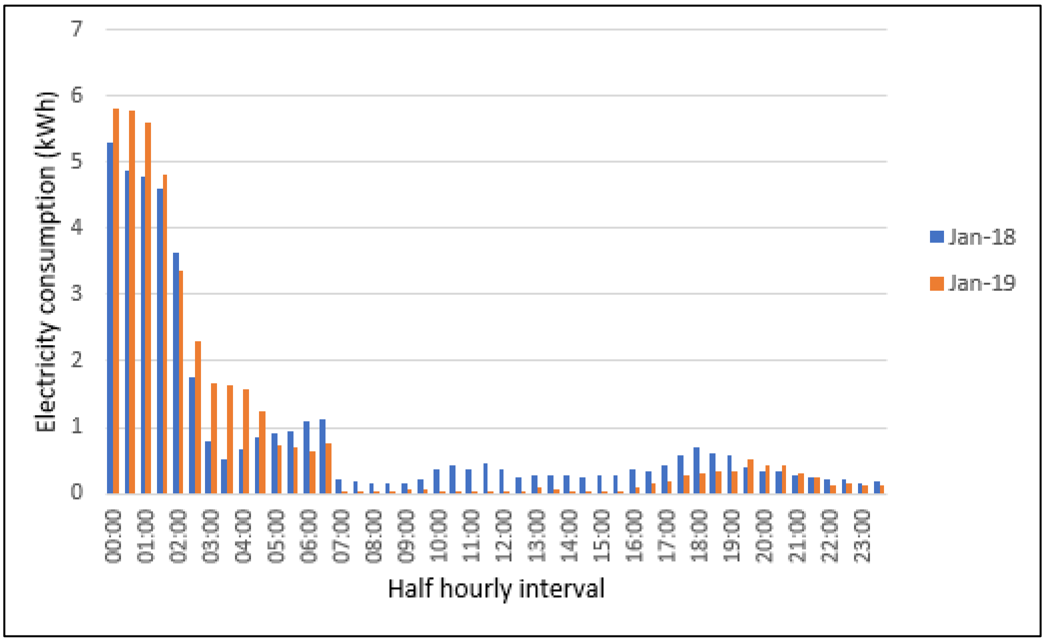


Figure 3.46 Plot comparing the average half hourly consumption values for household T-09 in Jan 18 with Jan 19

A similar plot is shown in figure 3.47 where half hourly meter readings were averaged in June 2017 and June 2018, summer months before and after the battery was running. The plot clearly shows the greater consumption overnight in Jun 18 due to the battery charging and negligible consumption during the day in Jun 18 compared to Jun 17. The average half hourly consumption during peak rate ranged from 0 to 0.11 kWh in Jun 18 compared to 0.08 to 0.63 kWh in Jun 17. On average there was a 92% reduction in the peak rate consumption between Jun 17 and Jun 18.

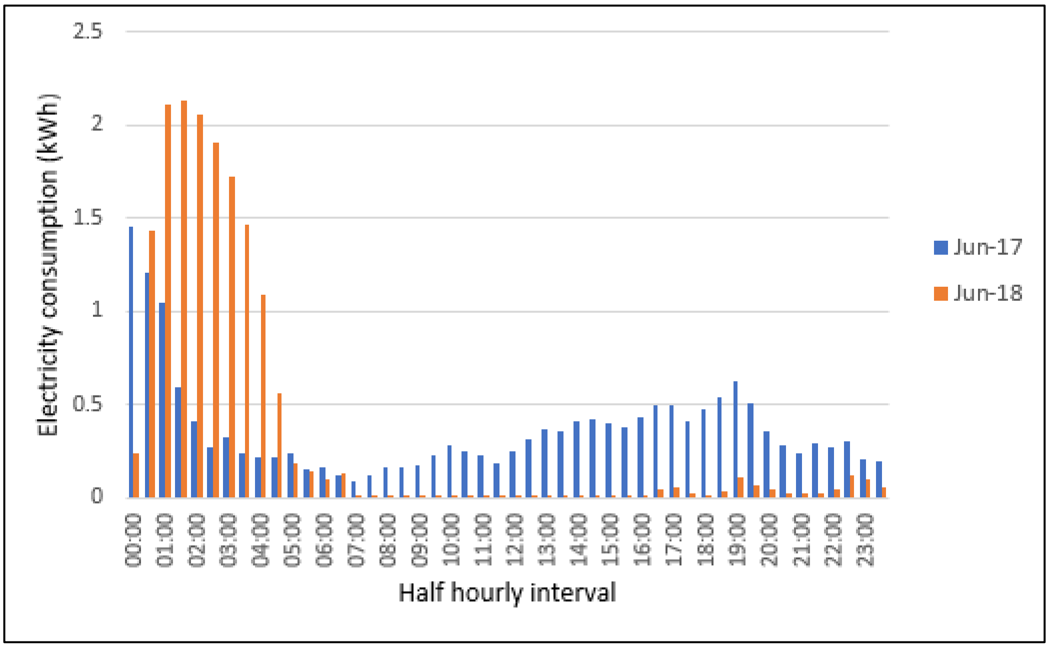


Figure 3.47 Plot comparing the average half hourly consumption values for household T-09 in Jun 17 with Jun 18

Table 3.48 compares the peak rate electricity consumption for equivalent months before and after the battery was running. As discussed above, there was a 92% reduction in the average peak rate consumption in June. The reduction was 63 to 70% for the Autumn months and 57% in January.

Month	Before battery Average Peak Rate Consumption (kWh/day)	Average consumption 16:00 to 18:00 (kWh/day)	After battery Average Peak Rate Consumption (kWh/day)	Average consumption 16:00 to 18:00 (kWh/day)	Reduction at Peak rate (%)	Reduction at 4pm-8pm (%)
Jun	10.87	3.99	0.86	0.36	92.05%	91.01%
Jul	10.41	3.61	1.80	0.31	82.75%	91.44%
Aug	9.44	3.40	2.87	0.77	69.65%	77.21%
Sep	9.69	3.11	3.36	1.00	65.36%	67.96%
Oct	9.86	3.39	3.04	1.39	69.11%	59.08%
Nov	9.71	3.43	3.55	1.19	63.46%	65.47%
Dec	11.19	3.90	4.52	2.15	59.65%	44.93%
Jan	10.85	3.94	4.65	2.19	57.20%	44.32%

Table 3.48 Electricity consumption of Household T-09 before and after the Tesla battery was operational

Table 3.48 also shows the consumption between 16:00 and 20:00 before and after the battery was operational. These are times when peak consumption tends to occur in winter on the electricity grid[49]. Green Energy UK have a more advanced time of use tariff than Economy 7 where there is a high cost period between 16:00 and 20:00 on weekdays. There is also cheap rate overnight (00:00 to 07:00) and a day rate comparable to a single tariff rate (07:00 to 16:00 and 20:00 to 00:00).[50] For June and July, the average reduction in consumption after the battery was fitted was 91%. The reduction was only 44 – 45% in December and January, but this was with the battery discharging from 07:00 and not reserving power to supply the most expensive 16:00 to 20:00 period.

[49] Seasonal variations in electricity demand https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/295225/Seasonal_variations_in_electricity_demand.pdf (Accessed 26 Feb 19)

[50] Green Energy UK and Tide – a new way to take control https://www.greenenergyuk.com/tide (Accessed 26 Feb 19)

The household had a 9.5 kW electric shower and there were typically 3 showers and 4 baths taken per week. After the battery was running, the household started using the daytime immersion heater and the daytime boost function on the storage heater.

The electric cooker was used between 17:00 and 19:00 daily. The dishwasher and washing machine were typically used overnight 3 – 4 times per week, although after the battery was fitted, there was no concern about using the washing machine during the day. A tumble drier was used during the day. There was a fridge-freezer and 2 additional freezers.

Figure 3.49 (a) shows a Tesla app screenshot showing the consumption and battery charge/discharge on 29 Jul 18. Apart from the baseload demand, the only other overnight consumption was from the battery charging. During the day, the battery was able to supply nearly all of the of the peak rate household demand. This installation had a G59 connection, which allowed the battery to discharge up to 5 kW. On some occasions when the increase in demand is particularly rapid, the system does not seem to supply the maximum power output, as may be the case with the 4 kW peak at 21:30.

The screenshot in figure 3.49 (b) shows the battery performance on 29 Dec 18. While the battery was able to supply the household throughout most days in the middle of summer, this was less common in the winter and the battery was depleted by 19:30 in this case. Overnight, apart from the battery charging, there appeared to be peaks in consumption due to water heating. An appliance was used in the morning before lunch which may have been the tumble drier. There was a peak of 6.9kW at 18:10 with 5 kW provided by the battery. The sharp peak may have been due an additional appliance being used while cooking the evening meal.

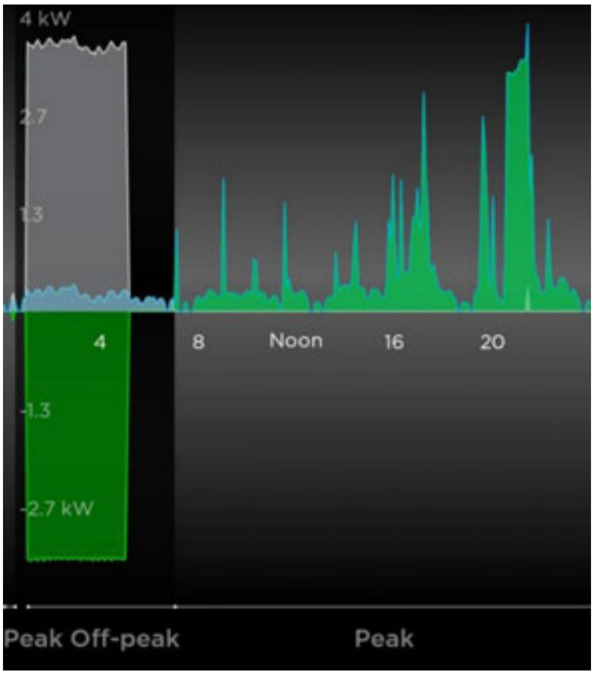


Figure 3.49(a) Tesla App screenshot for T-09 on 29 Jul 18

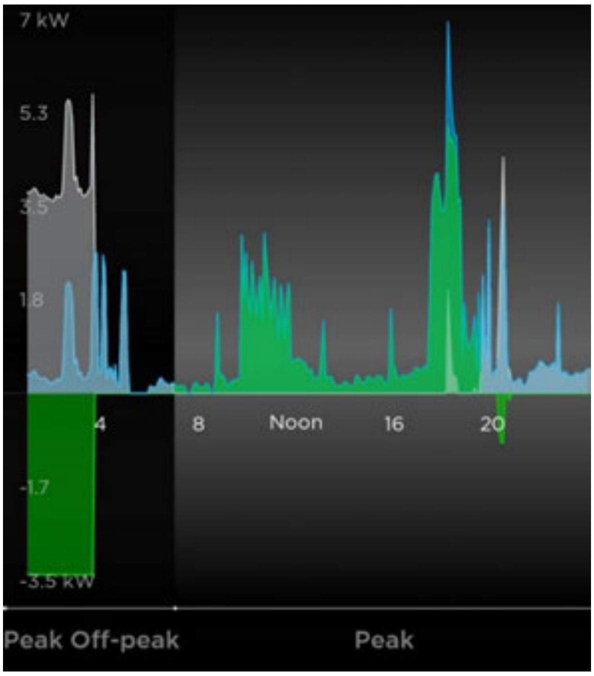


Figure 3.49(b) Tesla App screenshot for T-09 on 29 Dec 18

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
01-Apr-18	01-May-18	312.58	350.59	464.35	423.77	10.42	11.69	15.48	14.13	89.2%	£1.06
01-May-18	01-Jun-18	314.03	341.85	429.38	398.98	10.13	11.03	13.85	12.87	91.9%	£1.05
01-Jun-18	01-Jul-18	323.79	370.91	458.75	417.70	10.79	12.36	15.29	13.92	87.3%	£1.08
01-Jul-18	01-Aug-18	344.16	390.37	517.37	469.00	11.10	12.59	16.69	15.13	88.2%	£1.12
01-Aug-18	01-Sep-18	351.63	390.45	544.62	503.38	11.34	12.60	17.57	16.24	90.1%	£1.16
01-Sep-18	01-Oct-18	364.36	403.32	576.64	535.63	12.15	13.44	19.22	17.85	90.3%	£1.25
01-Oct-18	01-Nov-18	363.46	400.29	573.59	534.06	11.72	12.91	18.50	17.23	90.8%	£1.21
01-Nov-18	01-Dec-18	355.90	406.65	589.33	535.96	11.86	13.56	19.64	17.87	87.5%	£1.19
01-Dec-18	01-Jan-19	377.72	436.83	658.15	606.15	12.18	14.09	21.23	19.55	86.5%	£1.21
01-Jan-19	31-Jan-19	353.84	402.19	609.88	560.11	11.79	13.41	20.33	18.67	88.0%	£1.18
Total		**3461.5**	**3893.5**	**5422.0**	**4984.7**						

Table 3.50 Battery performance and household consumption measured by the Tesla battery system for T-09

While tables 3.44 to 3.45 were based on smart meter data, table 3.50 shows the battery performance and consumption for household T-09 as measured by the Tesla battery system. Between 1 Apr 18 and 31 Jan 19, the battery system measured the site import to be 5,422 kWh. Over the same period, the smart electricity meter recorded the grid import as 7,964 kWh. This significant difference from the value measured by the battery system was due to the installer not using a Y-splitter cable at this site to ensure that the battery could measure consumption from both the main and heating circuits. This suggests that the overnight storage heater consumption was 2,542 kWh between 1 Apr 18 and 31 Jan 19. The installer has agreed to return to this and other affected sites to ensure the battery measures both the main and heating electrical circuits.

The battery and off-peak immersion heater were connected to the main electrical circuit and charged during off peak hours at the lower tariff rate. The average site import due to the battery, water heating and household appliances ranged from 13.85 to 21.23 kWh/day. The average daily battery export was between 10.13 and 12.18 kWh/day. Taking into account the losses in the battery charge/discharge cycle, average savings due to the battery were between £1.05 and £1.25 per day using the standard tariff rates for Economy 7.

Household T-38

There were 4 residents in household T-38, with 2 adults not working due to chronic health conditions caring for children in full time education. In the year prior to the battery operating, the household consumption was 11,852 kWh, with 50.4% of this off peak. This equated to an annual cost of £1,476 using the standard Economy 7 tariff rates.

Table 3.51 shows electricity consumption for household T-38 during the 18 months before the battery was operational. The peak rate consumption was typically about 20 – 23 kWh/day in winter. At other times of the year it was usually in the range 11 – 16 kWh/day, although in the summer it could reach nearly 20 kWh/day, perhaps due to children being off from school.

The off-peak consumption was between 1.9 and about 9 kWh/day outside the heating season, but was between 14 and 45 kWh/day during the coldest months. The percentage of off-peak consumption was typically 45 to 70% in the heating season and 28 to 41% at other times.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
20-Aug-16	23-Sep-16	34	674	66	19.82	1.94	21.76	8.92%
23-Sep-16	30-Oct-16	37	566	304	15.30	8.22	23.51	34.94%
30-Oct-16	15-Nov-16	16	349	136	21.81	8.50	30.31	28.04%
15-Nov-16	16-Dec-16	31	703	670	22.68	21.61	44.29	48.80%
16-Dec-16	16-Jan-17	31	549	440	17.71	14.19	31.90	44.49%
16-Jan-17	27-Feb-17	42	808	671	19.24	15.98	35.21	45.37%
27-Feb-17	30-Mar-17	31	572	296	18.45	9.55	28.00	34.10%
30-Mar-17	03-May-17	34	375	260	11.03	7.65	18.68	40.94%
03-May-17	20-Jun-17	48	577	403	12.02	8.40	20.42	41.12%
20-Jun-17	27-Jul-17	37	509	320	13.76	8.65	22.41	38.60%
27-Jul-17	17-Aug-17	21	416	172	19.81	8.19	28.00	29.25%
17-Aug-17	18-Sep-17	32	498	275	15.56	8.59	24.16	35.58%
18-Sep-17	17-Nov-17	60	764	443	12.73	7.38	20.12	36.70%
17-Nov-17	30-Dec-17	43	988	1305	22.98	30.35	53.33	56.91%
30-Dec-17	30-Jan-18	31	598	1397	19.29	45.06	64.35	70.03%
30-Jan-18	27-Feb-18	28	579	1105	20.68	39.46	60.14	65.62%

Table 3.51 Electricity consumption of Household T-38 from electricity meter readings before the battery installation.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
30-Mar-18	03-May-18	34	240	705	7.06	20.74	27.79	74.60%
03-May-18	23-May-18	20	51	442	2.55	22.11	24.66	89.66%
23-May-18	21-Jun-18	29	55	554	1.90	19.10	20.99	90.97%
21-Jun-18	29-Jul-18	38	92	829	2.42	21.82	24.24	90.01%
29-Jul-18	16-Aug-18	18	142	407	7.89	22.61	30.50	74.13%
16-Aug-18	19-Sep-18	34	220	752	6.47	22.12	28.59	77.37%
19-Sep-18	29-Oct-18	40	228	835	5.70	20.88	26.58	78.55%
29-Oct-18	17-Nov-18	19	153	924	8.05	48.63	56.68	85.79%
17-Nov-18	04-Jan-19	48	514	2296	10.71	47.83	58.54	81.71%
04-Jan-19	01-Feb-19	28	285	1524	10.18	54.44	64.62	84.25%

Table 3.52 Electricity consumption of Household T-38 from electricity meter readings after the battery installation.

The electricity consumption after the battery was operational is shown in table 3.52. The average peak rate consumption was between 1.9 and 10.7 kWh/day, values which were approximately 10 kWh/day lower than equivalent periods before the battery was running. The off-peak consumption was consistently high and between 19.1 and 54.4 kWh/day. There were no longer periods outside the heating season when the off-peak consumption was under 10 kWh/day. The percentage of off-peak consumption was between 74 and 91%.

The household had a 9 kW electric shower and no bath and there were typically 8 showers taken per week. The washing machine was used overnight or in the morning on a daily basis, while the tumble drier was used in the morning on days when the washing could not be dried outside. The electric cooker was used weekdays between 17:00 and 18:00 and a 900 W microwave was also used daily. The kettle was used hourly for hot drinks and a large TV was on throughout the day. In October 2018, the old storage heaters were replaced with 2 Dimplex Quantum storage heaters, 2 modern Creda storage heaters and a 500W Creda panel heater which was used occasionally in the evening.

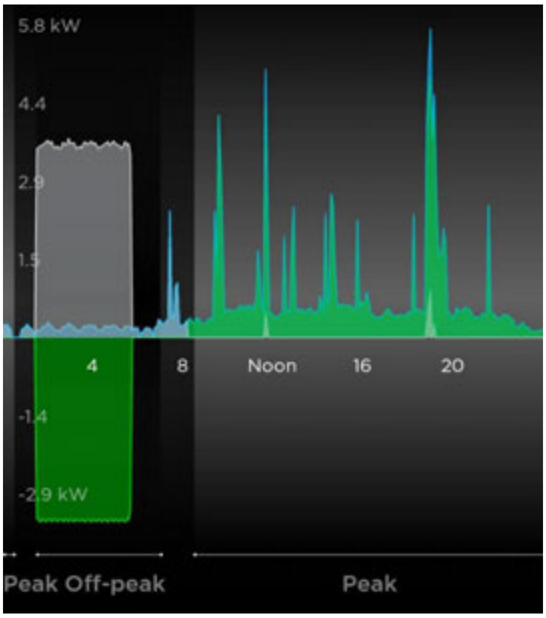


Figure 3.53(a) Tesla App screenshot for T-38 on 14 Jun 18

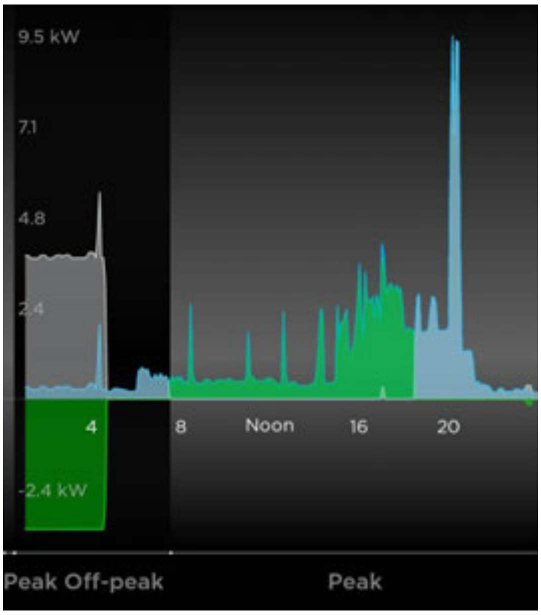


Figure 3.53(b) Tesla App screenshot for T-38 on 27 Jan 19

Figure 3.53 shows screenshots from the Tesla app illustrating examples of the consumption behaviour and battery performance for household T-38 in summer and winter. The off-peak period was from 01:30 until 08:30 during British Summer Time (BST), but 1 hour earlier during GMT.

There was quite a high baseload consumption of 500W or more during the day on 14 Jun 18, with multiple consumption peaks at up to 3 kW, perhaps due to a kettle and 3 larger peaks of about 4 to 5.8 kW in the morning, at noon and in the evening, which may have been due to cooking appliances. The battery was able to supply up to 5 kW due to a G59 connection and was able to power the home through the peak rate period on 14 Jun 18 with small top ups from the grid for the highest peaks in consumption.

The screenshot in figure 3.53 (b) shows consumption and battery performance on 27 Jan 19 with a site import recorded by the battery of 25.6 kWh compared to 16.6 kWh on 14 Jun 18. The baseload consumption increased to above 600 W at 06:00 and was consistently at this level apart from peaks of about 2.4 kW, possibly caused by the kettle. The consumption exceeded 2 kW between 15:00 and 21:00 which was partly due to cooking a Sunday meal. There was a peak in consumption of 9.5 kW at 20:10 due to the electric shower. The battery became depleted at 18:30 and during December and January, this typically happened between mid-afternoon and early evening.

Although there might be a water heating peak overnight in figure 3.53 (b), there was no consumption recorded from the night storage heaters by the Tesla app. Again, a Y-splitter cable was not fitted by the installer to ensure the heating circuit consumption was also recorded by the Tesla battery system. Between 30 Mar 18 and 11 Jan 19, the grid import measured by the utility meter was 9,900 kWh. Over the same period, the site import measured by the Tesla battery system was 6,037 kWh, suggesting about 3,863 kWh had been consumed by the heating circuit over this period.

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
01-Apr-18	01-May-18	335.41	393.07	608.38	548.64	11.18	13.10	20.28	18.29	85.3%	£1.10
01-May-18	01-Jun-18	334.77	364.53	504.44	472.39	10.80	11.76	16.27	15.24	91.8%	£1.12
01-Jun-18	01-Jul-18	326.79	374.83	488.62	443.58	10.89	12.49	16.29	14.79	87.2%	£1.09
01-Jul-18	01-Aug-18	360.48	405.73	597.00	549.63	11.63	13.09	19.26	17.73	88.8%	£1.18
01-Aug-18	01-Sep-18	325.96	369.05	726.73	681.62	10.51	11.90	23.44	21.99	88.3%	£1.06
01-Sep-18	01-Oct-18	355.85	397.49	656.31	612.88	11.86	13.25	21.88	20.43	89.5%	£1.21
01-Oct-18	01-Nov-18	280.13	320.64	551.53	509.48	9.04	10.34	17.79	16.43	87.4%	£0.90
01-Nov-18	01-Dec-18	378.22	427.06	804.68	753.98	12.61	14.24	26.82	25.13	88.6%	£1.27
01-Dec-18	01-Jan-19	352.80	410.02	771.70	715.38	11.38	13.23	24.89	23.08	86.0%	£1.12
01-Jan-19	31-Jan-19	380.46	429.62	789.91	740.75	12.68	14.32	26.33	24.69	88.6%	£1.28
Total		**3430.9**	**3892.0**	**6499.3**	**6028.3**						

Table 3.54 Battery performance and household consumption measured by the Tesla battery system for T-38

Table 3.54 provides a monthly summary of the battery performance and main electrical circuit consumption for household T-38. There was a difference of 471 kWh between the site import and the household load measured by the battery system between 1 Apr 18 and 31 Jan 19. This was due to losses in the charge-discharge cycle and battery self-consumption. This increased the household electricity consumption at a cost of £33 using a standardised off-peak tariff of 7p/kWh. Losses in the charge/discharge cycle of the battery were included when savings were calculated.

The average daily site import ranged from 16.27 kWh/day in May 18 to 26.82 kWh/day in Nov 18. These values were not as large and the range not so wide as for the average total consumption in table 3.52 due to the battery not recording the heating electrical circuit.

The average battery export was typically in the range 10.5 to 12.7 kWh/day. The exception was Oct 18 when the household were away for a week. The average savings ranged from £0.90/day in Oct 18 to £1.28/day in Jan 19.

Household T-61

There were 2 residents in household T-61 who both worked full time. The property was similar in style to household T-38. The battery at this site was installed on 6 Jun 18, later than others in the project. Another household had initially been selected for the final battery installation but cancelled at the last minute and it took time to recruit another suitable household, carry out surveys and install the system. There was an initial issue where the battery was fully charging and immediately fully discharging, but this was resolved by the installer after a couple days.

Table 3.55 shows the household consumption based on meter readings for periods before the battery was running. The average annual consumption between Jan 16 and Jan 18 was 5,868 kWh/year or an annual cost of £733 with standard Economy 7 rates. This was the lowest consuming household in the study. For a profile 2 meter, Ofgem class medium consumption as 4,200 kWh[51]. The percentage off peak consumption was between 48 and 50% for the 6 month and 2 year periods recorded. The average peak rate consumption was between 7.8 and 12.2 kWh/day, which was below the 13.5 kWh capacity of the Tesla Powerwall 2.

[51] Typical Domestic Consumption Values for gas and electricity (Ofgem, 2017) https://www.ofgem.gov.uk/system/files/docs/2017/08/tdcvs_2017_open_letter.pdf (Accessed 27 Feb 19)

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
10-Jul-14	06-Jan-15	180	1526	1413	8.48	7.85	16.33	48.08%
06-Jan-15	08-Jul-15	183	1749	1619	9.56	8.85	18.40	48.07%
08-Jul-15	09-Jan-16	185	1443	1428	7.80	7.72	15.52	49.74%
09-Jan-16	05-Jul-16	178	1828	1697	10.27	9.53	19.80	48.14%
03-Jan-18	06-Jun-18	154	1873	1753	12.16	11.38	23.55	48.35%
09-Jan-16	03-Jan-18	725	5812	5843	8.02	8.06	16.08	50.13%

Table 3.55 Electricity consumption of Household T-61 from electricity meter readings before the battery installation.

Start Date	End Date	Number of days	Peak rate consumption (kWh)	Off peak rate consumption (kWh)	Average peak consumption (kWh/day)	Average off peak consumption (kWh/day)	Average total consumption (kWh/day)	Percentage off peak (%)
01-Jul-18	31-Jul-18	30	21	215	0.70	7.17	7.87	91.10%
31-Jul-18	05-Sep-18	36	29	299	0.81	8.31	9.11	91.16%
05-Sep-18	02-Oct-18	27	17	190	0.63	7.04	7.67	91.79%
02-Oct-18	02-Nov-18	31	16	346	0.52	11.16	11.68	95.58%
02-Nov-18	06-Dec-18	34	20	631	0.59	18.56	19.15	96.93%
06-Dec-18	03-Jan-19	28	30	581	1.07	20.75	21.82	95.09%
03-Jan-19	31-Jan-19	28	34	679	1.21	24.25	25.46	95.23%

Table 3.56 Electricity consumption of Household T-61 from electricity meter readings after the battery installation.

A summary of the household consumption from electricity meter readings after the battery was operating is shown in table 3.56. The average peak rate consumption was under 1 kWh/day for all months apart from Dec 18 and Jan 19 and was only slightly above that in those months. The percentage of off-peak consumption was above 91% in all months. This indicates there could be a shift from an average of 50% off peak consumption over the year to greater than 90% following installation of the battery.

The property had an electric shower which was used 4 to 6 times a week and there was a washing machine that was used weekly. There was no dishwasher or tumble drier. The cooker had an electric oven and a hob fuelled by bottled gas. There was a microwave that was used daily and a TV consuming less than 100 W that was used nightly. There was a single fridge-freezer.

When interviewed, the resident said the 3 storage heaters and 1 panel heater in the property were never used due to the running cost. Instead, a 1,350 – 1,500 W oil filled electric radiator was used in the living room on weekday evenings and weekends in winter. There was also a 700W oil filled radiator that was used in a bedroom for short periods and a Dimplex fan heater in the bathroom. The residents in household T-61 were at home less than the other households in the study and had fewer appliances. As a result, their consumption was significantly less than the other households and patterns of consumption different.

Figure 3.57 (a) shows a screenshot from the Tesla app for Sunday 8 July 18. There were a few peaks of less than 1.5 kW during the day and a sharp peak of 6.7 kW at 21:00 due to a cool shower. Overnight there was a battery import of only 4.65 kWh as the battery had not fully discharged the day before. The Tesla battery system predicts the necessary level of charging based on previous patterns of consumption. The other peaks in consumption overnight are likely to have been due to the immersion heater on the hot water cylinder.

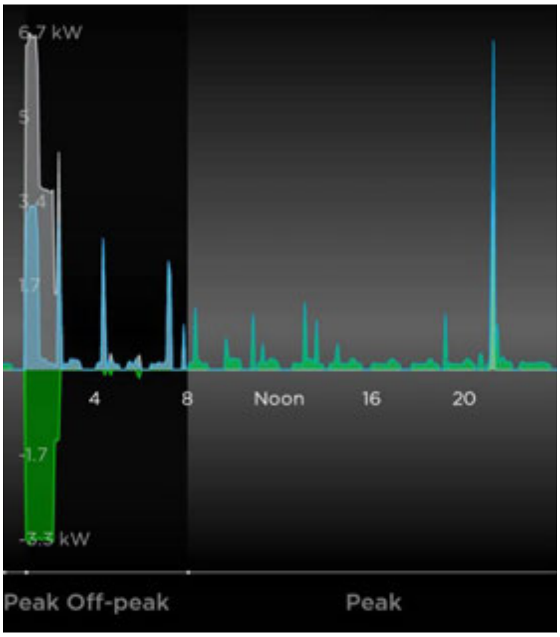


Figure 3.57 (a) Tesla App screenshot for T-61 on 8 Jul 18

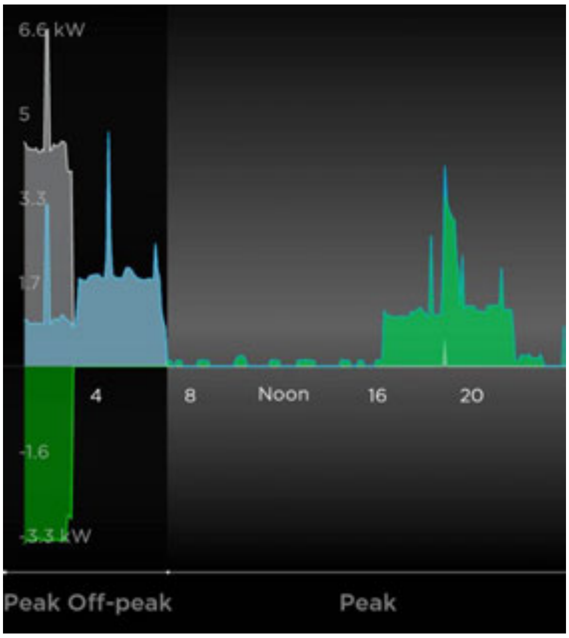


Figure 3.57 (b) Tesla App screenshot for T-61 on 21 Jan 19

Figure 3.57 (b) shows a screenshot from the Tesla app for 21 Jan 19, a working day in winter. There was low consumption during the day when the residents were out at work. The oil filled radiator in the living room was likely to be running between 16:00 and 22:00 and the additional peak at 19:00 may have been due to using the oven. The consumption overnight apart from the battery charging was likely to be due to the water heater and probably the oil filled radiator.

The total electricity consumption between 1 Jul 18 and 11 Jan 19 was 3,097 kWh as measured by the electricity meter. Using data recorded by the Tesla battery system, the site import was 2,577 kWh. This suggests only the main electrical circuit was measured by the battery current clamp and there was some use of the heating electrical circuit during this period.

The average battery export ranged from 2.9 to 3.8 kWh/day for the months June to September. In December and January it was 9.0 and 9.5 kWh/day respectively. This indicates that the household was typically not using the full 13.5 kWh capacity of the battery, particularly in summer.

Start date	End date	Battery Export (kWh)	Battery Import (kWh)	Site import (kWh)	Load (kWh)	Average battery export (kWh/day)	Average battery import (kWh/day)	Average site import (kWh/day)	Average household load (kWh/day)	Round trip efficiency (%)	Savings (£/day)
15-Jun-18	01-Jul-18	45.83	66.15	129.48	108.23	2.86	4.13	8.09	6.76	69.3%	£0.23
01-Jul-18	01-Aug-18	94.77	119.53	242.20	216.19	3.06	3.86	7.81	6.97	79.3%	£0.28
01-Aug-18	01-Sep-18	117.43	140.96	275.51	250.60	3.79	4.55	8.89	8.08	83.3%	£0.36
01-Sep-18	01-Oct-18	96.55	116.38	241.54	220.45	3.22	3.88	8.05	7.35	83.0%	£0.31
01-Oct-18	01-Nov-18	145.32	172.57	342.36	313.24	4.69	5.57	11.04	10.10	84.2%	£0.45
01-Nov-18	01-Dec-18	232.27	271.17	559.67	525.41	7.74	9.04	18.66	17.51	85.7%	£0.76
01-Dec-18	01-Jan-19	279.86	339.16	670.76	620.60	9.03	10.94	21.64	20.02	82.5%	£0.86
01-Jan-19	31-Jan-19	284.12	318.02	736.17	701.07	9.47	10.60	24.54	23.37	89.3%	£0.96
Total		**1296.1**	**1543.9**	**3197.7**	**2955.8**						

Table 3.58 Battery performance and household consumption measured by the Tesla battery system for T-61

Although there was little consumption of peak rate electricity after the battery in household T-61 was operational, the savings were lower than for the other households. This was due to the lower peak rate consumption and battery discharge. Savings ranged from £0.23/day in Jun 18 to £0.96/day in Jan 18 when there was greater consumption due to use of secondary heating during the day.

Summary of results and savings and comparison with other battery trial

Technical Reference Number	Number of Residents	Annual Electricity Consumption (kWh)	Start Date	End Date	Total battery discharge (kWh)	Range in average battery discharge (kWh/day)	Total savings (£)	Range in savings (£/day)	Percentage off peak consumption (%)
T-01	3	11,910	01-Apr-18	31-Jan-19	3,334	9.1 to 13.0	£328	£0.77 to £1.29	80.52%
T-03	4	13,952	01-Apr-18	31-Jan-19	3,693	10.8 to 12.9	£368	£1.08 to £1.27	81.9% to 92.9%
T-05	4	7,402	01-Apr-18	29-Jan-19	3,327	9.1 to 12.2	£336	£0.91 to £1.24	79.4% to 94.3%
T-06	6	13,224	04-Apr-18	31-Jan-19	3,271	8.3 to 12.5	£323	£0.79 to £1.24	84.6% to 92.6%
T-09	3	10,888	01-Apr-18	31-Jan-19	3,462	10.1 to 12.2	£351	£1.05 to £1.25	84.3% to 96.4%
T-38	4	11,852	01-Apr-18	31-Jan-19	3,431	9.0 to 12.7	£345	£0.90 to £1.28	74.1% to 91.0%
T-61	2	5,868	15-Jun-18	31-Jan-19	1,296	2.9 to 9.5	£125	£0.23 to £0.96	91.1% to 96.9%

Table 3.59 Summary of household consumption, battery discharge and financial savings

A summary of the results and savings is provided in table 3.59. This excludes household T-07 which switched from Economy 7 to a single rate tariff before the battery was operational. Values of annual electricity consumption were all for periods before the battery was installed apart from for household T-09. Here the annual consumption period included 70 days when the battery was operational. All households apart from T-61 were classed as high electricity consumers, having a consumption above 7,100 kWh/year.

Most of the batteries were running from Apr 18 to Jan 19 and the total battery discharge ranged from 3,271 to 3,693 kWh. For household T-61 the discharge was only 1,296 kWh, partly due to being installed later, but also because the daytime consumption was low at the site. The average daily battery discharge over the month was normally between 9 and 13 kWh/day. Only household T-61 had values consistently under 5 kWh/day.

For household T-01 between 4 Apr 18 and 18 Jan 19, with the battery operating, the percentage off peak consumption was 80.5%. For other households, it was possible to obtain the percentage of the off-peak consumption approximately every month from meter readings. This ranged from 74.1 to 96.9% over the period of the study.

Savings were calculated using standardized tariff rates of 18p/kWh for peak rate and 7p/kWh for off peak. Savings due to the battery were typically between £323 and £368 for the period between Apr 18 and 31 Jan 19. The maximum saving equates to an annual rate of £440/year.

For household T-61 the savings were £125 over a period of 230 days instead of 305. This on average equates to £0.54/day or £198/year.

The savings from this study can be compared with those from other battery storage trials. In the SunGain battery bank project in Thurrock, smaller batteries with a nominal capacity of 2 kWh and a usable capacity of 1.6 kWh were studied over a period of 2 years[52]. These batteries were fitted in properties with **pre-existing solar PV systems**. The average battery discharge for 9 Maslow batteries was between 0.42 kWh/day and 0.93 kWh/day, which equated to savings of £24 to £55 per year. For 6 PowerFlow Sundial batteries, the average battery discharge was between 0.39 kWh/day and 1.16 kWh/day. This was equivalent to savings of £23 to £67 using a standardised single rate tariff of 16p/kWh.

It is instructive to also estimate the savings that might be achieved with a 2 kWh battery charged using only off peak rates as in this project. Assuming the usable capacity of 1.6 kWh was discharged every day and 90% efficiency in the charge/discharge cycle, the annual savings would be about £60 with the standardized Economy 7 rates.

The Tesla Powerwall 2 battery is of the order of about 3 times more expensive than the Maslow and PowerFlow Sundial batteries. However, the highest savings from Tesla battery grid charging were over 6.5 times greater than the best savings recorded in the study by a PowerFlow Sundial battery and 8 times greater than the best savings measured from a Maslow battery.

4. Conclusions and recommendations

4.1 Conclusions

The project installed 8 Tesla Powerwall 2 batteries in off gas grid properties in North Devon which had night storage heaters and Economy 7 electricity tariffs

- Tesla Powerwall 2 batteries with a usable capacity of 13.5 kWh were installed in 8 homes owned by social landlord North Devon Homes Ltd. 5 of the installations had G59 grid connections where the batteries could provide up to 5 kW output while the other 3 had G83 connections and could supply 3.68 kW.
- The properties were off the gas grid and so the primary form of space heating available was from night storage heaters on an Economy 7 electricity tariff.
- The homes did not have solar PV and so the batteries only charged overnight on cheap off-peak electricity and supplied power to the home during the expensive peak rate period.
- The batteries were installed between January 2018 and June 2018 and installations were operational from late March 2018.
- The software update to allow grid charging on Tesla Powerwall 2 batteries had a limited initial release in the UK in March 2018 and the installations on this project were the first Tesla Powerwall 2 batteries in the UK to charge only from the electricity grid.
- The aims of the project included:
  - Assess performance of the Tesla Powerwall 2 batteries when grid charging
  - Assess the levels of resident satisfaction with the technology
  - Determine the battery performance and savings over about a year
  - Consider any challenges associated with deployment and operation of the technology when charging with time of use tariffs

[52] Paul Rogers and Michael Hamer, Sungain Battery Bank (NEA, 2019) http://www.nea.org.uk/wp-content/uploads/2019/01/CP775-TIF-REPORT-FINAL.pdf (Accessed 4 Mar 2019)

- As well as 8 households with battery installations, a further 3 households were studied as controls which had just night storage heaters.
- Monitoring included electricity meter readings, accurate daily data from Tesla, the Tesla app, Verv data loggers and current clamps. Households interviews were also carried out.

There were high levels of satisfaction with the battery technology and the installations although there were some issues during the project

- All 7 of the households interviewed thought the installation was neat and tidy, the battery was fitted in a suitable location and the installers were careful and respectful in their homes.
- When asked if they found it easy to use the battery, 6 of the households strongly agreed and a further household agreed.
- There were 3 households who strongly agreed they had seen savings on their electricity payments while a further 3 households agreed there were savings. A single household disagreed after analysing bills, but this included a unit rate price rise by their supplier.
- There was a household where the resident switched electricity provider before the battery was operational. This included the Economy 7 meter being replaced with a single rate meter. As a result, the battery was not able to charge at a cheaper rate and no savings were made by the household. There was also extra electricity consumption due to losses in the charge/discharge cycle of the battery. Attempts were made to resolve the situation with the household, however there were challenges in contacting the resident and finding them in when appointments were scheduled.
- There was an initial problem after installing the final Powerwall where the battery charged and immediately fully discharged. This was resolved by the installer after a couple days.
- There was a difference of 520 to 3863 kWh between the site import recorded by the electricity meter for 3 households and the values measured by the Tesla system. This was due to the installations not recording the consumption of the heating electrical circuit as well as the main electrical circuit. The installer had not used a Y-splitter cable with these batteries which allowed a current clamp to fit on both circuits. It has been agreed that this will be rectified. There were 3 households where both the main and heating electrical circuits were recorded and the difference between the site import measured by the utility meter and Tesla system was less than 1%

Economy 7 and control properties

- The times for Economy 7 can vary across the country and with supplier and meter type. There are Standard Settlement Configuration (SSC) codes which determine the times when the household supply switches from peak to off peak. For some older meters, the time for off-peak may alter by an hour as the clocks go forward or back. In this case the time for off peak charging needed to be switched on the Tesla app. More modern meters may maintain local time and so no changes were required to the Tesla app when the clocks changed.
- The consumption patterns of 2 control households were studied in depth. Household C-04 had 6 night storage heaters and the annual consumption ranged from 8,729 to 11,824 kWh/year over 6 years. The annual cost was between £999 and £1,282 using a standardized Economy 7 tariff. During 2018, the percentage of the off-peak consumption ranged from 54.3% to 75.6% over approximately monthly periods.

- The immersion heater on the hot water cylinder tended to run for about an hour and there were subsequently periodic short bursts of power to maintain the cylinder temperature. The consumption from the storage heaters depended on the number running and the input control. Overnight, the power consumed typically dropped as the storage heaters became warmer.
- Control household C-11 only used 1 storage heater and the immersion heater was switched on throughout the day not just overnight. The annual consumption was 6,547 kWh with a cost of £807. The percentage off peak consumption ranged from 17.3% to 69.6%.

Most of the households that received batteries were high electricity consumers

- Household T-61 had 2 working adults who were out during week days. The annual household electricity consumption was 5,868 kWh, which was the lowest among the households with battery installations. The annual cost using a standardized tariff was £733.
- The other households with batteries had 3 or more residents and had annual consumptions of between 7,402 and 13,952 kWh. These consumptions were above the Ofgem Typical Domestic Consumption Value (TDCV) of 7,100 kWh for a high electricity consumer on a profile 2 meter. The annual costs for these households ranged from £950 to £1,676.
- Out of the households who were high electricity consumers, 4 households had a member unable to work due to a chronic health condition and 1 household had a member who worked part time.

The battery was typically able to fully power appliances apart from the electric shower

- All 7 of the households interviewed with batteries had electric showers. These were rated at between 8.5 and 9.5 kW. The batteries with a G59 grid connection could supply up to 5 kW towards the power requirement, with the rest coming from the grid.
- Household T-06 had 6 residents and there were about 30 showers per week. The shower and cooking were the main causes of peak rate consumption.
- Other occasions where the battery could not fully power the household load included when there was use of several high consuming appliances, such as cooking and using supplementary heating or a washing machine. Such occasions were rare, particularly in summer.

Most households were dissatisfied with their storage heaters and some preferred supplementary heating which increased peak rate electricity consumption in winter

- When interviewed, 4 out of 7 households said they were very dissatisfied with the cost of running their heating system, the amount of control over the heating and how well the house kept in the heat.
- Some of the households primarily used supplementary heating in winter rather than the storage heaters. This included household T-07 which switched from Economy 7 to a single rate tariff apparently due concern over the cost of running the storage heaters.
- Household T-01 used 3 oil filled electric radiators throughout the winter. This meant that the household load had regular peaks throughout the day of 3kW or more. The battery was often depleted by mid afternoon in winter. In summer the battery normally lasted all day.

- Household T-61 also used an oil filled radiator in winter. During the week, the consumption increased from 16:00 to about 22:00. At the weekend it was used more consistently. The household was a medium electricity consumer and it was rare that the Tesla battery became depleted even with the supplementary heating use.
- Household T-38 had their storage heaters replaced in October 2018 with more modern models with timer and temperature controls. At the beginning of the project they were very dissatisfied with how warm their home got and the amount of control over the heating. In the final interview after the new heaters were fitted, this had changed to being satisfied.

There was a large drop in peak rate consumption and increase in the percentage of off-peak use after the Tesla Powerwall 2 was operational

- For household T-01, before the battery was fitted, the average peak rate consumption over a year was 18.3 kWh/day and 43.7% of the electricity consumption was off peak.
- The average peak rate consumption for household T-01 with the battery running was 4.8 kWh/day between 4 Apr 18 and 18 Jan 19. Over this period the average percentage off peak consumption was 80.5%
- Household T-38 had an average peak rate consumption for approximately monthly periods in the range 11 to 23 kWh/day without the battery and between 1.9 and 10.7 kWh/day with the battery. The percentage off peak consumption was typically between 28 and 70% before the battery and 74.1 to 91% after the battery was operational.
- Medium consuming household T-61 had an average peak rate consumption of 7.8 to 12.2 kWh/day before the installation and this decreased to between 0.5 and 1.2 kWh/day with the battery. The percentage off peak consumption increased from 50.1% over the previous 2 years to between 91.1 and 96.9% between July 18 and January 19.

Household T-09 had a smart meter which provided accurate data on the change in household consumption due to the battery

- Smart electricity meter data was available for household T-09 during the evaluation period and going back to June 2017.
- Before the installation, the monthly average peak rate consumption ranged from 9.4 kWh/day in August 2017 to 11.2 kWh/day in December 2017. The average monthly percentage off peak consumption was between 36.4 and 79.4%.
- After the battery was running, the monthly average peak rate consumption dropped to between 0.84 and 4.65 kWh/day, with the average percentage off peak consumption between 84.3% and 96.4%. In April 2018, there were 18 days when the percentage off peak consumption was 99% or more.
- It was also possible to compare the peak rate consumption before and after the battery was running for the months of June to January. The peak rate consumption fell by 92.05% between June 2017 and June 2018, while it fell by 57.2% in January 2019 compared to January 2018.

The average battery discharge was high throughout the year for all but 1 household

- For household T-61, the average battery discharge was 2.86 kWh/day in June 2018, but increased to 9.47 kWh/day in January 2019. The household made little use of the 13.5 kWh battery capacity in summer and often still did not use the full capacity in winter.
- The average battery discharge over the month for the other households was high throughout the year, ranging from 8.3 to 13.0 kWh/day.
- Household T-01 had an average battery discharge ranging from 9.1 to 13.0 kWh/day over the year. The higher winter discharge was like household T-61, due to supplementary heating use.

Households saved up to an average of £1.21/day over the evaluation period

- Savings were calculated using standardized rates of 18p/kWh for peak rate consumption and 7p/kWh for off peak.
- For the batteries that were operational between April 2018 and January 2019, the total savings for households were between £323 and £368 over the period. This equated to average savings over the evaluation period of up to £1.21/day using the standardized tariff rates.
- When assessed over monthly periods, the average savings were between £0.77 and £1.29/day for household T-01. All other households were within this range apart from T-61.
- The battery for household T-61 was operational from June 2018 and the average savings were £0.23/day in June due to the low discharge. In January 2019 the average savings increased to £0.96/day.
- The total savings between 15 June 2019 and 31 January 2019 for household T-61 were £125. This equated to an average saving of £0.54/day over the shorter evaluation period.
- The savings from the Tesla Powerwall 2 battery grid charging were significantly larger than for smaller 2 kWh batteries in another study. These batteries were time shifting excess generation from solar PV systems and saved from £23 to £67/year.

The site import for 7 of the households increased by between 437 and 553 kWh between April 2018 and January 2019 due to inefficiencies in the battery.

- Due to inefficiencies in the inverter and consumption by the battery system, there was an increase in the grid consumption of the households due to the battery operation.
- For the households with batteries running from April 2018 until the end of January 2019, the extra site import due to the battery operation was between 437 and 553 kWh.
- This extra consumption took place during the off-peak period at a cost of between £30.59 and £38.71. The charge/discharge cycle of the battery was accounted for when calculating the savings due to charging on off peak and discharging during peak rate.
- Household T-07 switched to a single rate tariff and so there were no savings from charging at an off-peak rate. The extra site import due to the battery operation was 463 kWh between 14 Apr 18 and 31 Jan 19. As a result, the extra cost from the battery operation was £74.08 using a standardized rate of 16p/kWh for a single rate tariff.

4.2 Recommendations for potential future installations

It is important to select an experienced installer with a good reputation for a project. This will limit problems and ensure better quality installations. A local renewable energy installer is normally a better option as those based a long distance away will be reluctant to return for any maintenance or snagging issues and installations may be rushed. Some other NEA funded projects suffered from this. During the selection process photos of previous installations should be provided by the candidate installers to confirm the quality of their work. The cost of a Tesla Powerwall 2 battery is the same for single or bulk purchases. Savings on large numbers only come from economies of scale on the delivery, surveys and installations.

For a social landlord and others carrying out installations of batteries in larger numbers, it is important to allow sufficient time for recruitment of households for a project. It may take 3 – 6 months with communications provided by email and letter as well as community engagement events to build trust.

A full survey is required at each property a period before the installation. A suitable location should be available for the Tesla battery and the gateway, with sensible cable runs between the battery, gateway and consumer unit. Separation distances from walls recommended by the installation manual should be followed. All wiring should be fitted in plastic trunking to ensure neatness and safety. The battery has a fan and pump producing noise about the level of a refrigerator. Suitable locations for the battery include utility rooms, garages or outdoors away from direct sunlight. The battery needs access to the internet and so it must be confirmed that the household would be willing to allow the battery to connect to their WIFI router. This is usually done using TP Links between the Gateway and WIFI router.

The annual household electricity consumption should be assessed as part of the survey. Households with a high electricity consumption (particularly during the day) are likely benefit from greater savings from a battery charging at off peak rates. Note that if the battery is charging just from solar PV, a high daytime consumption can mean there is little excess solar generation to charge the battery.

If the battery will be charging on Economy 7 or another time of use tariff where night storage heaters will be also charging, the survey should also assess the maximum overnight electricity demand of the household. This should ensure that the addition of the battery would not take the overnight demand above the limit for the household supply. Western Power Distribution (WPD) assess the maximum demand by adding up the ratings for all the night storage heaters, the 3 kW immersion heater and include a residual load of 1.5 kW to 2 kW.

There was an update to the Powerwall 2 in January 2019, where the system measures the household grid import and if this approaches a set limit, the battery charge rate can be reduced. This however requires that the battery accurately measures the household supply. It is therefore important that the installer ensures both the main and heating electrical circuits are measured by the battery system and where necessary they use a Y-splitter cable. At the time of writing WPD has not approved the charge rate reduction of the Tesla battery as a means to allow installation at homes where the maximum overnight demand might approach the limit for the household supply.

During the recruitment process, documentation should be provided to households explaining the project, the benefits of the battery and how it works. If the battery will be charging only from the grid on a time of use tariff, this should be made clear to the household. An explanatory guide should also be left with the household after installation and labels left on the battery and by the electricity meter if charging off a time of use tariff. Information should also be provided if there is a change of tenant. It is important to ensure that households do not mistakenly switch from a time of use tariff to a single rate tariff if the battery is charging only from the grid. Project managers should consider dropping households from the list of installations if they do not adequately engage with the project and the technology. Problems over the installation are more likely to occur with these households.

At the time of the survey, details of the times for Economy 7 should be collected and the Standard Settlement Configuration (SSC) code. The electricity supplier should be contacted to confirm the times of off-peak electricity and if they alter when the clocks switch from GMT to BST.

Households should be provided with access to the Tesla app soon after the installation and a guide on how to use it. This will allow them to monitor their consumption and the battery output. This may encourage behaviour change, allowing additional savings to be made. The Tesla app should be set up with the appropriate times for off peak electricity and advice should be provided to each household on whether they need to switch the time when the clocks go forward or back.

Project developers should where possible install solar PV as well as the Tesla Powerwall 2 battery. The solar PV installation will increase the SAP rating of the property and provide free charging of the battery. This would improve savings for the household and reduce peak rate grid consumption further. However, this project shows that significant savings can still be achieved for high consuming households where the property does not or cannot have a solar PV installation.

The Tesla Backup Gateway 2 was released in Spring 2019. It costs about £1000 more than the standard version of the Gateway and enables the Tesla Powerwall 2 battery to operate during power cuts. Other advantages include the site metering improving from 1% to 0.2% accuracy. The Backup Gateway 2 should particularly be considered for households in rural areas which have greater risk of power cuts and for those on the Priority Services Register where the impact of a power cut is more severe.

Some lower consuming households do not make full use of the stored capacity of the battery. There is potential to use spare battery capacity for grid services in the future, improving the economics for the installation of a battery. It is currently not possible to provide grid services via the Tesla app. however it may currently be possible to provide grid services with a Tesla battery by adding a third-party control system. Tesla is likely to offer the ability to provide grid services in the future.

There were challenges on this project using the Verv data loggers. The large volumes of data produced were not straightforward to analyse. At times there were gaps in the data available online. 2 loggers were not connected to the monitoring portal and it was necessary to return these to the manufacturer. It was discovered that a fuse had blown in these and data was corrupted. It is recommended that consideration is given to utilising alternative systems, possibly linked to smart metering systems.

4.3 Impact on fuel poverty

This project has shown that significant savings are possible for high electricity consuming households on Economy 7 by adding a Tesla Powerwall 2 battery charging off the grid. For high consuming households the savings ranged from £0.77 to £1.29/day. For a household with a medium annual electricity consumption the savings were between £0.23/day in summer and £0.96/day in winter. Between April and the end of January, the maximum savings among the high consuming households was £368.

Greater savings could be achieved for households by adding a solar PV installation to allow the battery to charge for free from excess solar generation as well as at lower cost from the grid at off peak rates.

4.4 Economic business case for installation of measures

Measure	Equipment Cost (£)	Installation Cost (£)	Total Cost (£)	Annual energy saving (£, from study)	Indicative payback time (years)	Assumptions
Tesla Powerwall 2 (high electricity consumer)	£5,708	£1,000	£6,708	£440	15.2	• Prices are ex VAT • Installation with standard Gateway • average saving of £1.21/day •Peak rate 18p/kWh, off peak rate 7p/kWh
Tesla Powerwall 2 (medium electricity consumer)	£5,708	£1,000	£6,708	£198	33.8	• Prices are ex VAT • Installation with standard Gateway • average saving of £0.54/day •Peak rate 18p/kWh, off peak rate 7p/kWh

Table 4.1 A simple assessment of the business case for the Tesla Powerwall 2 battery when only grid charging

It is helpful to make a simple assessment of the payback time for the Tesla Powerwall 2 when operating with grid charging. The cost of the Tesla Powerwall 2 battery at the time of writing was £6,200 including VAT at 20%. The price for the standard Gateway is £650 and the new Backup Gateway 2 is £1700 including VAT at 20%. If the battery is fitted at the same time as a solar PV system, VAT is chargable at 5% and if the system is fitted as part of a new build then VAT can be 0%. Social landlords who own the property can claim back the VAT.

In this study the standard Gateway was used. Costs shown in table 4.1 are ex VAT and so the total equipment cost is £5,708 ex VAT. Tesla estimate installation costs of between £950 and £2800. For this assessment it is assumed that multiple installations would be taking place and the economies of scale on delivery, surveys and installations may allow an installation cost of about £1000.

Savings from the study were calculated using a standard Economy 7 rate of 18p/kWh peak rate and 7p/kWh off peak rate. The real savings for households will depend on their actual tariffs, in particular the difference in the cost between the peak and off peak rates. The savings for the high electricity consuming household were based on the average savings of household T-03 between 1 Apr 18 and 31 Jan 19, assuming this average rate occurs across the year. The savings for the medium energy user were similarly based on the average for household T-61 between 15 Jun 18 and 31 Jan 19 and converted to an annual saving.

The payback for the high electricity consumer is better than for smaller batteries fitted in households with solar PV[53] [54]. In these cases the payback was between 20 and 50 years. The Tesla Powerwall 2 has a guarantee for 10 years and the payback time for the high electricity consumer grid charging was about 15 years. This was within the likely operating lifespan of the battery. The payback for the medium consuming household was about 34 years, which may be beyond battery lifespan.

The business case for a battery can be improved by extra income and additional benefits:

- Charging of the battery from a solar PV system as well as the grid
- Using excess battery capacity to offer grid services. This includes income from:
  - The local Distribution Network Operator (DNO) – supplying power to the local network at times of the highest demand in areas where the network is constrained.
  - National Grid – Firm Frequency Response (FFR) – providing power to the network when the grid frequency deviates too far away from 50 Hz.
- Allowing more extensive installation of solar PV in an area. Where a social landlord or developer plans for multiple domestic solar PV systems to be installed in a small area, the DNO may limit the number of installations allowed to ensure there is not too much PV export onto the grid. The DNO is likely to allow a greater number of PV installations if installed with battery storage as charging of the batteries would reduce the PV export.
- The Tesla Powerwall 2 can operate during a power cut when fitted with the Backup Gateway 2. Households in rural areas more prone to power cuts or where maintaining power is important for health reasons may be willing to pay the approximately £1000 extra for the Backup Gateway 2 to ensure the household electricity supply is maintained.
- The Tesla app can also monitor the performance of an associated solar PV system. This would make it easier to detect when a fault develops to avoid potential lost income from the PV system. The app can also be used to analyse the household consumption and encourage behaviour change and a lowering of bills.

[53] Paul Rogers and Michael Hamer, Sungain Battery Bank (NEA, 2019) http://www.nea.org.uk/wp-content/uploads/2019/01/CP775-TIF-REPORT-FINAL.pdf (Accessed 4 Mar 19)

[54] Paul Rogers and Michael Hamer, 24/7 Solar (NEA, 2019) https://www.nea.org.uk/hip/24-7-solar-london-borough-camden/ (Accessed 4 Mar 19)

Appendix 1: Glossary of Terms

AC	*Alternating Current*
BEIS	*Department for Business, Energy & Industrial Strategy*
BST	*British Summer Time*
DC	*Direct Current*
DNO	*Distribution Network Operator*
DOD	*Depth of Discharge*
EPC	*Energy Performance Certificate*
GMT	*Greenwich Mean Time*
HIP	*Health and innovation Programme*
IHD	*In Home Display for smart meter*
kWh	*Kilowatt hour – a measure of electrical energy*
LED	*Light Emitting Diode*
MCB	*Miniature Circuit Breaker*
MCS	*Microgeneration Certification Scheme*
NEA	*National Energy Action – the National Fuel Poverty Charity*
NDH	*North Devon Homes LTD*
PV	*Photovoltaic*
RCD	*Residual Current Device*
RECC	*Renewable Energy Consumer Code*
SAP	*Standard Assessment Procedure (for assessing home energy efficiency)*
SOC	*State of Charge*
SSC	*Standard Settlement Configuration code*
TDCV	*Typical Domestic Consumption Value*
TIF	*Technological Innovation Fund*
TP Link	*A brand of powerline network device which uses household electrical wiring to act as a wired data network*
WPD	*Western Power Distribution*

Appendix 2: Example recruitment materials

NEA Tesla Powerwall 2 Battery Storage Study Information Sheet

Who is NEA?

National Energy Action[55] (NEA) is a National Fuel Poverty Charity. We are working with North Devon Homes to help them fit battery storage units into homes which are off the gas grid and using Economy 7 (or time of use tariffs). We will be assessing the benefits of the new battery storage systems on these households. .

An invitation to take part:

You are being invited to register your interest to be considered for a trial where you will receive a new battery storage system. The Tesla Powerwall 2 unit would be fitted to one of the outside walls of the house and a cable will connect it to the mains supply near your electricity meter.

The battery will be able to charge during off peak (cheaper) electricity at night and provide some of the power for appliances during the day when they would otherwise consume expensive peak rate electricity. This will be particularly beneficial for larger households with high electricity consumption. We estimate the maximum potential savings per year to be £250 to £300.

The trial is likely to last about six to nine months. The battery will remain at the property where it is installed after the trial so you will be able to continue to benefit from the battery, and make savings. If you would like more information about the technology, you can contact NEA or NDH.

Households receiving the batteries will be required to provide access to an internet connection where the wifi router is left on 24 hours a day. This will be necessary for the operation of the battery and the online monitoring. The data traffic is extremely low, and you'll not notice any impact on your broadband performance.

Several other projects are taking place, trialling different technologies, across the country. As this is a trial, only those eligible households selected by North Devon Homes who agree to take part in the monitoring will receive the measures. We would very much appreciate you being involved, to

[55] More information on NEA available at http://www.nea.org.uk/

help us learn how the new technology works in your home, and understand your experiences of using it.

What is the purpose of the study?

The research will help housing providers and Government to target investment in energy saving products and services which have the most beneficial impact on households.

Do I have to take part?

It is up to you to decide whether or not to take part, but we value your views and hope that you will help us by being involved. If you decide to take part, you will be asked to sign a consent form. This will record the fact that you give your permission for NEA to keep your data for the purposes of this study and that you are happy to be involved. It also confirms that all data we collect is confidential and that you will not be identified in any report or publication.

What happens if I agree to take part in the study?

It will be necessary for the installer to conduct a survey of your home to determine where the battery can be fitted and whether any ancillary electrical work may be needed. The battery installations are taking place in January or February. NEA staff will also agree a convenient time to visit you at your home prior to the installation work, and again at the end of the study period, which is likely to be during Summer 2018.

When we visit, we will fit small data logging devices which monitor your electricity use. These are likely to be fitted near your electricity meter, to record how much electricity your heating system and appliances use. We will also fit small battery powered temperature and humidity loggers which can be hidden behind an ornament etc. We may also fit another logger for electricity which plugs into a mains socket, but only consumes a very small amount of power. Pictures below illustrate what the loggers look like. Our visits will last around an hour. At the first visit, we will ask you about your energy use and the energy efficiency of your property.

Temperature & humidity logger (below left), energy logger (middle) which clips around the wires of your electricity meter (right). Where possible, we may fit an additional electricity logger powered by a mains socket

As energy use is a key part of the project, we will need **copies of your electricity bills from the last year. If you don't have these, we'll ask you to help us to obtain copies from your supplier**. We will ask you to provide bills (or meter readings) for the coming winter – we may ask to obtain these from your electricity supplier. We would like to read your energy meters when we visit, and we will ask you to take regular meter readings during the study. (We'll show you how, and give you a log book.)

When we visit again at the end of the study we will ask about your new battery storage system, what benefit it has provided you, and your views on using it. At this time we will also collect your completed meter read log book, data loggers and copies of any energy bills you have, so that we may assess the performance of the battery in detail. We may ask you to help us to obtain energy data from your energy supplier if you have a suitable meter.

What will I gain from taking part?

Firstly, you will receive a new Tesla battery storage system. As a thank you for taking part in the trial, to recognise the time you have given during the surveys, recording your meter readings and providing electricity bills, we will give you a £50 shopping voucher on the final visit when we collect our data loggers.

How many households will be taking part in the study?

At present we are planning to install 8 Tesla Powerwall 2 systems in NDH properties which are off the gas grid and on Economy 7. There are also opportunities for others to be part of the study by taking part as one of the *control group*. These households will not receive the battery, but there will still be monitoring of their electricity consumption and interviews to compare with the other households. The control group will also receive £50 in shopping vouchers. Taking part as one of the control group may be suitable for households who are unable to have a battery installation or are just interested in being part of the project.

Will my taking part in the study be kept confidential?

YES, all information collected about you and your household during the study will remain strictly confidential. Your contact details will only be kept if you agree to be involved in our study and will be stored securely on NEA premises. Personal details will not be shared with anyone outside the team involved in this study.

You will not be personally identified in any report or publication: Any quotes we use in our final report will be anonymous: no names of people, addresses or organisations you are part of will be used. If you think there is any other way that it might be possible to identify you from the discussions then please let us know and we can talk about it further.

What will happen to the results of the study?

The results of this study will be used to write a report on the benefits of the Tesla Powerwall 2 battery storage system for residents using Economy 7 and the savings that can be achieved. The study may influence decisions on whether to install battery storage like the Tesla Powerwall 2 in social housing in the future.

If you would like any further information on this study, please contact:

NEA's Technical Co-ordinator for this project, Paul Rogers, on 01271 855332

Our head office address is:

National Energy Action (NEA),
Level 6, West One,
Forth Banks,
Newcastle-upon-Tyne
NE1 3PA

Thank you

Figure 5.1 Recruitment leaflet produced by NEA for North Devon Homes customers

Appendix 3: Health and Innovation Programme 2015 – 2018

The Health and Innovation Programme (HIP) was a £26.2 million programme to bring affordable warmth to fuel poor and vulnerable households in England, Scotland and Wales.
The programme launched in April 2015 and was designed and administered by fuel poverty charity National Energy Action as part of an agreement with Ofgem and energy companies to make redress for non-compliance of licence conditions/obligations. To date, it remains the biggest GB-wide programme implemented by a charity which puts fuel poverty alleviation at its heart.

The programme comprised 3 funds

- **Warm and Healthy Homes Fund (WHHF):** to provide heating, insulation and energy efficiency measures for households most at risk of fuel poverty or cold-related illness through health and housing partnerships and home improvement agencies

- **Technical Innovation Fund (TIF)**: to fund and investigate the impact on fuel poverty of a range of new technologies

- **Warm Zones Fund (WZF):** to install heating and insulation and provide an income maximisation service to households in or at risk of fuel poverty, delivered cost-effectively through partnership arrangements managed by NEA's not-for-profit subsidiary Warm Zones Community Interest Company

What it involved

- **Grant programmes** to facilitate the delivery of a range of heating and insulation measures and associated support. Grant recipients were encouraged to source match and/or gap funding to increase the number of households assisted and to enhance the support provided to them
- **Free training** to equip frontline workers with the skills needed to support clients in fuel poverty
- **Outreach work and community engagement** to provide direct advice to householders on how to manage their energy use and keep warm in their homes

In addition we undertook substantial **monitoring and evaluation** work, to assess the effectiveness and measure the performance of the technologies, and to understand the social impacts of the programme. Our **communications programme** helped partners to promote their schemes locally as well as share best practice with others. The programme generated a considerable amount of **knowledge and insight** which will be made freely available to help support future policy and delivery.

Proper investment of advanced payments allowed us to generate interest which, along with efficiency savings, was reinvested back into the programme in the form of additional grants and support which helped us further exceed our targets.

For more information see www.nea.org.uk/hip

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NEA
Action for Warm Homes