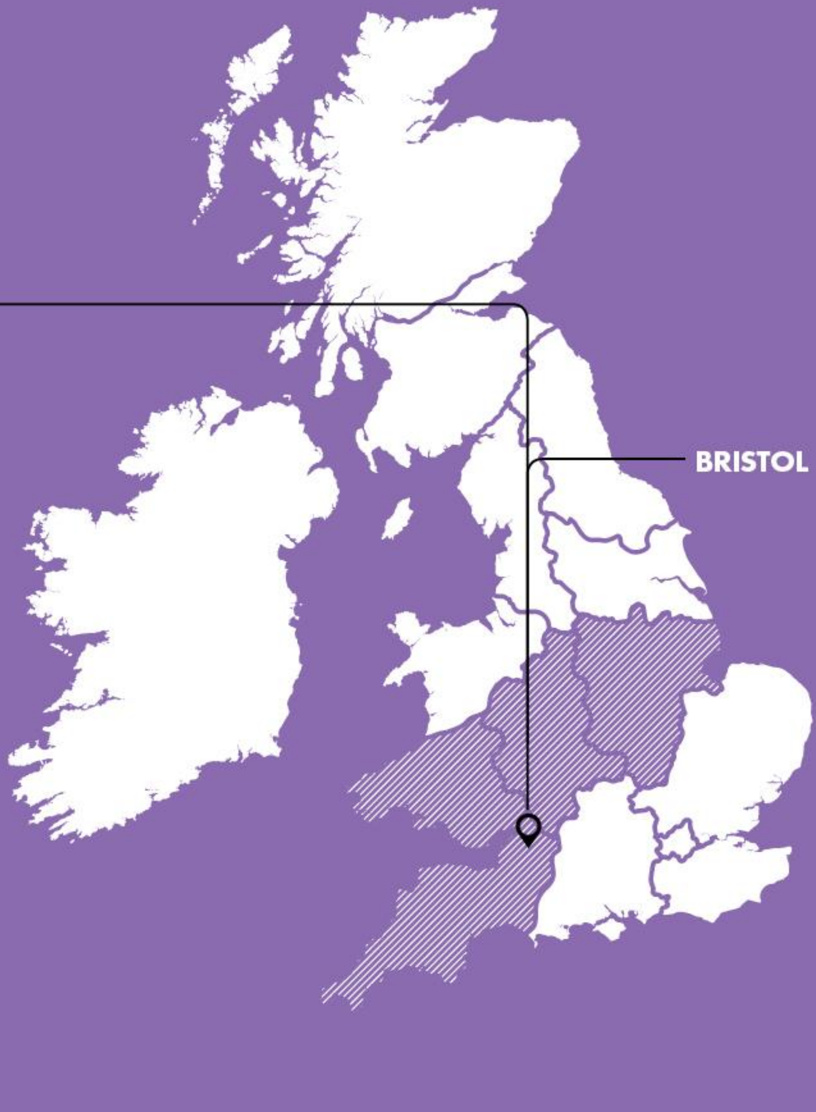
WESTERN POWER DISTRIBUTION

SOLA BRISTOL

PROJECT SOLA BRISTOL



Sola Bristol

Measured impact on the LV network SDRC 9.5

LCN Fund Low Carbon Networks · Bristol City Council · University of Bath · Knowle West Media Centre · SIEMENS

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Contents

Glossary

Abbreviation	Term
LVD	Low Voltage Disconnect
SOC	State of Charge
WPD	Western Power Distribution
LCNF	Low Carbon Network Fund
E7	Economy 7
DNO	Distribution Network Operator
DC	Direct Current
AC	Alternating Current
PV	Photo Voltaic
DRE	Data Repository Equipment
SE	Substation Equipment
UPE	User Premises Equipment
EMS	Energy Management System
BSP	Battery status processor
U-bat	Battery Voltage

1 Executive Summary

This report is an early learning report looking at the preliminary Network Benefits seen at substations that form part of the Sola Bristol Tier 2 LCNF Project.

The report looks at the network benefits from substations that have participating domestic, educational and Office customers connected to them. It looks at the actual data captured and compares this to the theoretical assumptions made at the project outset.

This is an early learning report with the intention of driving changes within the project to maximise the learning for the final report due in January 2016.

The report will also examine and record how the required operational changes have been discussed and implemented prior to this report, and how they will continue to evolve during the remainder of the project

As part of the previous early operational learning report, it was recognised that the assumptions made with regard to the domestic load profiles needed to be reviewed and multiple settings for the different load profiles introduced. These have recently been implemented to provide 3 different profiles: Normal, Economy 7 and high daytime load. The effect of these changes will continue to be monitored and any future adjustments will be implemented.

Meeting notes on the operational performance that drove the system updates are included in **Appendix 2**

The recently approved change request CCR005 allows the creation of 2 test units, one at Bath University and one at Siemens smart Lab in Newcastle University, and these will make the testing of new settings possible before they are introduced to 'live' customer properties.

The schools and office were installed in September 2014, when data capture commenced.

A network request simulation has been trialled in April 2015 and the results of this have been analysed and form part of this report.

2 Project Overview

SoLa Bristol is an alternative method to enable high density photovoltaic solar generation to connect to the Low Voltage network more efficiently through using an in-home battery and variable tariffs. The project aim is to address the technical constraints that DNOs expect to arise on Low Voltage networks as a result of the adoption of solar PV. The trial uses in-home battery storage to provide benefits to customers and aid the DNO with network management. Twenty six houses, five schools and an office have now been commissioned, with solar PV and a battery installed. With the domestic properties, the solar PV will be connected directly to the battery using a DC/DC converter. The AC lighting circuits in all the premises will also be converted to DC, and a set of DC outlets will be installed to enable customers to run small USB connected appliances directly from the PV/battery. The battery will be "shared‟ between the customer and the DNO. The customer will be provided with a pseudo variable tariff to encourage electricity use at times of high PV generation and to use electricity stored by the battery when the network is heavily loaded. The DNO will be able to communicate with the battery to charge and discharge it to help with network management.

The project will aim to:

- solve the network problems that arise when a number of customers in a local area connect PV solar panels to their house
- investigate how a battery installed in a property can help customers to manage their energy usage and save money on their bills
- test how customers respond when offered different electricity tariffs throughout the day
- explore the benefits of utilising direct current (DC) in the home, rather than the traditional alternating current (AC).

3 Network Overview

This distributed generation with local storage, on demand grid voltage support contribution demonstration network, consists of eleven substations with associated user premises. To recap a brief overview is shown below.

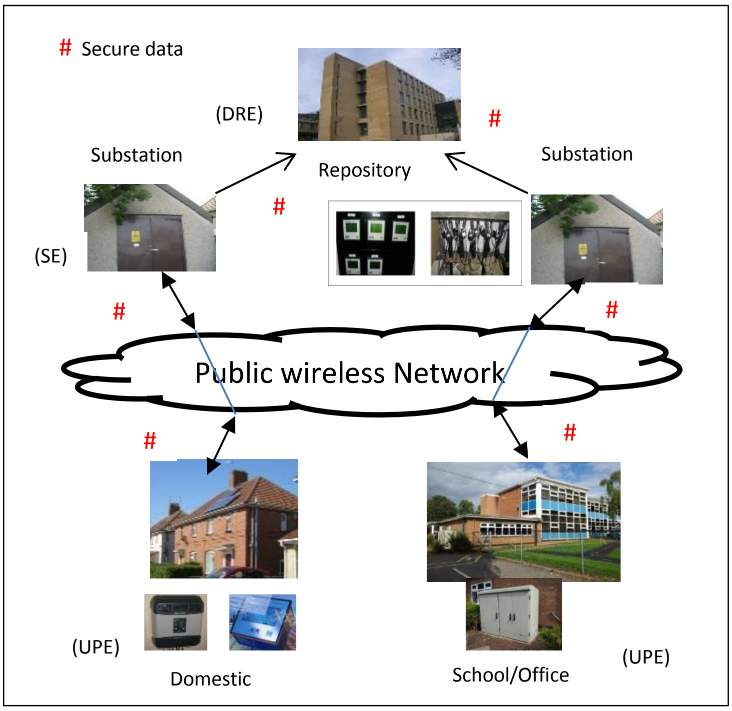

Figure 1 Sola Bristol DG-storage system

3.1.1 Substation monitoring

As mentioned in earlier reports, the substation equipment was designed to provide monitoring and communication capabilities at the substation. The supply-side monitoring data at the substation is used for quality of supply study. This equipment is a vital communication link to and from the associated sites. Each group of domestic, school and the office installation has its own associated serving substation.

A total of 11 substations have been equipped with monitoring equipment. The equipment provides the capability to monitor five feeders per site. The metering equipment displays are shown in fig 2 below.

Figure 2 Substation monitoring meters

The substation feeder current monitoring sensors are shown below, fig 3.

Figure 3 Substation Sensors

4 Capturing & Sharing Early Learning – Measuring the Network Benefits

During this learning period various studies are being conducted using the available site data. This section briefly describes some of results relating to the substation data and how it can be used in future systems.

4.1 Load profile comparison

In the following section, the network impact on power, based on measured data of power is analysed in detail and the investment deferral of network brought by the EMS system is calculated accordingly.

4.1.1 Domestic

This section covers three topics: a) the EMS behaviour; b) measured network load change; and c) network investment deferral.

a) EMS behaviour

Analysis of data collected between 1st August 2014 and 22nd March 2015 led to the identification of 6 periods, which show different daily battery charging/discharging and household export/import behaviours. These are shown in table 1. All of the identified periods share two characteristics:

- When there is Photo Voltaic (PV) output, the PV charges the battery first and then exports its surplus output to the main grid;

- The battery discharges 20%-40% of its capacity to export during the evening and night high demand time (16:30-22:00).

The behaviour variances focus on different battery charging and discharging behaviours overnight, in the morning, and in the afternoon. The behaviour variances among the 6 periods are listed in detail in table 1. There are different battery charging and discharging behaviours overnight, in the morning, and in the afternoon.

Period 4 of table 1 relates to the system when the lighting systems were powered from the grid and not from the battery system.

Table 1 Daily battery charging/discharging and household export/import behaviours

Period	Date	Time of Day				
		Overnight	Morning	Noon	Afternoon	Evening
1	4/8-24/10	1.Discharge to 50% SOC 2.Main grid charge to maintain 50% SOC	Discharge to 40%-50% SOC	PV charge (Surplus PV output exports to main grid)	PV charge (Surplus PV output exports to main grid)	Discharge to support load
2	25/10-23/11	1.Discharge to 50% SOC 2.Main grid charge to maintain 50% SOC	1.Discharge to 50% SOC 2.Main grid charge to maintain 50% SOC	PV charge (Surplus PV output exports to main grid)	PV charge	Discharge to support load
3	24/11-16/12	1.Discharge to 30% SOC 2.Main grid charge to maintain 30% SOC	1.Discharge to 30% SOC 2.Main grid charge to maintain 30% SOC	PV charge (Surplus PV output exports to main grid)	Main charge	Discharge to support load
4	18/12-15/1	Main charge to 90% SOC	Discharge to support load	PV charge (Surplus PV output exports to main grid)	PV charge	Discharge to support load
5	16/1-29/1	1.Discharge to 30% SOC 2.Main grid charge to maintain 30% SOC	1.Discharge to 30% SOC 2.Main grid charge to maintain 30% SOC	PV charge (Surplus PV output exports to main grid)	1.PV charge 2.Main charge	Discharge to support load
6	3/2-22/3	Main charge to average 80% SOC	Discharge to support load	PV charge (Surplus PV output exports to main grid)	PV charge	Discharge to support load

With the different household export and import behaviours, upstream network demand changes accordingly. Theoretically, the household import behaviours introduced by battery charging result in network demand increase. On the other hand, the export behaviours brought by battery discharging and PV output lead to network demand decrease.

In the following section measured network demands are compared to assess the real influences of household export and import behaviours. The network demand analysis is conducted by comparing the demands between consecutive periods, or within an individual period since the original demand and weather conditions are similar.

Network configuration

The Illminster Avenue substation is taken as an example to demonstrate the household export and import influences. The network configuration of Illminster Avenue substation is shown in fig.4. 11 tested houses are located at this substation. The houses' connection points are listed in table 2.

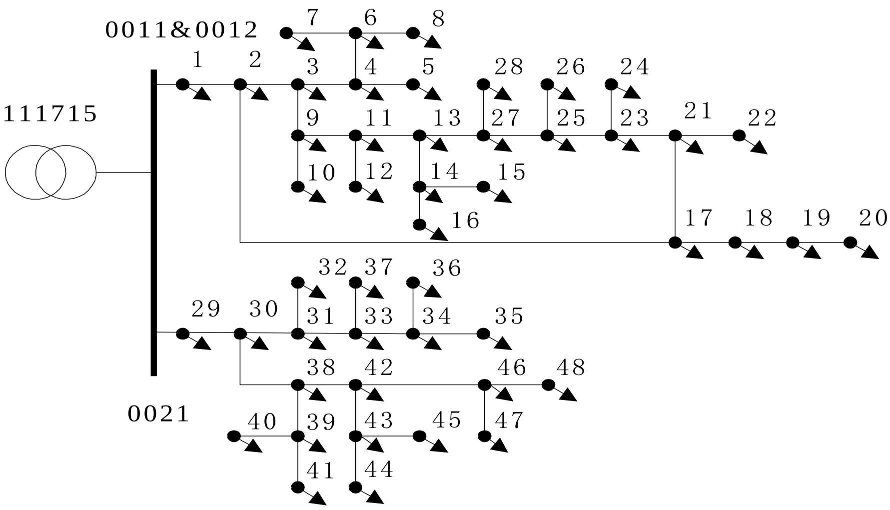

Figure 4 Network configuration of Illminster Avenue substation

Table 2 Customer connection information

Feeder No.	House No.	Connection point
1	13	Node 3
	15	Node 6
	16	Node 6
2	6	Node 18
	7	Node 18
	20	Node 10
	21	Node 10
	22	Node 11
	23	Node 2
	24	Node 5
	26	Node 3

The total number of customers linked to Illminster Avenue substation and the energy management system (EMS) installation number are shown in table 3.

The installed EMS ratio in feeder 2 (8:121) is higher than that in feeder 1 (3:136). Therefore, the potential demand change on feeder 2 should be larger than that on feeder 1. Consequently analysis is conducted on feeder 2 as that should provide a clearer example of the data.

Table 3 Customer and EMS number in substation Illminster Avenue

Feeder No.	Total Customer No.	Customer with EMS No.
Feeder 1	136	3
Feeder 2	121	8
Total	257	11

b) Measured network load change

In this section, the measured data of battery SOC and EMS import/export power, household consumption power and feeder 2's demand are analysed to investigate the EMS system impacts on the network.

In the project, a network push/pull trial was applied to Illminster Avenue substation on 20th, 22nd and 28th April. In the network push/pull trial, the battery will follow the request of the network regardless of household needs. The goal of the network push/pull trial is to test the battery reaction capability to the network requirement and to facilitate the analysis of the battery network impact.

The following analysis includes two parts:

1) Network demand change analysis on normal days;
2) Network demand change on network trial days.

1. Network demand change analysis on normal days

1.1 Network demand increase analysis

In this section, the demand comparison between periods 4 and 5 in feeder 2 (Illminster Avenue) is conducted. The aim is to verify whether there is the network demand increase brought by battery charging behaviours. The original load profiles and weather conditions during these two periods are similar because period 4 and 5 are consecutive periods in wintertime.

The examples of household battery charging behaviours in period 4 and 5 are shown in fig.5, fig.6 and fig.7. In fig. 5 showing “Battery current and power”, the positive values indicate that the battery is being charged while the negative values means the battery is exporting. In fig. 5 the graph showing “BSP-Ubat and SOC”, the blue line shows the battery voltage and green line gives the SOC. In period 4, as shown in fig.5, the battery is charged by main grid overnight between 21:00 to 4:00 and the battery SOC increases from 50% to 90%. The maximal charge power around midnight is nearly 1kW.

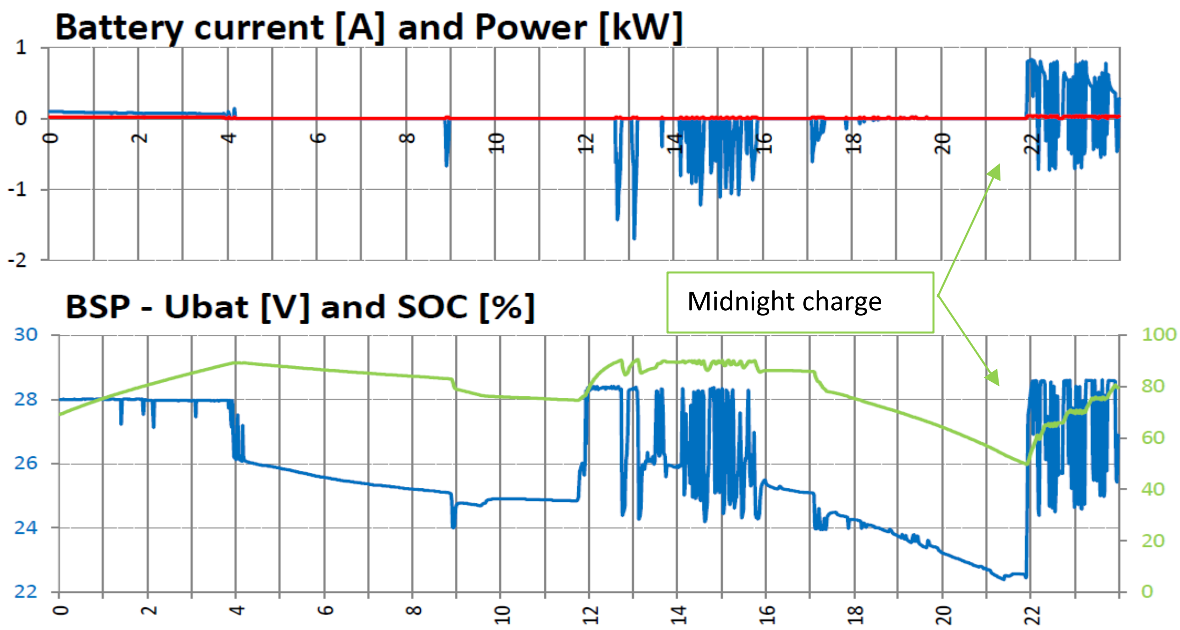

Figure 5 Household battery input power, voltage and SOC in period 4

In contrast, in period 5, the battery slowly discharges at midnight and is charged by the main grid to maintain the SOC at 30% in the early morning. During the daytime, it is charged either by PV output, as shown in fig.6, or the main grid, on low tariff between 14:00-16:30 when PV output is small as shown in fig.7.

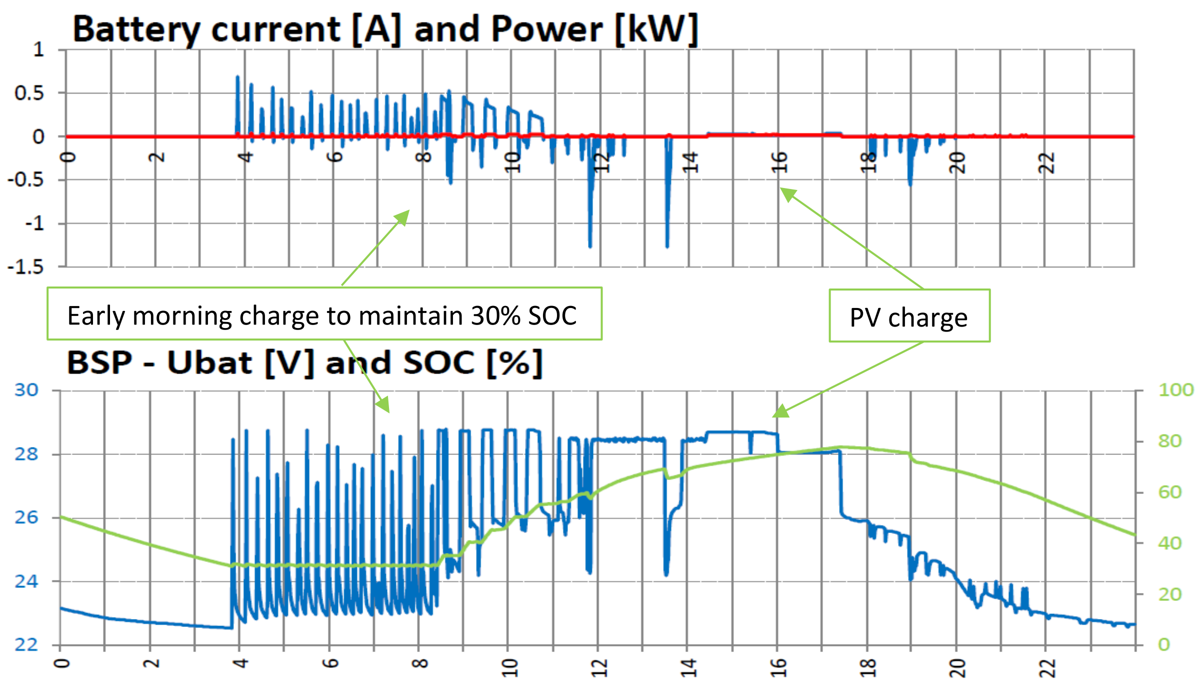

Figure 6 Household battery input power, voltage and SOC in period 5 (high PV output days)

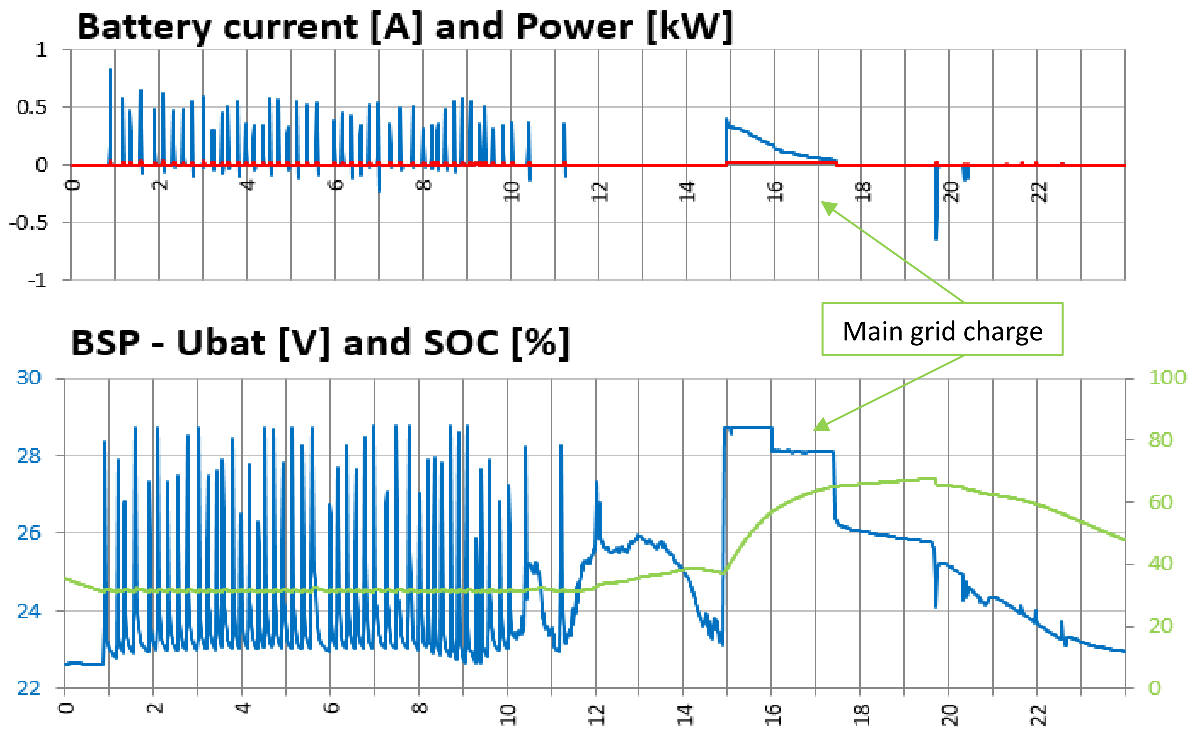

Figure 7 Household battery input power, voltage and SOC in period 5 (low PV output days)

The average households' power consumptions in periods 4 and 5 are shown in fig.8. The blue line shows the average house power in period 4 and red line represents that in period 5. The demand between 22:30 to 5:30 is high since there are two Economy 7 customers (house 6&7) among the 8 tested customers. During period 4, there is a clear demand increase from 21:15 around 0.43kW, as indicated by the purple arrow, compared with that in period 5. Additionally, the average demand between 14:00 to 16:30 is higher in period 5 indicated by the green arrow. It is likely that this is due to the PV output being lower during this period and consequently the main grid charges the battery.

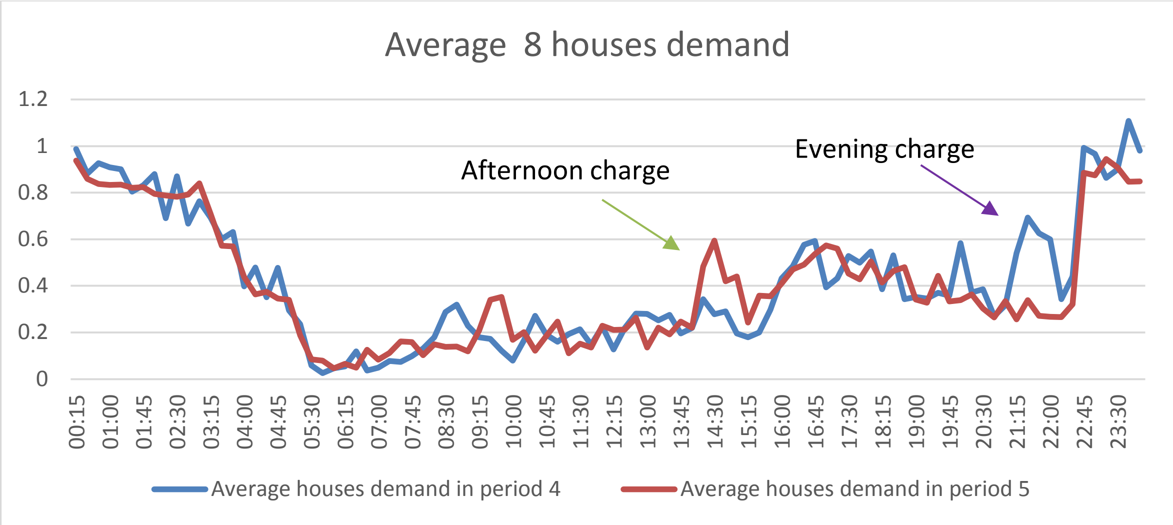

Figure 8 Houses power comparison between periods 4 and 5

The average feeder load profiles are shown in fig.9. It is apparent that when compared with the feeder demand, the 8-tested house total demand has limited impact. The evening peak of the feeder (140kW) is around 35 times of total evening peak of tested houses (4kW). The demand increase of 2-4 kW, brought by battery charging behaviour shown in the house power in period 4 and 5, from 21:15 and between 14:00 to 16:30 respectively, cannot be clearly reflected at the feeder demand.

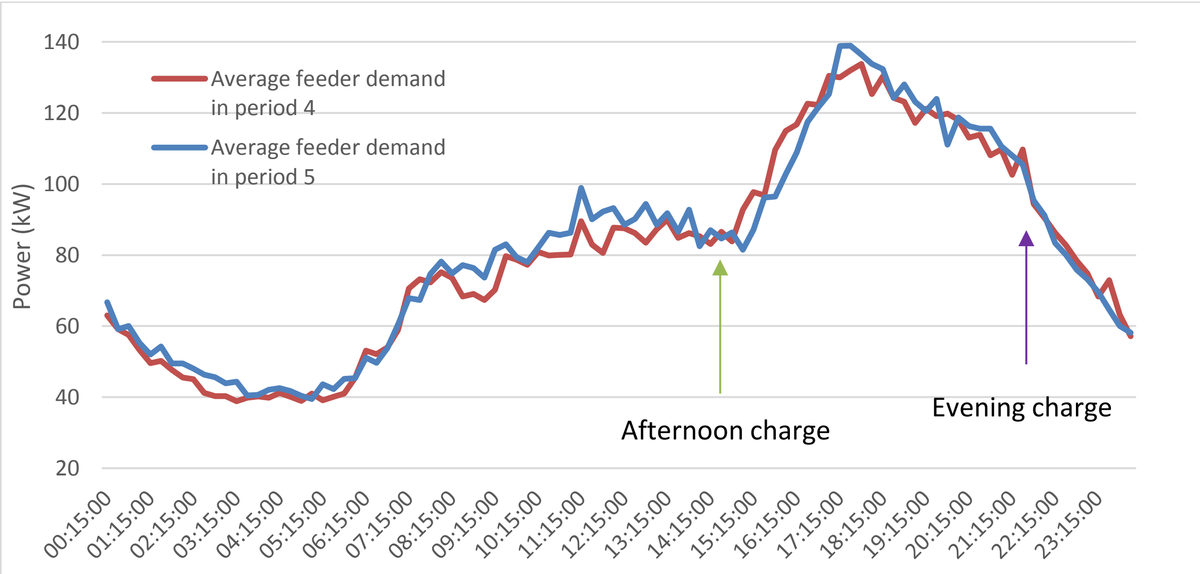

Figure 9 Illminster Avenue Feeder 2 load profile comparison

1.2 Network demand decrease analysis

To investigate the network demand decrease, comparison of high PV output days and low PV output days data from feeder 2 (Illminster Avenue) in period 1 are taken as examples to show the network demand changes brought by EMS exporting behaviour. The EMS exporting power comes from both battery discharging and PV output. Generally, the PV output is higher during period 1 since period 1 includes days from high summer and autumn.

In this section we compare dates in October. In the graph below, fig.10, we show the hours of sunshine recorded for each day, this allows us to judge the level of PV output. Seven days with high PV output; 3rd through to 9th of October, can be compared to 7 days with low PV output; 12th through to 15th, 18th, 23rd and 24th.

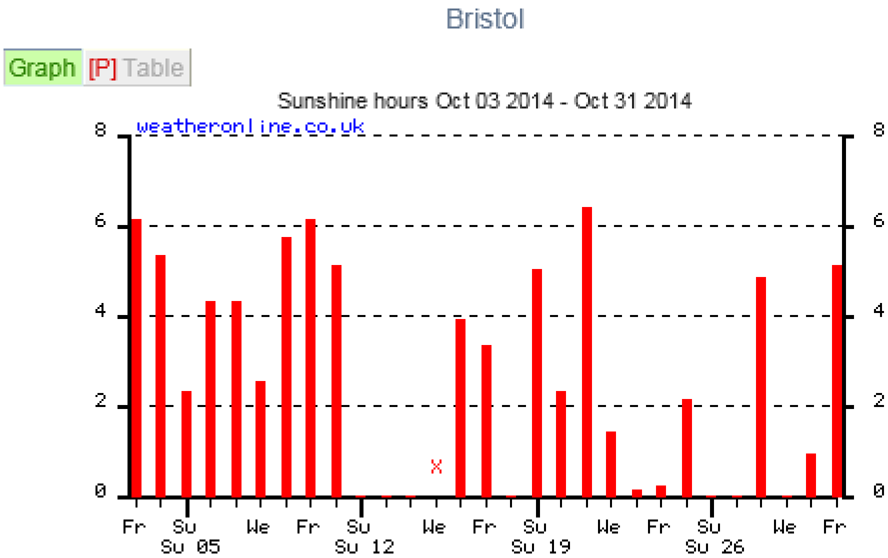

Figure 10 Weather condition in Oct[1]

On high PV output days, both battery and PV support the main grid. In the daytime, when the battery is fully charged by PV output, the surplus PV output is exported to the main grid. During the evening peak time, the battery discharges 20%-40% of its capacity and the available PV output is exported to the main grid. However, on low PV output days, only the battery discharges to support the main grid during evening peak time with limited stored energy.

Two examples of household exporting behaviours on a high PV output day and on a low PV output day respectively in October 2014 are shown in fig.11 and fig.12. In the graph, "Battery current and power", the positive values indicate battery is being charged and the negative values means the battery is exporting and supporting DC load. In the graph

1 [1] "Weather Online," 1 May, 2015; http://www.weatheronline.co.uk/weather/maps/city.

"BSP-Ubat and SOC", the blue line shows the battery voltage and green line gives the SOC. On the high PV output day, as shown in fig.11, the battery is charged to 90% SOC by PV output between 11:00 to 17:00. At the same time, the surplus PV output is exported to the main grid with maximum power of 1.5kW. During the evening time, both battery discharging power and available PV output are exported to the main grid. Meanwhile, on the low PV output day, as shown in fig.12, the battery is slowly charged to approximately 60% SOC and discharges to support network demand during evening demand peak time. There is very little surplus PV output to support the main grid during the daytime.

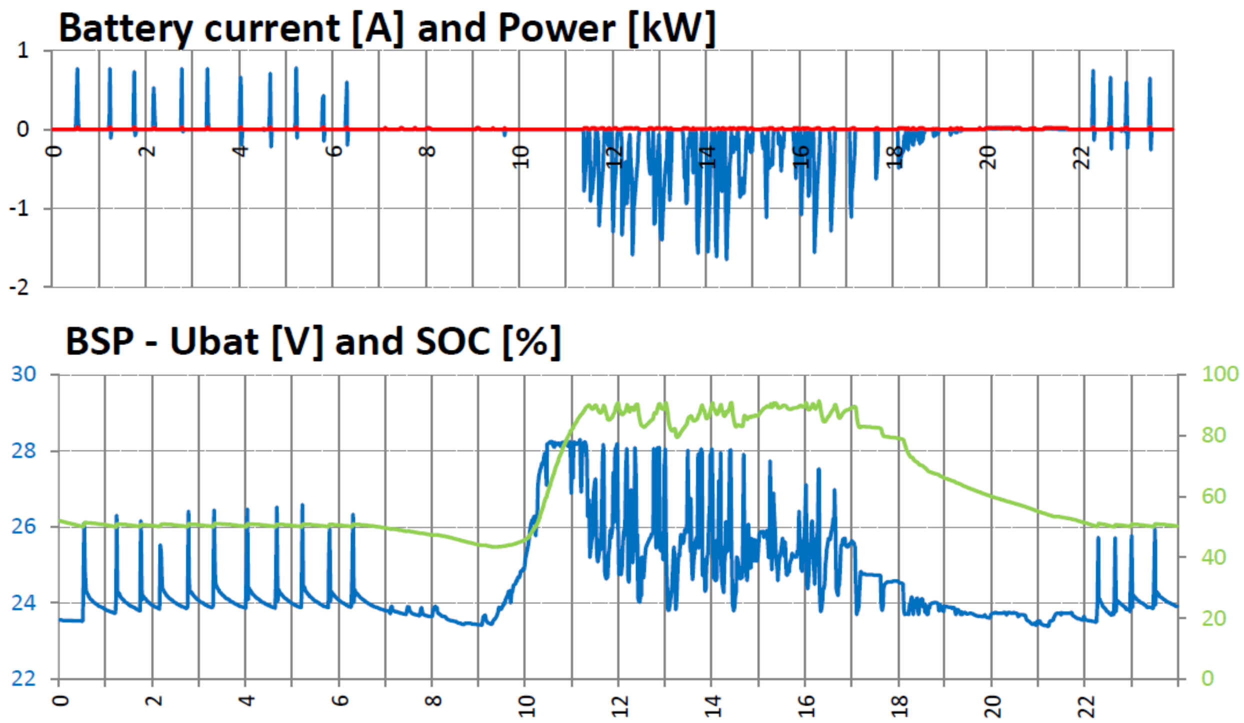

Figure 11 Household battery input power, voltage and SOC in period 1 with high PV export

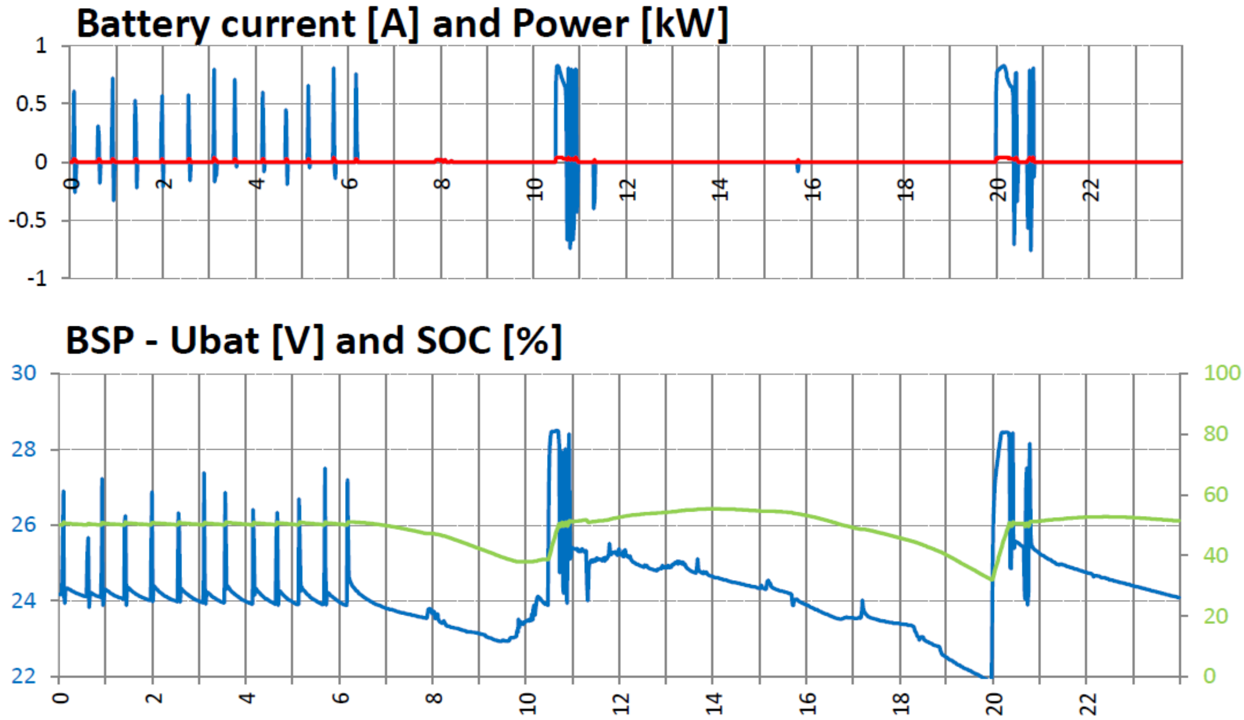

Figure 12 Household battery input power, voltage and SOC in period 1 with low PV export

The households' power consumptions on high and low PV output days are shown in fig.13 with blue and red lines respectively. Generally, from 11:00 to 20:30, the demand of high PV output days is lower than that of low PV output days, which indicates the EMS system exports more power and reduces more demand on high PV output days. The maximal demand difference is 0.7kW. The demand between 6:15-10:45 and between 14:30 to 16:00 on the high PV output day is slightly higher, which may suggest that the original demands (without EMS system) of the selected high PV output days are higher than those of selected low PV days.

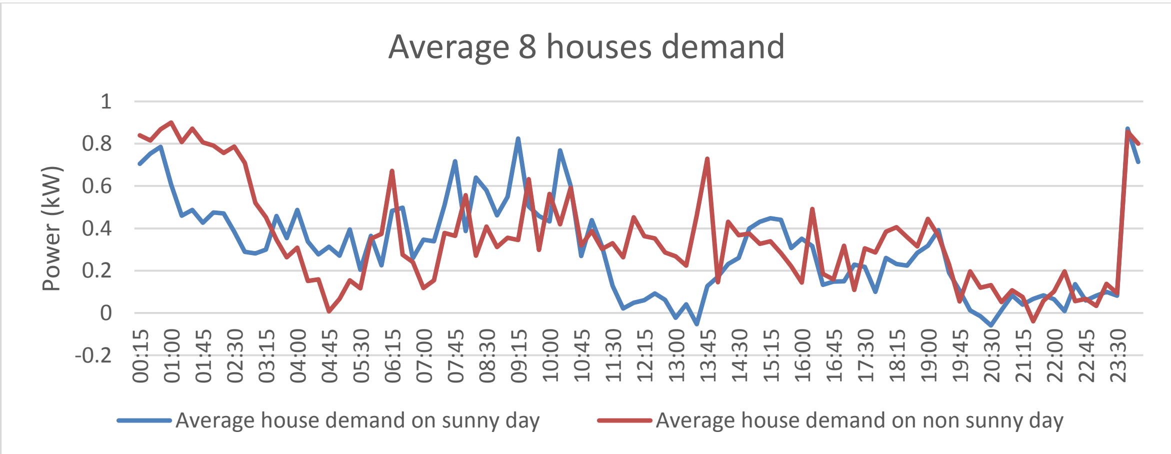

Figure 13 House power comparison

The comparison of average feeder 2's load profiles between the selected high PV output days and low PV output days is shown in fig.14. It is clear that the average demand on the high PV output day is lower than that on a low PV output day during the daytime. During the daytime, including demand peak time, there is an average 10kW reduction of network demand on the high PV output days compared with the low PV output days. However, based on the average houses demand shown in fig.13, the optimal contribution of the 8 houses' PV and battery system is about 5kW. Another important reason of demand reduction may be the customers' energy usage behaviour change on high PV output days compared with low PV output days, such as reduced usage of lighting and heating.

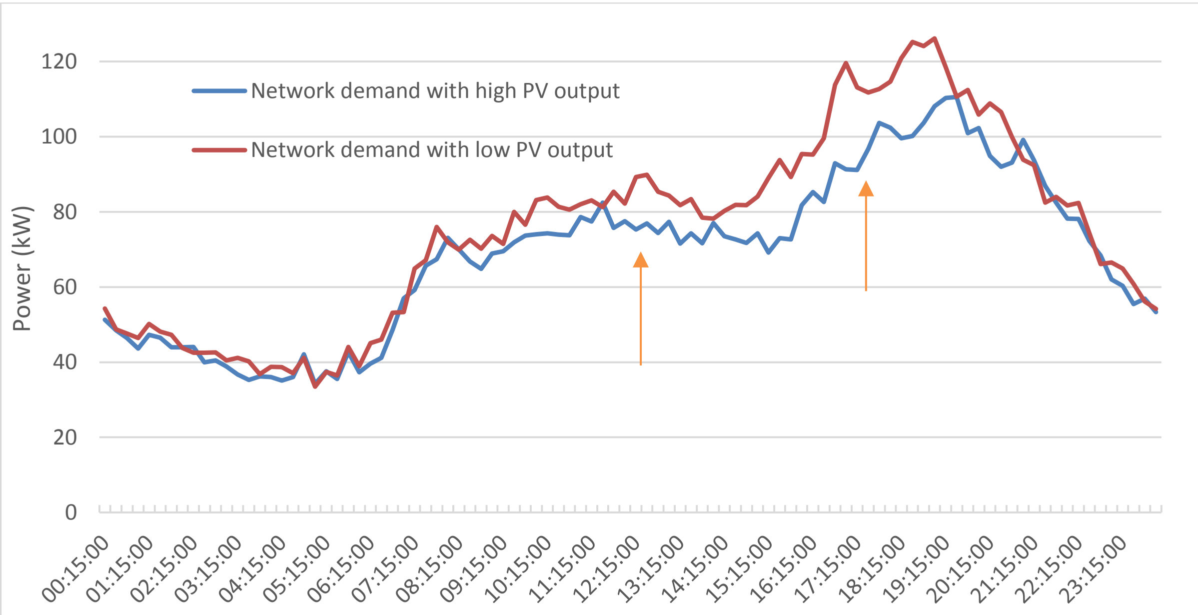

Figure 14 Illminster Avenue Feeder 2 load profile comparison

Discussion

The network demand increase and decrease analysis suggests that battery charging behaviours had relatively little impact on the network based on the current level of the EMS system installed at the Illminster Avenue substation. Among all the houses (121) linked to feeder 2, only 8 houses are installed with battery storage. The averaged maximal power contribution of the 8 batteries is 3.5kW, which is 2.5% of the feeder's peak demand. Therefore, it is difficult to identify the demand change on the network brought by battery behaviours. However, considering the results shown on the individual household demand change that each battery contributes average 0.5 kW to the network, the impact on the network will largely increase with the increase of installed battery number.

Additionally, the comparison results suggest that the PV output had a slightly larger impact on reducing network demand compared with battery. The averaged maximal power contribution of the 8 PVs is 5kW. However, the impact largely depends on weather, time of the day and season. On high PV output days, during late morning to afternoon, each EMS system can export up to 1.5kW to the network by PV output. In the evening peak demand time, the contribution of the PV is limited with reduced PV output. During winter there is very little PV output during evening peak time due to the reduced hours of daylight.

2. Network push/pull trials analysis

A network push/pull trial was conducted around Illminster Avenue substation on 20th, 22nd and 28th April. The network push/pull trial strategy is shown in table 4.

Table 4 Network push/pull trial strategy

Time of Day	Substation request	Aim
00:00-14:29	No force charging/discharging	--
14:30-16:29	Force charge the battery	Ensure the battery has enough stored energy to support the network requirement
16:30-16:59	Remove the force charging from the battery	Logic operated and battery slowly discharged to the target SOC of 89%
17:00-18:14	Force discharge of the battery	Various rates discharging between 1-2 kW at each 15 min interval
18:15-18:59	Force charge the battery	Reach the target SOC of 60%
19:00-23:59	No force charging/discharging	--

The trial results show that in the three days, the performance of the batteries could be concluded into two categories as show in fig.15. There are 4 houses in the total 8 houses (50%) with “hard push/pull battery” shown in the left graph. The SOC of the “hard push/pull battery” increases to 100% after the “force charge” stage and decreases 30%-70% of SOC in the “force discharge” stage. Meanwhile, the batteries in the remaining 4 houses (shown in the right graph) are charged up to 70% of SOC and discharges on average 10% of SOC during the “force discharge” stage.

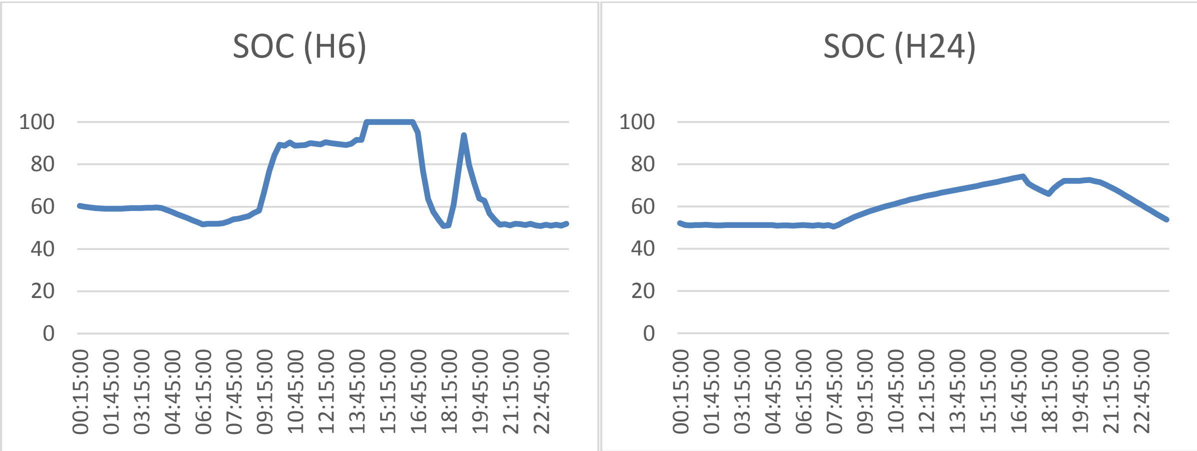

Figure 15 Typical SOC in network push/pull trials

The demand of the 8 houses included in the network trial during the trial days (20th, 22nd and 28th April) and non-trial days (21st, 23rd and 27th April) are shown in fig.16 with red and blue line respectively. The weather during all six days was sunny (high PV output), which leads to power exporting during noon time shown in both blue and red lines. On trial days, the increase brought by forcing charge request is relatively clear shown in the demand comparison. Between 14:30-16:00 and 18:15-18:59, the house average demand during trial days is higher than during non-trial days with maximal 0.8kW. However, the house demand decrease is only shown at 16:45 and 17:00.

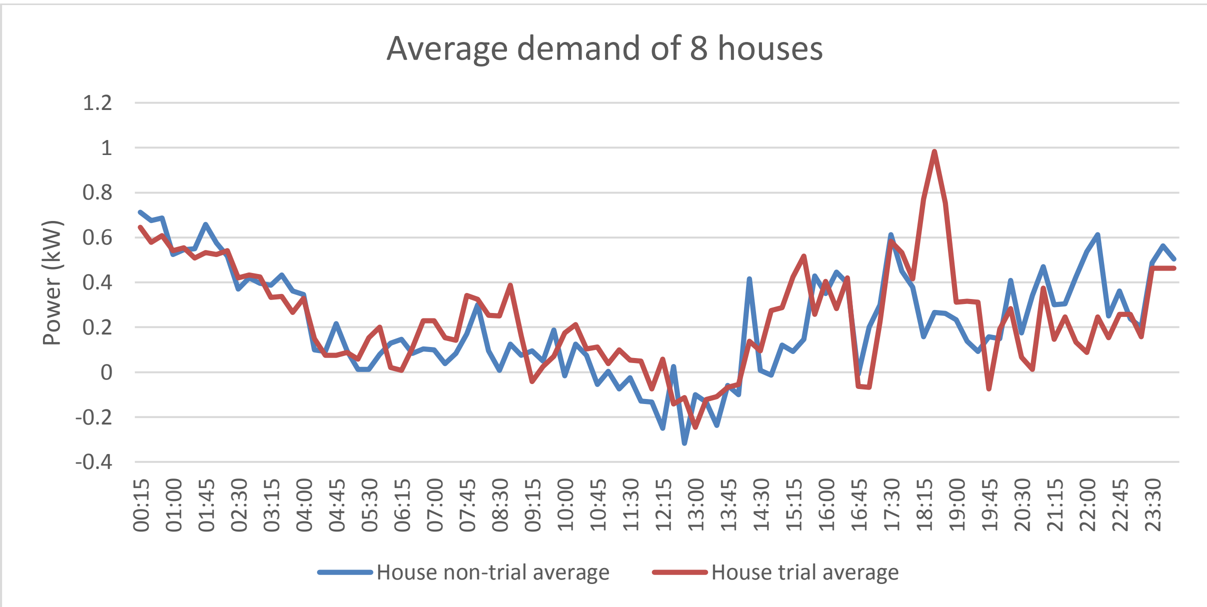

Figure 16 Houses demand comparison

Furthermore, the performance of network push/pull trials is analysed based on "hard push/pull batteries". The trial and non-trial demand of two houses, which are linked to the same phase of feeder and both with hard push/pull batteries, are shown in fig.17. The blue line shows the average house demand during the non-trial days and the red line represents that during trial days. It is more obvious that between 14:30-16:00 and 18:15-18:59, the house average demand on trial days is more than 1kW higher than that on non-trial days. Between 17:00-18:14 ("force discharge" stage), the demand on trial days is generally lower than that on the selected non-trial days. The negative demand means the houses support the main grid by generating power. The average exporting power on trial days and selected non-trial days are 0.3kW and 0.2kW respectively. During non-trial days, the exporting power comes from available PV output and normal battery discharging behaviour and on trial days, it is the discharged power of the battery as requested from the substation.

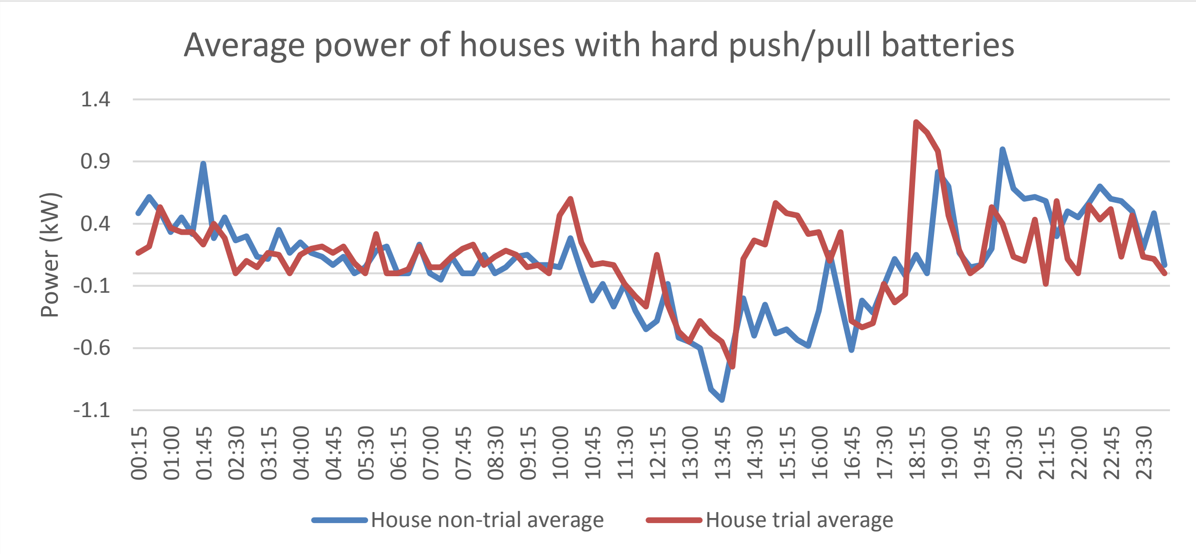

Figure 17 Houses demand comparison with hard push/pull batteries

The network impact brought by the network trial is analysed by comparing the corresponding phase load profiles of the feeder and houses load profiles on trial and non-trial days. In the project, 4 tested houses are connected to phase 3 of feeder 2. In those 4 houses, 2 of them (50%) have hard push/pull battery, which has been already demonstrated in fig.17. The ratio of hard push/pull battery connected to phase 3 is higher than that in other phases. Therefore, the relative demand change in phase 3 should be more obvious.

Consequently, the average feeder 2 phase 3 load profiles and those of the connected houses are shown in fig.18. The total tested house demands on trial and non-trial days are shown in purple solid and green dash lines. The house demand increase brought by the force charging request is clearly shown between 14:30-16:29 and 18:15-18:59 and the house total demand decrease is only shown at 17:00. The high demand during "force discharge" stage (between 17:00-18:14) on trial days comes from house 24, which has especially high demand on two of the trial days.

The phase demands on trial and non-trial days are represented by red solid and blue dash lines. The daily demand of non-trial days is generally higher than that on trial days.

Therefore, the 2kW and 4kW demand increase introduced by “force charge” stages between 14:00-16:29 and 18:15-18:59 are not clearly reflected on the phase demand comparison between trial and non-trial days.

Despite this, interrogation of the phase demand change data can provide an insight into the impact of the battery. On trial days, there are two small demand peaks, one between 14:00-15:30, as indicated by the green arrow, and one at 18:15 as indicated by the orange arrow (between two larger peaks); these may be caused by the force charging of the battery.

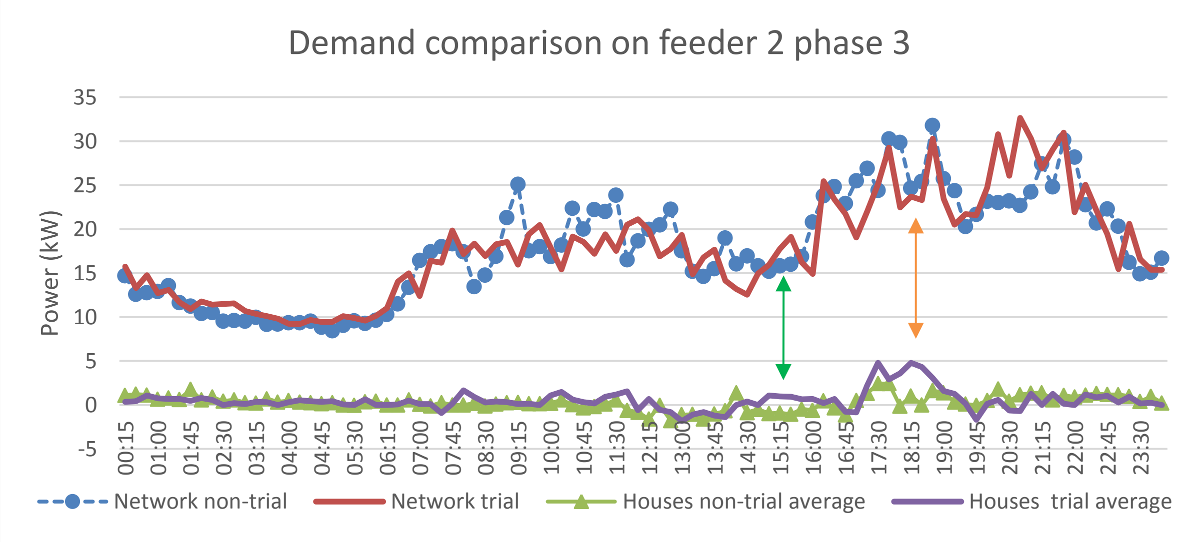

Figure 18 Phase demand comparison

Discussion

The results of the network push/pull trials suggest that the operation of the battery effectively changes the load profile of the customer. The trial results of house demand indicate that the forced discharging power not only fulfils the demand of houses themselves, but also supports other customers’ demand by an average 0.3kW.

The comparison of the houses’ demands on trial and non-trial days suggests that the operations of the EMS system is suitable for different seasons and weather conditions. The results of comparison shows there is very little difference on the exporting power during “force discharge” stage between trial and non-trial days. In order words, the PV and battery effects of non-trial operation are similar to the battery effects under network request. However, when the PV output increases in the summer time, non-trial operation may export more power and when the PV output significantly decreases, such as in the winter time, the trial operation could guarantee the network benefit brought by the EMS system.

The battery importing and exporting impact can be reflected on phase demand but most of the impacts are masked by the large and volatile network demand. Firstly, the house demand differences between trial and non-trial days are not very obvious. The maximal demand difference is 4kW at 18:15. In most times of the day, the demand difference of the 4 houses is less than 2kW. Moreover, the network demand variety is large because only three days' average demand are compared. As shown in fig.18, there are several small demand spikes in both trial and non-trial days. The demand difference brought by the battery could be masked by the demand difference of the network itself.

c) Network investment deferral

In this section, the investment deferral of Illminster Avenue substation is calculated based on the method written in the appendix 1. The network utilization of the Illminster Avenue substation is 41%. With the assumption of 2% load growth and 5.6% discount rate[2], the time-series power flow shows that in the next 6 years, the feeder connected nodes 29, 30 and 38 will reach the thermal limits shown in fig.19. The EMS systems of 8 houses at feeder 2 can defer network investment for one year. The typical unit cost of feeder is £67200/km and the unit cost of transformers is £26400[3]. The result of potential network investment deferral is shown in table 5. The investment deferral if the penetration of EMS is increased to 30% and 50% are also calculated. This will defer network investment for 4 years and 6 years respectively.

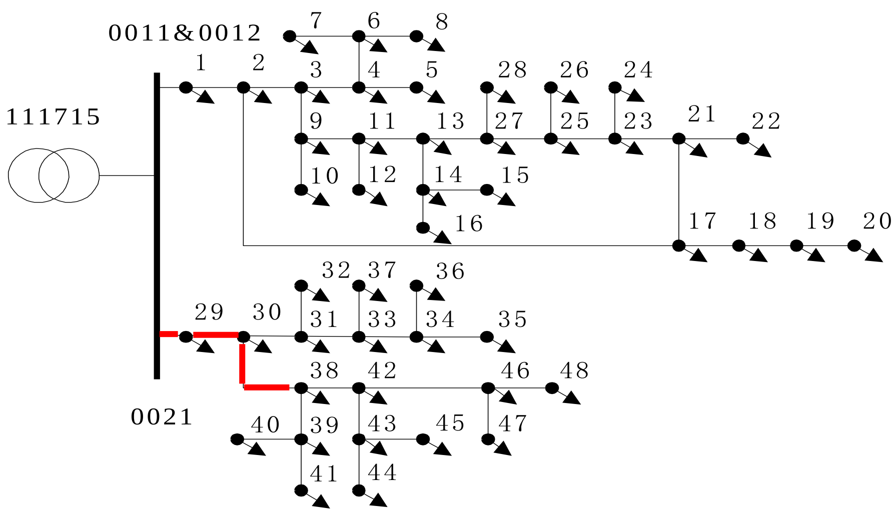

Figure 19 Network congestion location

Table 5 Network investment deferral

[2] [2] W. P. Distribution. "CDMC-ARP-April-2015-Pre-Release-South-West-v2," 2014; http://www.westernpower.co.uk/docs/system-charges/CDCM-Annual-Review-Pack/2015/CDMC-ARP-April-2015-Pre-Release-South-West-v2.aspx.

[3] [3] "Electricity Distribution Price Control Review Final Proposals - Allowed revenue - Cost assessment appendix " O. o. G. a. E. Markets, ed., Office of Gas and Electricity Markets 2009.

	Current penetration	30% penetration	50% penetration
Transformer	£273	£1725	£2786
Feeders	£197	£1261	£2049
Total	£470	£2986	£4835

4.1.2 Schools

This section covers three topics: a) the EMS behaviour; b) measured network load change; and c) network investment deferral.

a) School EMS behaviour

The battery charging/discharging and school export/import behaviours follow the same pattern from Dec 2014 to April 2015. The example of weekday school battery total charging and discharging behaviours in 24th March is shown in fig.20. In the graph "System power", the positive values indicate the battery is being charged and the negative values means the battery is exporting and supporting DC load. In the graph "BSP-Ubat and SOC", the blue line shows the battery voltage and green line gives the SOC. The battery is charged by the main grid overnight at maximum charging power of 6kW from 40/50% to 70/80% of SOC. In the daytime when the school is open, the battery discharges 20-40% of its capacity to support the school's DC lighting and computers. In the afternoon, the battery is charged at maximum 6kW between 15:00 to 18:00 in order to discharge after 18:00 to support the network.

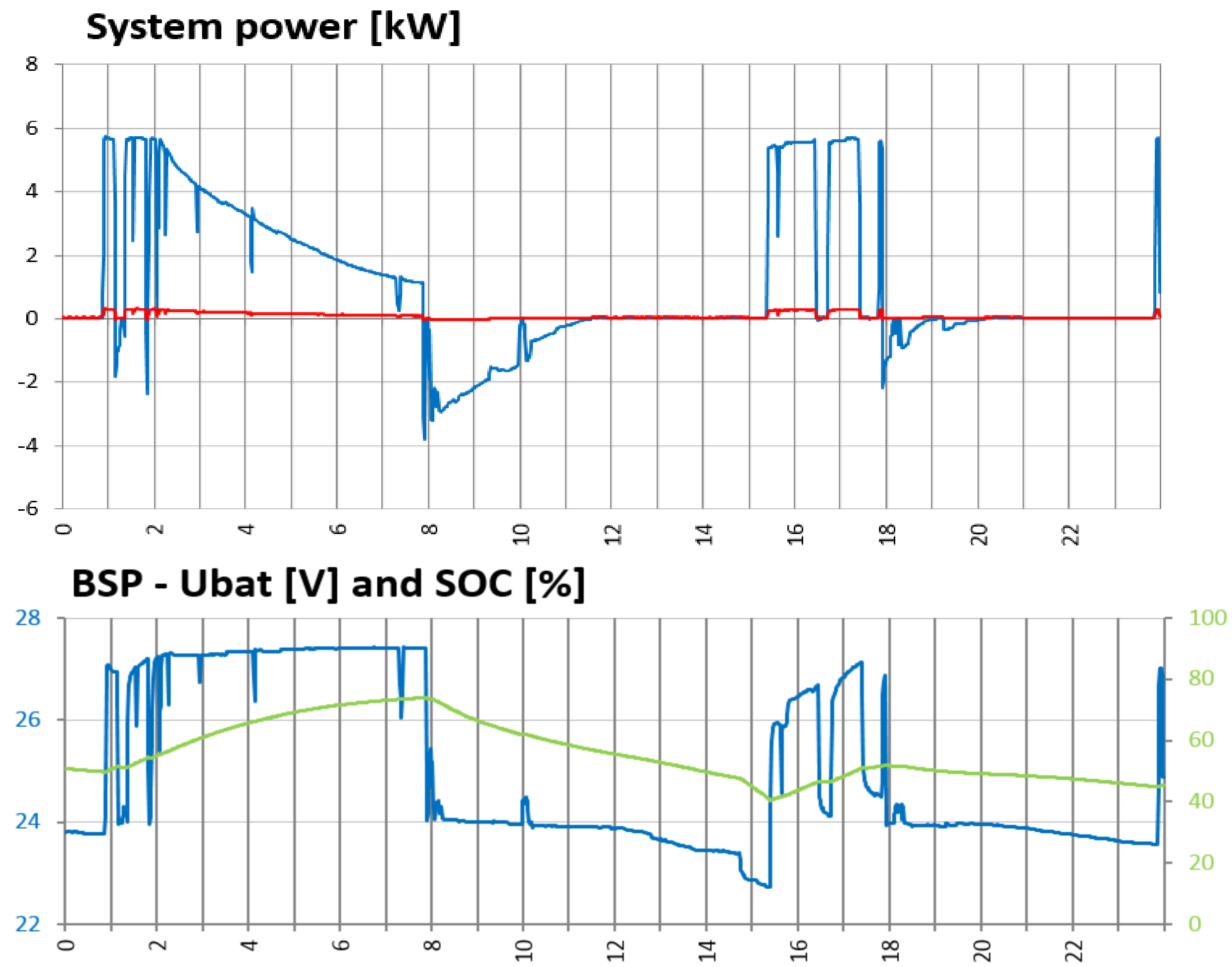

Figure 20 School battery input power, voltage and SOC

Specifically, the EMS system of the school is connected to three phases of the network. It facilitates the three phase balancing of the network by importing power from one phase and simultaneous exporting power to another phase. Fig.21 below shows the four modes of operation of a three phase system. The colour associations are Red (L1), Yellow (L2) and Blue (L3) for the individual inverters (solid line) and the dotted green line is the net battery current.

All currents shown here are DC currents. Positive values indicate currents flowing in, towards the battery and the DC load, and the negative currents are flowing out of the battery towards the respective three phase inverters as well as all attached DC loads.

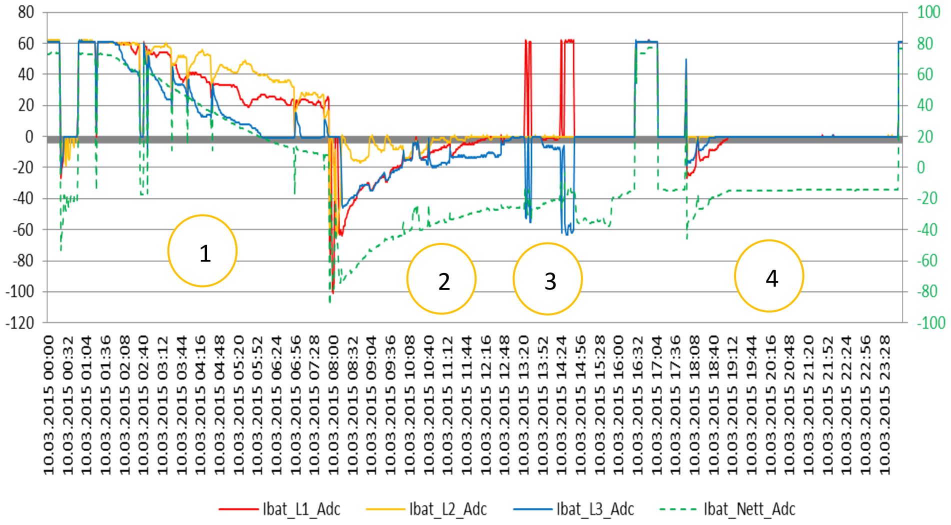

Figure 21 School battery three phase charging/discharging current

During Mode 1 operation, which spans from 00:00 to 08:00, the battery is being charged from all three phases with slightly different current during off-peak charging period.

During Mode 2 operation, from 08:00 to 13:00, the net negative battery current shows battery being discharged during DC load support while the AC power is also being exported to the grid on all three phases with one phase exporting less than the other two.

During Mode 3 operation, which is phase balancing mode, the plots show power being imported from “red (L1)” phase (positive current) and simultaneously being exported to “blue (L3)” phase (negative current).

Operational Mode 4 shows no significant inverter activity as all three phase currents are near zero. The battery current which is negative in value is supporting the system load.

Network configuration

The network configuration of school connected substation is shown in fig.22. The school is connected at node 14. There are total 123 customers connected at this feeder including the school

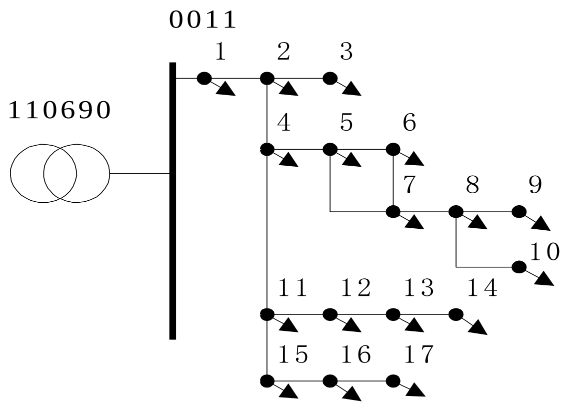

Figure 22 Network configuration

b) Measured network load change

In this section, the measured network demand change is illustrated by comparing network demand on different days with different school battery behaviours. Generally, the battery behaviour of school follows the same patterns on weekdays and weekends respectively. However, there is a minor difference in the overnight charging start time between days. On some days, overnight charge begins at early night about 21:00. In contrast, on other days, the overnight charge begins later at about 2:00-3:00.

The weekday overnight network demands and school demands on two different days are shown in fig.23. The dash lines represent the network and school demands on 17th April and solid lines represent those on 20th April. As shown in the graph, from 0:00 to 6:15, the school demand on 17th April (green dash line) stays between 7kW to 4kW because the battery starts to charge at the night prior to 21:00. The overnight network demand on 17th April (blue dash line) varies from 23kW to 35kW. In contrast, the school demand on 20th April (purple solid line) increases from 0kW to 7.5kW at 2:45 because the battery starts to charge at 2:45 as indicated by the yellow arrow. At the same time, there is a 9kW demand increase in the network as indicated by the green arrow (red solid line). However, the network demand decreases 10kW at 3:00 while school demand still stays at 7-9kW. The demand decrease shows that the network demand change is a result of greater uncertainty. Therefore, the school battery charging/discharging behaviour cannot be clearly identified at the network level.

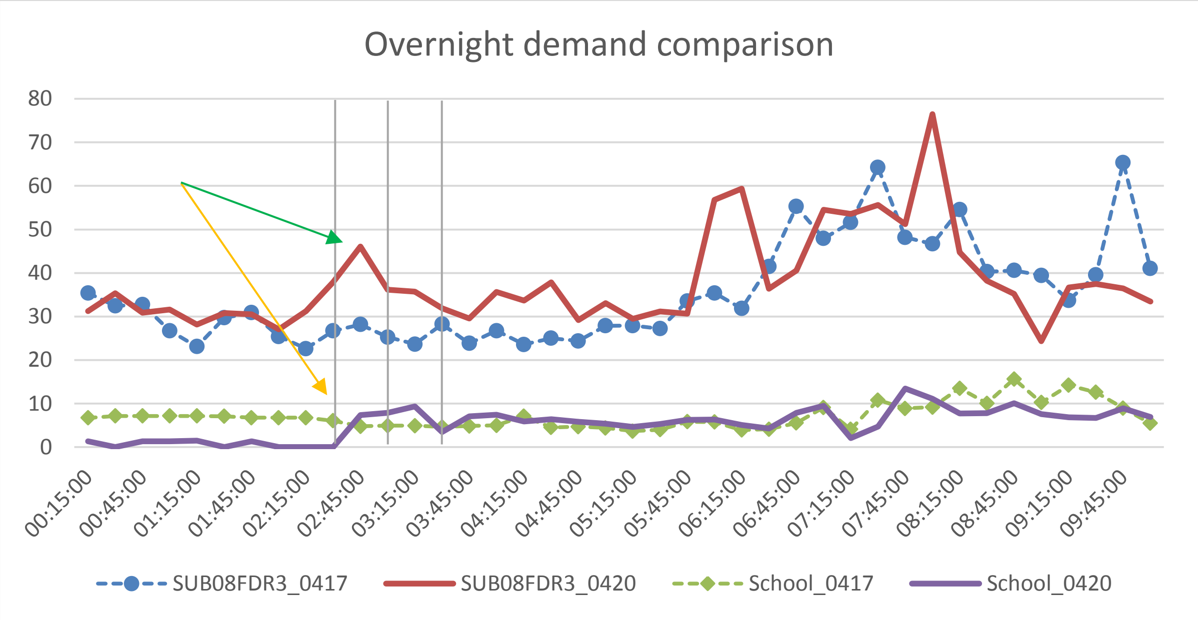

Figure 23 Network overnight demand comparison

Discussion

The school battery impact on the network demand cannot clearly be shown in the demand comparison. Theoretically, the averaged 5.3kW school demand increase would bring at least 5.3kW network demand increase. (With little power loss on the LV distribution network, the network demand increase should be equal or slightly larger than 5.3kW.) Besides, school battery charging power, 4-7kW, accounts for relatively larger portion in the overnight network demand, 20-30kW. The school demand increase should be more influential.

The comparison result suggests that the battery installed at school had little impact on the network. The reason may come from: 1) the small size of school battery; 2) the large demand variance at the monitored feeder. The averaged charging power of the battery, 5.3kW, is equal or smaller than the demand variation. The network demand change brought by school battery may be masked by demand variation led by other connected customers.

Further investigation will be conducted and discussed in the Final Report.

c) Network investment deferral

In this section, the investment deferral of the school linked substation is calculated. The annual peak of the substation is 280kW during January. The network utilization is 56%. With the assumption of 2% load growth, in the next 19 years, the feeder connected 1 and 2 will reach the thermal limit as shown in fig.24.

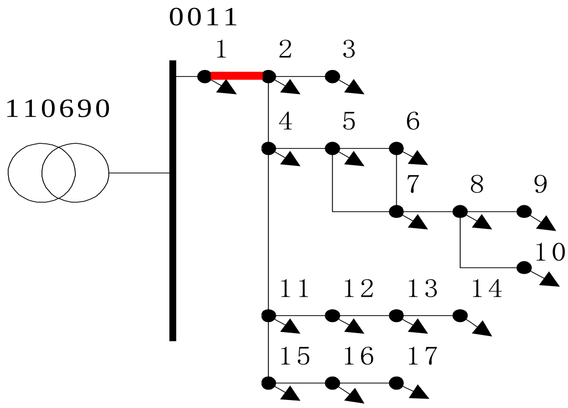

Figure 24 Network congestion location

Before May 2015, the school was charged by the main grid during 15:00 to 18:00 and discharged to support network demand after 18:00. However, the daily peak of the substation is during 17:00-18:00, as shown in fig.25 indicated by the red arrow, when the battery of the school is charged by the main grid. Therefore, the school battery cannot reduce the network demand peak. However, after May, the time of charging is adjusted to 14:00 to 16:00.

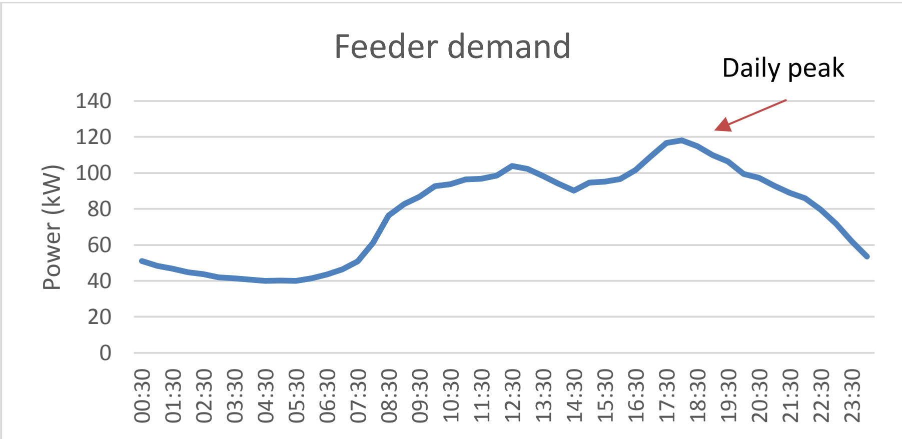

Figure 25 Network demand

By changing the battery charging time, the battery of the school could reduce the network peak demand by 4kW, which can defer network investment for one year. The result of potential network investment deferral is shown in table 6.

Table 6 Network investment deferral

	Investment deferral by school
Transformer	£71
Feeders	£140
Total	£211

4.2 Network voltage profile

In the following section, some key findings in voltage from the measured data are demonstrated.

Fig.26 below shows voltage only correlation between one serving substation's single feeder and its associated two homes. The plot covers a 48 hour period from midnight to midnight. The solid lines are the three phase voltages (red L1, yellow L2 and blue L3) at the substation and the dotted lines are the voltage profiles, as seen at the domestic properties. For clarity these plots contain rolling averages. This data set consists of discrete samples taken at 15 minute intervals.

It provides a multitude of information about the feeder, for instance: The voltages are within the permissible limits, between 216.2-253V. Phase loading can be seen, where Blue (L3) phase is lightly loaded compared to Yellow (L2) phase, which has the heaviest loading. Further, it can be seen that at around 10am (pointed by blue arrow) all voltages, substation and domestic, increase nearly simultaneously, indicating an upstream 'tap-change' activity.

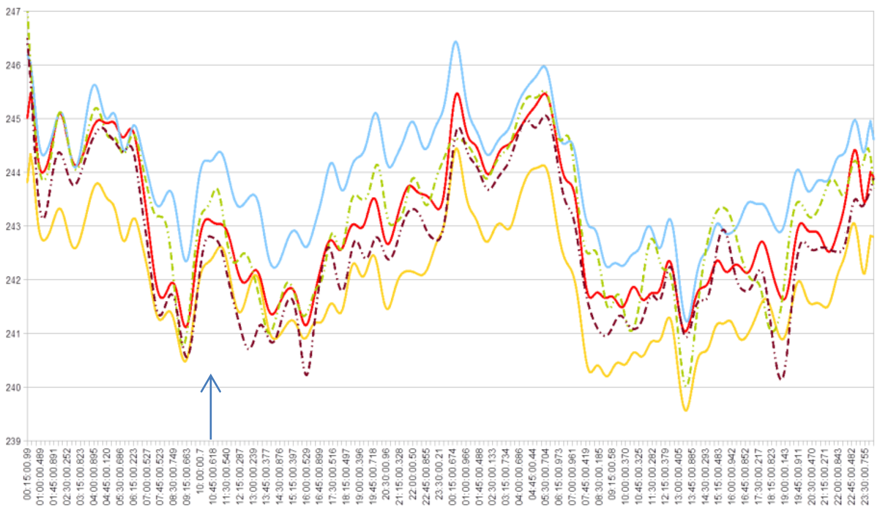

Figure 26 Example of voltage profiles of substation and two houses

Looking further within the same small sample of the data, as shown in fig. 27 below, the domestic houses phase relationships with substation phase can be determined in a moderately loaded system. In fig. 27, the solid voltage curve is Red phase of the feeder from the substation and the dotted voltage profile is the captured data one property.

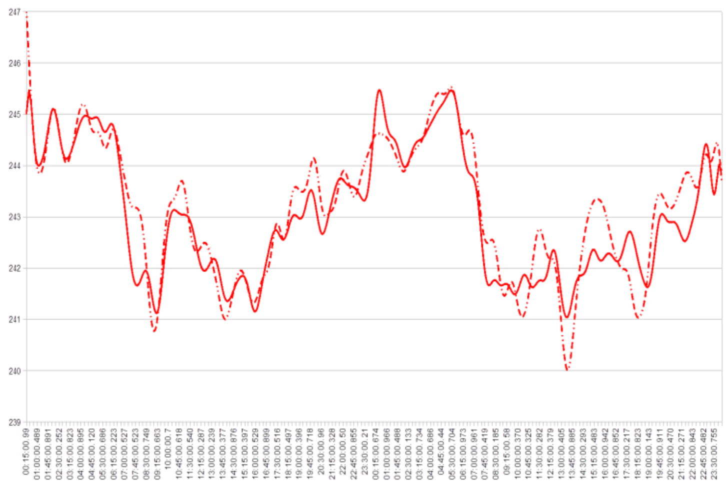

Figure 27 Voltage profiles of one phase of substation and connected house

It is also possible to glean further information on the relative positions of the houses to the substation and even between properties, as shown below in fig.28. The solid line is the voltage profile at the property closer to the serving substation and the dotted curve is for a property further away from the substation can be clearly noticed.

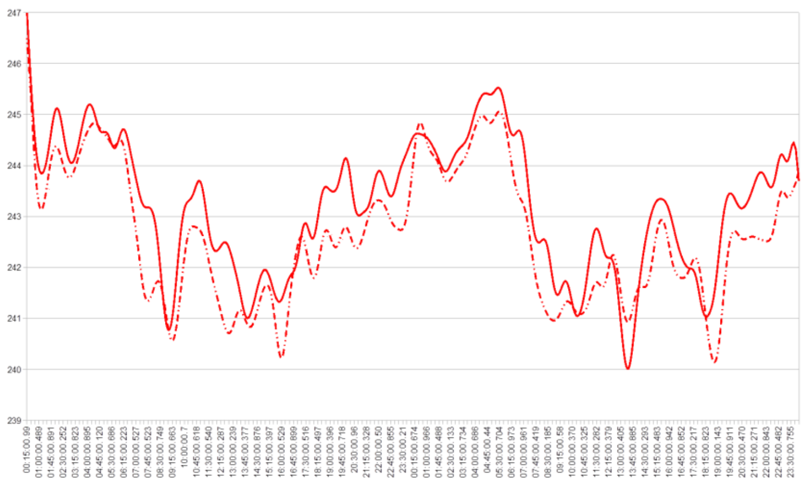

Figure 28 Voltage profiles of houses at different location

Though beyond the scope of the study at present, with the available large dataset from this project alone, models can be constructed which can estimate physical separation between installations. Further still, a limited access to historic metering data can assist in these network related studies without infringing on user privacy.

5 Conclusions

- From Aug 2014 to Mar 2015, there are 6 domestic EMS control strategies and corresponding export/import behaviours. In all of the control strategies, PV exports the available power and battery discharges 20%-40% of its capacity (nearly 0.3 kW) to the main grid during evening and night high demand time. The school battery charging/discharging and export/import behaviours follow the same pattern from Dec 2014 to April 2015. The battery supports the main grid in the morning when the school is open and evening after 18:00. By analysing the demand of the school connected network, the operation change is made in May, which is starting to support the main grid earlier at 16:30.

- The power consumption of the analysed houses suggests the EMS system effectively reduces the demand during daytime by PV output (shown in the fig.13) and shifts the demand by increasing either overnight or afternoon demand and decreasing evening peak time demand (shown in the fig 8. and 13). This can be controlled by adjusting the EMS system.

- The measured data of the network demand shows little evidence of the effect of EMS systems. The reasons might come from:

    - Compared with total network demand, the demand change is small because of the current low EMS penetration level.
    - There is large demand variance at the monitored feeders, which may even be larger than the exporting/importing power of EMS.

  Therefore, the demand change brought by the current installed EMS system could be masked.

- The results of the network push/pull trials suggest that 50% of the batteries could respond to the network request exactly and help reduce network demand effectively. The results of demand comparison between trial and non-trial days shows there is minor difference on the exporting power during evening peak demand time, which means the PV and battery effects of non-trial operation are similar to the battery effects under network request on an April high PV output day. According to these results, it is deduced that with more PV output, trial operation may export more power; with less PV output, such as on low PV output days and winter time, the trial operation could guarantee the network benefit brought by the EMS system.

- With the assumption of 2% load growth, based on the current penetration of domestic located EMS systems, the investment deferral of the network is £470. If the penetration of the EMS is increased to 30% and 50%, the investment deferral would be £2986 and £4835 respectively. The investment deferral brought by the school EMS system is £211.

- The domestic located EMS system could defer network investment for one year, and with 30% and 50% penetration, the deferral would be 4 and 6 years respectively. The school located EMS system could defer network investment for one year.

- The EMS system connected with three phases of network can facilitate three phase balancing of the network by importing power from one phase and simultaneous exporting power to another phase.

- From the measured voltage data of substation and houses, it is possible to estimate which phase the house is connected to by matching the domestic properties voltage with substation phase voltage. Besides, the relative positions of the properties to the substation and even between properties could be deduced by comparing the voltage magnitude with each other.

- Currently, the measured EMS exporting power is larger than the estimated EMS exporting power in the project outset. With the assumption of 100% EMS penetration in domestic connected substation, the estimated peak demand reduction made at the project outset is 52kW[4]. Based on the measured data of battery and house power, if the EMS penetration is 100%, the peak demand reduction could be 77kW.

6 Further Work

This report is a preliminary study and further analysis of the network impact is continuing. The final project report, due in January 2016, will have the final conclusions taking into account the full data set and updated system configurations, and will include power quality impact.

[4] [4] Z. Wang, C. Gu, F. Li, P. Bale, and H. Sun, "Active Demand Response Using Shared Energy Storage for Household Energy Management," *IEEE Transactions on Smart Grid,* vol. 4, no. 4, pp. 1888-1897, 2013.

7 Appendix 1-Benefit quantification methodology

The benefit in network investment deferral is quantified by evaluating the changes in the present value of the future investment before and after integrating energy management system. The mathematical formulation is shown as follows:

$$\Delta PV = PV - PV_{new}$$

Where PV and PV_{new} are present values of the future investment before and after integrating energy management system.
The present values can be calculated as:

$$PV = \frac{Asset}{(1+d)^n}$$

$$PV_{new} = \frac{Asset}{(1+d)^{n_{new}}}$$

Where: $Asset$ is the modern equivalent assets cost; d is discount rate; n and n_{new} are the years to invest a network asset before and after integrating energy management system.
It is assumed that the investment will occur when the feeder/transformer is fully loaded. With this assumption, the years to invest a network asset is determined by the load peak, the network component (asset) capacity and load growth rate as shown below:

$$n = \frac{logRC - logD}{\log(1+r)}$$

$$n_{new} = \frac{logRC - logD_{new}}{\log(1+r)}$$

Where: RC is the network component (asset) capacity, D and D_{new} are the network peak load before and after integrating energy management system, r is the load growth rate.

8 Appendix 2 – Meeting Notes

"Notes from the project meetings discussing operational performance (changes to the LV voltage profiles, feeder demand profiles and power quality) will be recorded and stored."

In the following section we provide a number of learning points that emerged during review of our meeting notes and email communications. 26 sets of notes from the project meetings were reviewed. We focus here on the operational performance and the decisions made in relation to SDRC 9.5.

Further notes of interest can be found in the site visit reports[5]

The 39 learning points are categorised into 8 categories.

Batteries
Data Analysis
Data Management
Economy 7
Householders
Installation
Schools
System Amendments

		Learning Point	Evidence *Comments in italics*
Batteries	L1	Regular checking of equipment can provide an opportunity to identify potential issues and amendments to be made.	**16.12.14** H27 – Battery Discharge, this was occurring beyond the threshold, during checks for this, an additional problem was found with the DC DC convertor, both these faults will be reviewed 17/12/14. A spare DCDC should be available in the store, and the faulty one will be refurbished and a failure fault will be produced. The LVD may also be faulty.
Batteries	L2	Early analysis can indicate where settings can be changed to optimise performance.	*Battery state of charge settings have been updated.* *Early analysis indicated that the battery settings were not optimum. Analysis showed that PV was the primary source for benefit. Updates to the battery settings may change the extent to which the battery supplements the system.* **16.12.14** PV is bringing the largest benefit, with the battery supplementing this but not a great extent; it is expect that this is due to an unstable state of charge for the battery (NB battery state of charge settings have now been changed).
Batteries	L3	Changing the charge profile of the batteries can influence the extent to which savings occur. These can be managed to benefit the householders or the grid.	**16.12.14** Changing the charge profile of the batteries can influence the extent to which savings occur. – Looking to gain a benefit for the customer and the grid.

[5] Accessible here http://www.westernpowerinnovation.co.uk/Document-library/2014/WPDT2003_Appendix-1-SoLa-BRISTOL-Site-Visit-Report.aspx

	L4	Understanding errors is important. Looking at additional information can help interpret the data	**15.4.14** KWMC is set at 80% (as it's a larger battery, so 80% benefits it more as more can be easily discharged). On the graphs there was a noticeable drop off for the KWMC data, MD noted that this was due to a comms error rather than a battery error, if the communication goes down then the data reports zero, we can tell it is comms because the chart immediately goes up again, if the issue was not comms it would take time to return.
	L5	Analysis of the data suggests that the systems charge at two different times.	**4.2.15** Analysis of the data suggests that there are two types of charging, overnight vs. afternoon.
	L6	The battery state of charge can change more than anticipated	**4.2.15** SOC drops during peak period. It also drops gradually overnight and early in the morning. Sometimes we see a dramatic drop in the peak morning period which results in it dropping lower than 35%.
	L7	Data can be unexpected so it is important to check everything.	**4.2.15** The actual PV output is lower than anticipated.
	L8	As this is a trial the extent to which it can be seen to impact the system may be minimal. It is important to consider this when analysing and extrapolating the results	*As there may not be enough load on the substation to see the impact of our intervention on the system, the substation with the largest load from our houses is chosen to be the test.* **10.2.15** However there may not be enough load on the substation to actually see the impact of our project
Data Analysis	L9	It can be hard to manage the granularity of data to ensure you see changes, while ensuring that you are not recording noise. Remaining aware of the granularity, amending settings and supplementing with additional data can help us to understand the output data	**10.2.15** The meter (p50/p55) input has two settings (1amp or 6 amp). An update to the granularity from Siemens has dropped it from 6 amps down to 1. The meter was set to .3% but it has now increased to 1%. Anything in this range is seen as noise consequently this means we may be unable to interpret some of the data as it wont be clearly recognized. If we lower the % then we risk mistakes due to noise. To move past this we can supplement the data with the additional data in the extender.
	L10	Households have varying characteristics; different settings are needed to ensure the battery stays charged in all scenarios.	*High load houses have updated settings to protect the system reliability* **2.3.15** In high load houses, the high load and the discharge during t3 can affect the volts, which is when we have seen most of the houses have issues. – If it drops to 22volts, then it will force charge to 35% battery, this is being changed to 60%.
	L11	When systems are based on estimations it is expected that some houses will fall outside of this range and consequently the systems may fail	**2.3.15** State of charge is based on estimation, which may explain why some of the houses fail.
	L12	You cannot always rely on data from the houses.	*Remain aware that the state of charge reported by the batteries may not be accurate* **2.3.15** House 13 - says it is at 70% charge, but this seems to be incorrect. So how much can we trust the state of charge – every second Sunday we 100% charge the batteries to ensure that they have a regular charge.
	L13	Changing the settings can help to normalise extreme cases	**30.3.15** There is similarity between high load and normal. Suggesting that our recent adjustments are working.
	L14	Outside factors such as the weather can have an impact on the system. Using historic weather data can help with the data analysis	**30.3.15** On a sunny day the PV output is considerably higher. But the actual load profile does not differ. The PV output can be seen to charge the batteries.

Data Managemen	L15	If data is collected locally, disruption to the householders should be minimised by copying the data when visiting the householders for other events.	**4.2.15** Some of this data is only accessible from the SD cards located in the lofts; this data can be discussed in the 6 monthly reports rather than the SDRC 9.5. Opportunities should be taken to take a copy of the SD card when we are accessing the homes for other reasons to minimize disruption to the householder.
	L16	A large amount of data can be generated during these types of project. Automation can help. Care and attention are needed to ensure the files stay correctly labelled and connected to metadata	**13.6.14** Currently the daily data is producing 3 files (each about 2gb), each file represents 8 hours. Each house has 34 variables, The intention is to automate this, but doing this daily will generate a lot of data.
	L17	It is important to review the data capture and ensure that relevant data is collected. In some cases it may not be possible to collect all forms of data, in these instances a decision needs to be made about the best approach.	**13.6.14** AC meter – looks at what is exported from the property – but it doesn't tell you what the property is actually using. – Does this need to change, should we put it on the house side? Either way you'd lose some kind of data.
Economy 7	L18	Economy 7 houses can provide interesting learning,	**16.12.14** H06/7/8 – These houses have economy 7 settings. They are producing non-standard results as the batteries were not planned for Economy 7 profiles (high load), changes are being explored. Midnight -7am should be when the eco 7 is in control, with our system pausing during this process. Eco 7 – unexpected but will provide some really interesting learning.
	L19	Unexpected inclusion of economy 7 meant that the settings were not appropriate for all the houses in the project	*Economy 7 houses have bespoke settings.* **4.2.15** The best option may be to look at midnight – 6, when this is a low tariff we should charge the battery. **2.3.15** Analysis by FL shows a problem with economy 7 where the demand is being taken from the battery rather than AC – this puts a high demand on the battery.
	L20	Seasons may affect how the householders use energy.	*Economy 7 houses reverted to 'normal settings' when householders turn off heating.* **27.3.15 (Email communication)** Update required for summer will be to change the 3 E7 homes to mirror the 'Normal' homes, the tricky bit will be deciding when to do this, as it is dependent on when the individual homes decide to switch off their heating.
	L21	Minimising the impact on the customers is important.	*To ensure customer service, houses were switched to power pack during the Christmas period to minimise the risk of black out.* **16.12.14** Power Packs – Should we change everybody to power packs during the Christmas period to ensure there is no risk? BCC electricians will be reduced during this time, as the project is limited there are reduced personnel able to support the project, and they may be unavailable over Christmas. Decision needs to be made to ensure houses are booked in. Siemens will be off so unable to offer support, however they would have been interested to see how the systems cope during this period. The battery system will continue, the only thing will be ensuring the lights are not connected to DC.
	L22	The impact of the social circumstances of the householders is currently unclear and may provide an insight into the extent that batteries will minimise the PV impact on the network	**16.12.14** PV installed on the system in the long term will impact the network, however the installation of batteries will minimise this. It will be interesting to explore how the different social circumstances of the householders also impact when there is a heavy load (e.g. householders at home during the day in comparison to those that are out during the day).
	L23	Understanding the householders can be just as important as collecting the meter data for understanding the load on the houses	**4.2.15** It looks like homes could be classified into 3 smaller groups, but they still show a lot of variation – this may partly be due to the houses involved. E.g. number of tenants, lifestyle

Householders	L24	Houses cannot be expected to perform as well as those based in theory. Reminding householders that the project is research and development can help minimise disappointment and frustration around system changes.	**4.2.15** A concern is that if the designed system doesn't closely emulate our houses then changing the system may not improve the reliability – however, it is likely that it will be an improvement even if it is not perfect. On the whole the consumers are aware that this is R&D and are flexible with issues.
	L25	In some instances system failures may have been due to householder input rather than problems with the settings. Discussions with householders can provide insight into the likelihood of problems being due to payment rather than the system.	**4.2.15** It is possible that some of our failures may have been because they ran out of money on the mains meter. We could look at the data to understand if the AC went off.
	L26	Not all houses will respond in the same way. Each house should be considered on a case by case basis	**10.2.15** House 24: does not seem to charge above 60% (once a fortnight it is supposed to charge to 100%) this does not appear to be occurring.
	L27	Typical load profiles differ not only between the customers, but also within the customers on a day-by-day basis.	**16.12.14** Typical Load Profiles are different between the customers, and within the customers based on day-by-day use. The extent to which houses benefit from the install will depend upon their load, some will see financial gain while others could experience a loss.
Install	L28	A staggered install, while time consuming can allow for changes to be made as the systems are installed, minimising the disruption to the householder and making the system more effective.	**9.5.14** KWMC – target voltage here is set at 80% not 50%, this is going well, but we might review this to see if the parameters can be changed to make it more efficient, e.g. running it at a lower state of charge, this would allow KWMC to use more of the energy rather than selling it back.
	L29	Schools use the system differently to houses. Changes need to be made during the holiday period	**16.12.14** Remind schools to switch PC's and Laptop Trolleys off during the Christmas Break (this will reduce the likelihood of drain on battery
Schools	L30	Amending the school settings sometimes had unexpected consequences to the comms system.	**16.12.14** Ashley Down – update to the settings impacted the comms causing the LVD to start, a factory reset has resolved this issue.
	L31	Without context it can be hard to understand why a system fails. Information gathering is an important aspect of troubleshooting.	**6.10.14** The Brentry system went flat. While we are currently unclear as to the exact reasoning SK noted that we currently do not know how the PCs are configured, for example at what point does it go to sleep mode. – This means there is continuous use of both PC and monitor (If it were to go into sleep mode it would reduce the load from 120 down to 30/40 amps). The PCs also need to be serviced. These factors may be involved in the battery running flat. Normally the PCs are switched off in the eve/weekend. It is possible that they may have stayed on over the weekend, in theory the mains should have continued charging the battery so further exploration is needed here.
	L32	It can be useful to visit the substations to understand the logic behind unexpected settings noted in the documentation.	**16.12.14** H17 – Substation was set up incorrectly – this was a database error, with the substation and homes set up incorrectly. This has been amended and will be up and running following changes due 17th December 2014

	L33	Do not underestimate the value of real world data. It can provide guidance to theory informed systems and decisions	**4.2.15** The collected data provide more of an insight into the system. Siemens made a best guess to begin with, now Bath has more data these can be updated to provide a theoretically informed system configuration.
	L34	Consider and plan system updates to minimise disruption to the householders. Hypothesising and trial running can help test settings prior to the live update.	**4.2.15** This can't be updated too often, as access to the houses is needed to update the systems.
System Amendme	L35	It is important to continually review the data to see if settings can be refined	**9.5.14** Might be worth reviewing data after a bit more data to see if we can make the discharge more efficient for the customers.
	L36	To prevent disruption to customers it is important to add a failsafe to prevent system failure	**30.3.15** We're adding a failsafe to all of them of 22 volts and it will then charge to 60%.
	L37	Tariff design in theory can have many more options than that which can be introduced in reality. Ensure that constraints are discussed and designs include the restrictions to gain the most benefit	**19.2.14** 3-tariff system - this will be the starting point; if it doesn't fit perfectly 2/4 will also be considered. Siemens might have more flexibility here than in the domestic process which was limited to 3 tariffs.
	L38	There can be different ways to collect the same data, it is important to explore options and choose the optimum method for the scenario	**6.10.14** Substation Meter- It is possible to reconfigure the substation to change which harmonics are recorded, SK could do this, this means we wont need a PM7000 (Power monitor) this would only do one feeder, while reconfiguring the existing meter will allow use to look at all 5 feeders and 3 phases.
	L39	It is important to test out options and review the responses. Flexibility is key.	**6.10.14** SK noted that there is 100 MB of storage within each meter; these can be configured to record different parameters. SK is trialling different configurations at the moment.