Customer-Led Network Revolution

CLNR Post Trial Analysis

Residential DSR for Powerflow Management

DOCUMENT NUMBER
CLNR-L223

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ISSUE DATE
07/01/2015

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Contents

Executive summary

This report describes the results of demand side response (DSR) trials carried out with residential customers located throughout the Northern Powergrid region which were called by the CLNR active network management (ANM) system designate as GUS. The results of these trials are applied in simulation to the CLNR test-bed network at Rise Carr, and are used to draw conclusions of relevance to the UK as a whole.

Residential DSR responses were called based on three test cells, test cell 9a time of use (TOU), test cell 11a DSR with smart washing machines and test cell 14 Air Source Heat Pump (ASHP) DSR, to mitigate thermal overloads. The active DSR responses were called to mitigate thermal overloads that were observed by the GUS system.

As the distribution networks where GUS has been deployed have been selected to be robust, thermal overloads were highly unlikely to occur during the trial. As per the CLNR trial design methodology, the thermal limits of the transformer were tightened to stimulate the required response in order to study the entire system from detection of thermal limit violation, the decision making in the GUS system, actuation by the GUS system and the actual DSR responses observed at the appliance level. The trials therefore demonstrate how DSR can be fully integrated with a distribution network management system which utilises transformer ratings to evaluate its control actions.

This data from the trials has been used to test the Rise Carr network capacity to connect large quantities of low carbon technologies (electric vehicles (EV) or air source heat pumps (ASHP)) without breaking the transformer thermal limit (23MVA).

The results of the post-trial analysis, using the VEEEG methodology, from the TOU trials and the washing machine DSR trials were comparable. It was observed that the increase in capability to connect EVs and ASHPs is much greater, if all customers downstream of the Rise Carr 33/6kV substation have TOU tariffs rather than washing machines equipped with DSR. It should be noted that the TOU tariff is always in place and it therefore impacts and depends on long-term customer behavioural change. However, the impact of "tariff fatigue" on these customers is not clear. In contrast, the washing machine DSR response might only be required during periods of high load and under n-1 conditions, where the static thermal limit of the transformer is approached, which may only occur on a couple of occasions per year.

Furthermore, in CLNR, the impact of only one DSR enabled household appliance (washing machines) was trialled in each household. The addition of other household appliances to the DSR system would increase the capability of an actively managed distribution network to connect additional EVs or ASHPs.

Post-trial analysis of the ASHP based residential DSR, considered the capability of this system to accommodate additional ASHPs only. The initial study indicated that DSR reduced the capability of the network to accept these ASHP systems. This was due to greater energy use during the trial days and the impact of the "rebound" effect when the ASHPs restarted after the DSR event. This indicates that the capability to modulate the "bounce back" or "rebound" following the DSR event has a large effect on the ability of ASHP based DSR to enable the connection of additional ASHP units. An additional enhancement phase of post-trial analysis was carried out which considered normalised, for energy, and modified "rebound" profiles where the rebound was spread over a longer time period. These studies indicated that an additional 20%, over the baseline number of ASHP units, could be connected to the downstream Rise Carr network.

As per the washing machine DSR service this capability might only be required during periods where the static thermal limit of the transformer is approached, which may only occur on a couple of occasions per year. Moreover, for both active DSR systems the addition of RTTR on the 33/6kV transformers would reduce the frequency of these events further resulting in fewer DSR requests.

1 Introduction

In this work, post-trial analysis of the residential demand side response (DSR) trials carried out as part of the CLNR power flow management (PFM) trials was carried out. This report begins with an introduction to the winter peak load profile at Rise Carr primary substation with/without DSR control and the low carbon technology (LCT) profiles.

Detailed information about the time of use tariff (TOU) and residential DSR trials carried out as part of CLNR can be found in [1-3] however, a summary of the three test cells (TCs) is presented below:

1.1 Residential time of use tariff (TOU) trial (TC9a)

TC9a involved a total of 628 participants who volunteered to undertake a trial of a three band static TOU tariff and were equipped with an in-home display unit which provided a near real time signal of their current electricity load through a traffic light system and retrospective visualisations of electricity consumption [1]. The rates and time bands of the tariff are shown in Table 1.

Table 1: Tariff structure for a TC9a customer

<table>
<tr><th colspan="2">• Tariff Band</th><th>Times</th><th>Price in Relation to the Standard Rate (1.00)</th></tr>
<tr><td rowspan="3">Weekday</td><td>Day (R2)</td><td>07:00 – 16:00 (Mon – Fri)</td><td>0.96</td></tr>
<tr><td>Peak (R1)</td><td>16:00 – 20:00 (Mon – Fri)</td><td>1.99</td></tr>
<tr><td>Off Peak (R3)</td><td>Mon: 00:00 – 07:00
Mon – Thurs : 20:00 – 07:00
Fri: 20:00 – 00:00</td><td>0.69</td></tr>
<tr><td colspan="2">Weekend (R3)</td><td>All-day</td><td>0.69</td></tr>
</table>

1.2 Air source heat pump (ASHP) DSR trial (TC14)

TC 14 involved direct control of eight customers' air source heat pumps (ASHPs) which were installed alongside a large thermal storage unit to allow interruptions to occur without a loss of heating [2]. During the trial, 14 interruptions were called. Four lasted half an hour and ten lasted an hour.

1.3 Wet White Goods (Washing Machine) DSR Trial (TC11a)

TC11a involved direct control and monitoring of 96 customers' smart washing machines [3]. During the trial, data was collected during interruptions which were all called during weekday peak times. Each event lasted for four hours, from 4pm to 8pm.

1.4 LCT Profiles and Methodology

In this work, LCT includes electric vehicles (EV) and air source heat pumps (ASHP). The Validation, Extension, Extrapolation, Enhancement and Generalisation (VEEEG) methodology is adopted to analyse trial results. An introduction of VEEEG methodology can be found in this study. In the next chapter, post-trial simulations results, including the validation, extension, extrapolation and enhancement studies are given and finally conclusions are drawn.

2 Methodology and Assumptions

2.1 Overview

In order to ensure that the objectives of the CLNR project are met, a programme of systematic evaluation of the results from the network flexibility field trials has been developed. This approach is derived from previous experience of trials. It is required that the results from the trials are firstly used to validate the network and network component models [4-7]. The results from the trials should then be extended and augmented to ensure that the results are applicable to 80% of the GB distribution network.

The systematic approach proposed consists of five steps: -

1. **V**alidation
2. **E**xtension
3. **E**xtrapolation
4. **E**nhancement
5. **G**eneralisation

This methodology is designated as VEEEG (Validation, Extension, Extrapolation, Enhancement, Generalisation) and is illustrated diagrammatically in Figure 1.

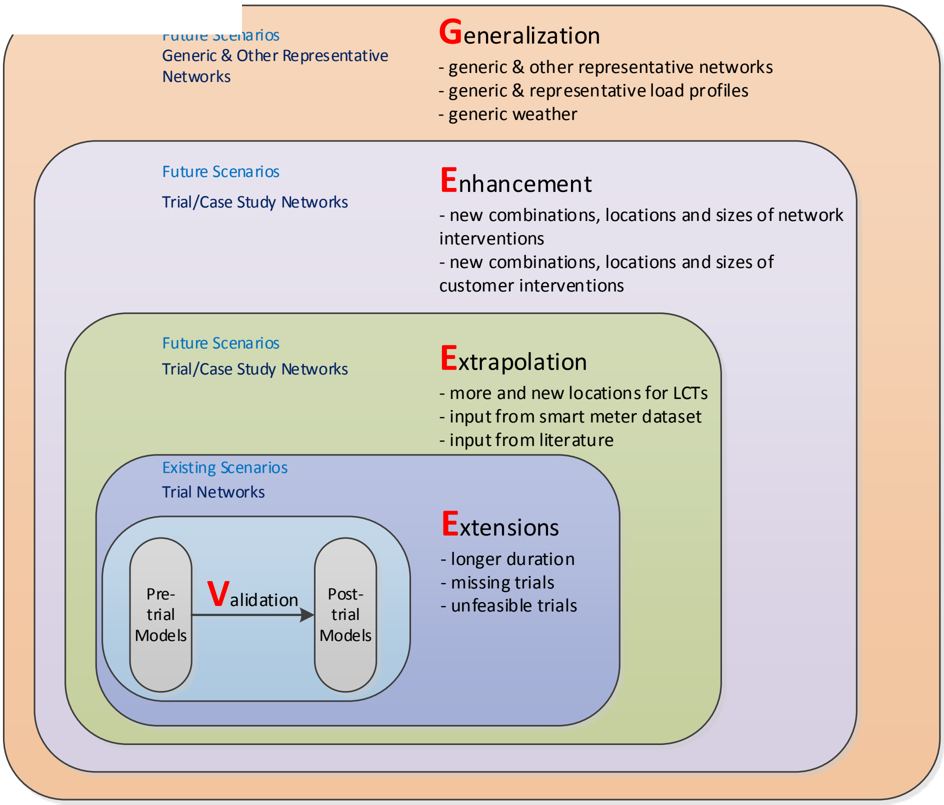

Figure 1 Post-trial analysis methodology (VEEEG)

For further details of the post-trial analysis methodology please refer to [5-7].

3 Profile Development

3.1 Primary Substation Load profile

A winter peak load profile from Rise Carr primary substation, from the 12 Feb 2014, is shown in Figure 2. This is derived from data on the CLNR Flexible Data Warehouse (FDWH).

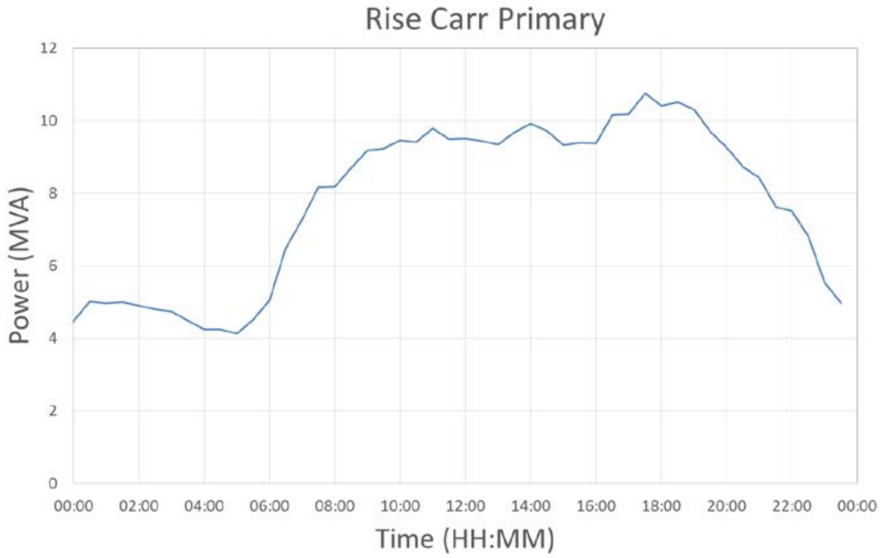

Figure 2 Winter peak load profile on Rise Carr primary

3.2 Residential time of use (TOU) tariff trial (TC9a)

The load profiles with and without a domestic time of use tariff applied are shown in Figure 3. In this work the mean reduction per customer is calculated as TC1 (weekday mean) – TC9 (weekday mean) as per CLNR data [1]. A peak reduction of 0.068kW is determined at 18:30.

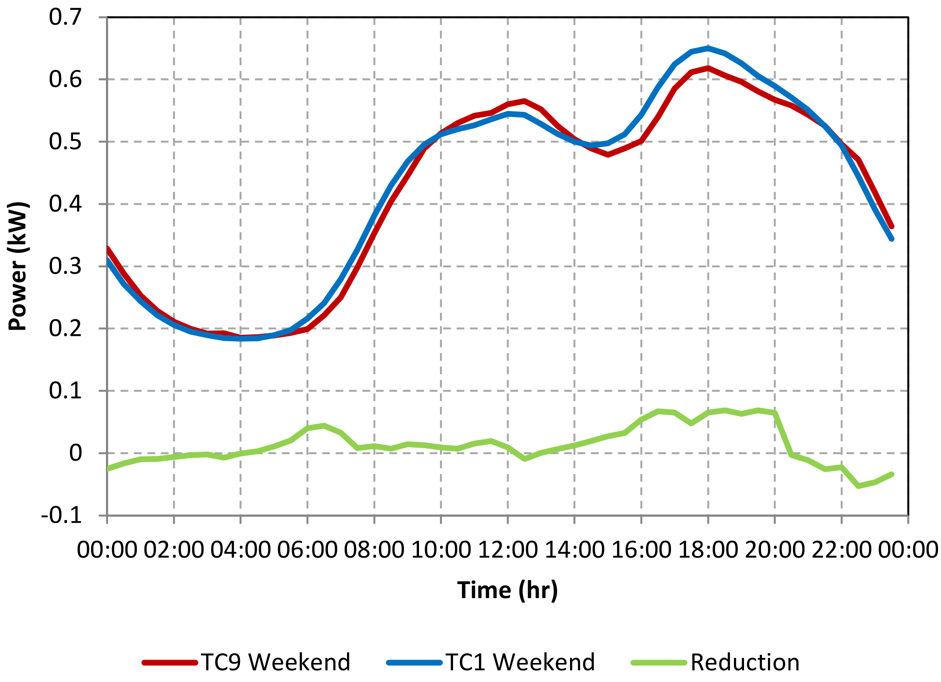

Figure 3 Mean domestic residential profile data for weekdays

The red line represents the mean load profile of the customers with a TOU tariff and the blue line represents mean load profile of the customers with no TOU tariff. The green profile represents the change per customer due to the application of the TOU tariff.

3.3 Air source heat pump (ASHP) DSR trial (TC14)

Figure 4 shows the mean load profiles of ASHP with and without DSR events called at 18:00. The *Non-trial day* data is taken as the mean of the data from the TC14 trial data on the 15th, 16th and 18th March 2014. The trial days are 10th 13th and 14th March 2014 and the mean of these days is the *Trial Day* data [2].

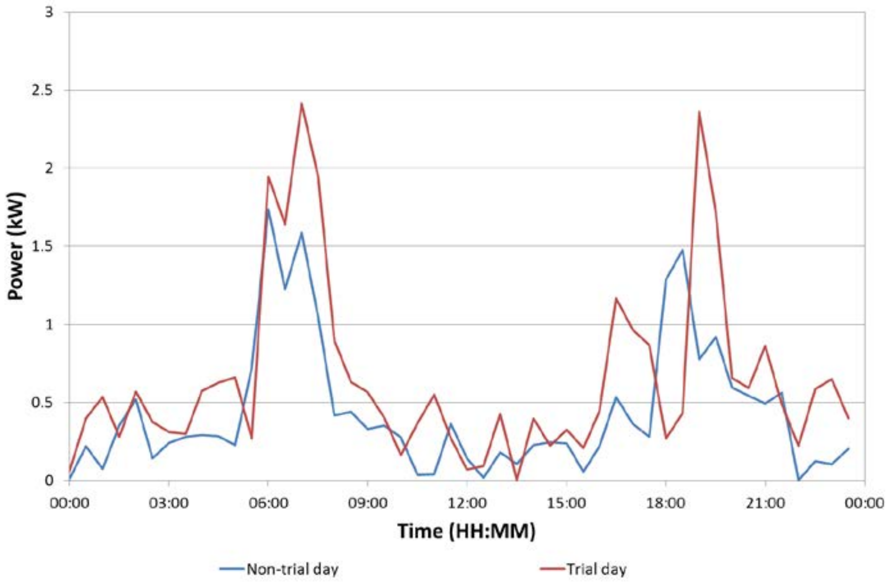

Figure 4 Mean *Trial Day* and *Non-trial day* ASHP profiles

3.4 Washing machine DSR trial (TC11a)

Figure 5 shows the mean profiles of the washing machine direct control trial with and without DSR events called at 18:00. The *Non-trial day* data is taken as the mean of the data from the TC11a trial data on the 15th, 16th and 18th March 2014. The trial days are 10th 13th and 14th March 2014 and the mean of these days is the *Trial Day*. Direct control reduction is calculated as *Non-trial day mean all customers – Trial day mean customers received signals* from the TC11a dataset [3]. This is the trace titled *Reduction* in Figure 5.

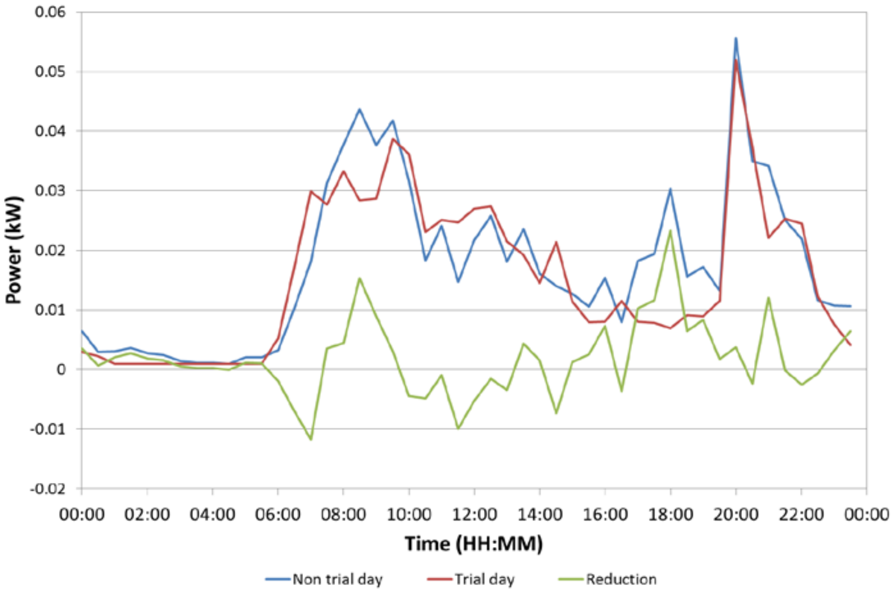

Figure 5 Domestic washing machine load profile

3.5 Low carbon technology profiles

The air source heat pump (ASHP) and electric vehicle (EV) profiles used in the analysis are from CLNR trial data. The ASHP mean load profile shown in Figure 6 is from the entire month of February 2014 from TC3 [8]. The EV mean load profile is from the 1 February 2014 from TC6 [9]. The profiles are shown in Figure 6.

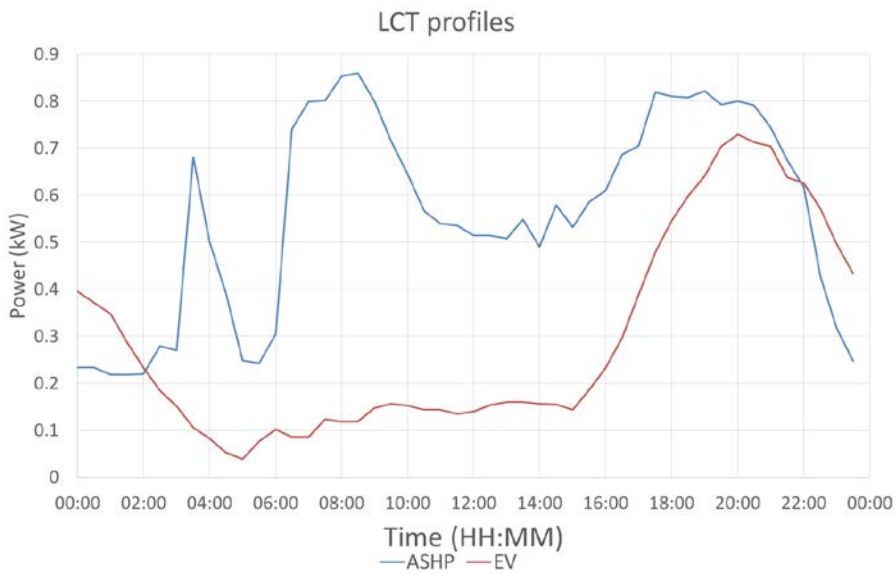

Figure 6 ASHP and EV mean daily consumption profiles from CLNR trial data [8, 9]

4 Post-Trial Analysis – Extension and Extrapolation

In this section, the headroom created by using residential DSR is evaluated by the number of additional EVs and ASHPs that can be accommodated on the Rise Carr network. It is assumed that the network is under n-1 condition and therefore the static rating of one of the transformers (23MVA) applies. Other criteria such as feeder end voltage limits and feeder rating limits are not considered for this analysis. The network model of Rise Carr is validated by running 24 hours' worth of load flows at 1 minute resolution. The validation work of the network has been detailed previously [10].

4.1 Residential time of use (TOU) trial (TC9a)

In this work the mean TOU tariff profile presented in Figure 3 is used to evaluate what additional numbers of EVs and ASHPs can be accommodated in this network if all the downstream domestic customers have a TOU tariff.

4.1.1 Electric Vehicle - Extrapolation

The load profiles of the Rise Carr 33/6kV substation, connecting the maximum number of additional EVs under n-1 conditions, considering existing customers and customers that have a TOU tariff are shown in Figure 7.

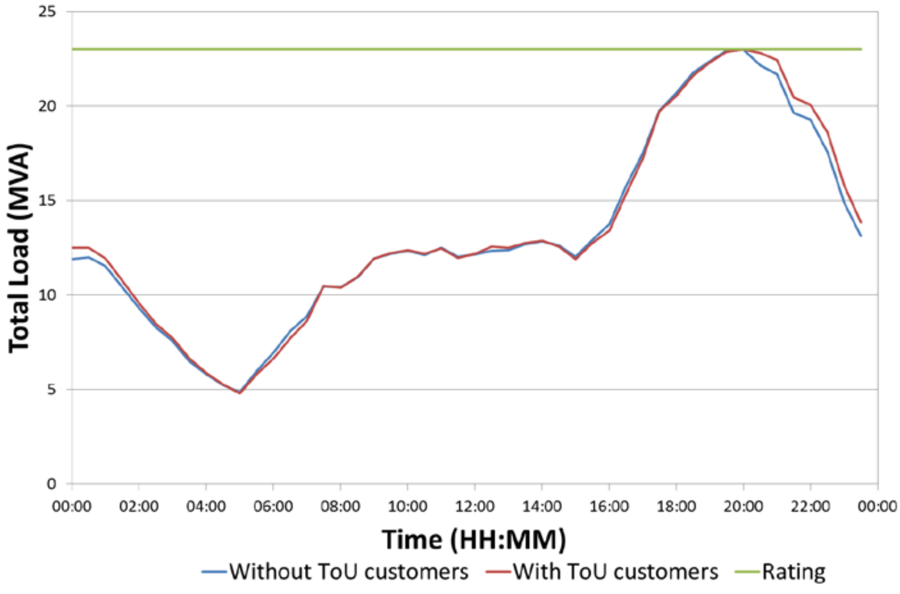

Figure 7 Load Profiles of Rise Carr Network EV with and without TOU customers downstream

Considering the existing customers, the maximum number of EVs that can be connected is 18,827 (penetration is 189.5%). Considering a scenario where all these customers have a TOU tariff, the maximum number of EVs that can be connected is now 19,709 (penetration is 199.3%). It can be seen that the number of EVs that can be connected to the network with a TOU tariff applied to all the customers is greater than the existing arrangement. It should be noted however, that this increase is comparatively small.

4.1.2 Air source heat pump - Extrapolation

The load profiles of the Rise Carr 33/6kV substation, when accommodating additional ASHPs under n-1 conditions, considering existing customers and customers that have a TOU tariff are shown in Figure 8.

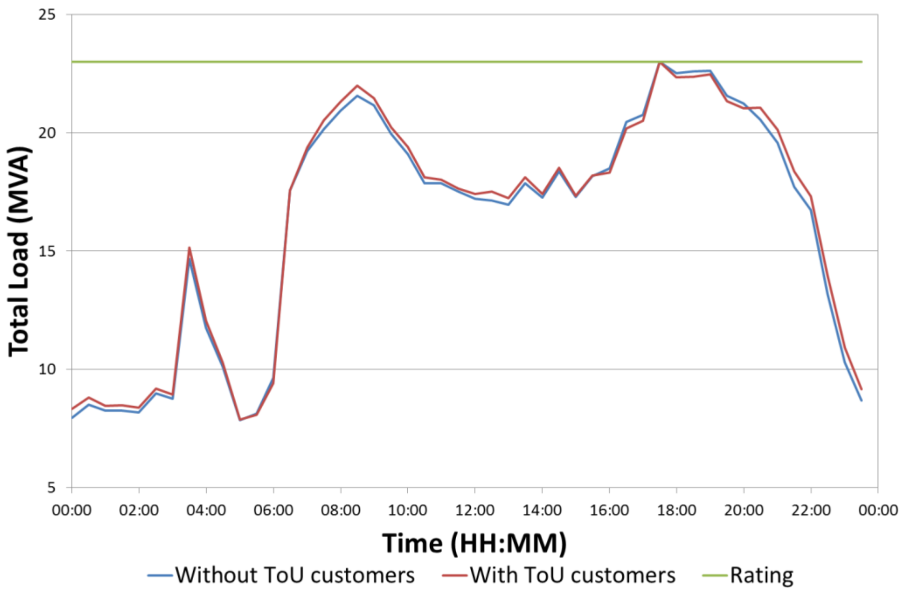

Figure 8 Load Profiles of Rise Carr Network ASHP when DSR is applied or not

Considering the existing customers, the maximum number of ASHPs that can be connected is 14,963 (penetration is 150.6%). Considering a scenario where all these customers have a TOU tariff, the maximum number of ASHPs that can be connected is now 15,539 (penetration is 156.4%)). It can be seen that the number of ASHPs that can be connected to the network with a TOU tariff applied to all the customers is greater than the existing arrangement. It should be noted however, that this increase is comparatively small.

Table 2 Summary of TOU Impact

	Baseline	Enhancement	Percentage increase
EV	18,827	19,709	3.85%
ASHP	14,963	15,539	4.68%

*N.B. Rise Carr 33/6kV substation load + LCT + reduction * 9,937 (number of customers in Rise Carr)*

4.2 Air source heat pump (ASHP) DSR trial (TC14)

In this work the mean profiles of ASHP with and without DSR events presented previously in Figure 4 is used to evaluate the additional numbers of ASHPs that can be accommodated in this network if all the downstream domestic customers are equipped with a DSR capability.

It should be noted that the ASHP data used in this analysis is not the TC3 data used previously to develop the LCT profiles detailed earlier. The ASHP units in the TC14 trial are from another manufacturer and crucially have a substantially larger electrical consumption and heat output and were installed in larger domestic residences. Therefore, comparison with the larger TC3 dataset is not appropriate. Thus data from the non-trial days of TC14 was used as the comparator as heat loads are likely to be comparable during this period. This is necessary to maintain consistency between the different phases of the analysis.

We have not considered scenarios with large numbers of EVs connected for this analysis, as it is assumed that a network requirement for an ASHP DSR service is driven by concentrations of ASHP units in an area of distribution network.

4.2.1 Air source heat pump - Extrapolation

The load profile of the Rise Carr 33/6kV substation when accommodating additional ASHPs under n-1 conditions, considering existing customers equipped with an ASHP (corresponding to the baseline capability for these ASHPs in this network) and customers that have an ASHP with DSR capability (corresponding to the extrapolation capability for these ASHPs in this network) are shown in Figure 9. The DSR response is derived from the CLNR trial data.

In this analysis the baseline data for customers is based on the mean of the TC14 customers on a *Non-trial Day* and extrapolation data is based on the mean of the TC14 customers on a *Trial Day.*

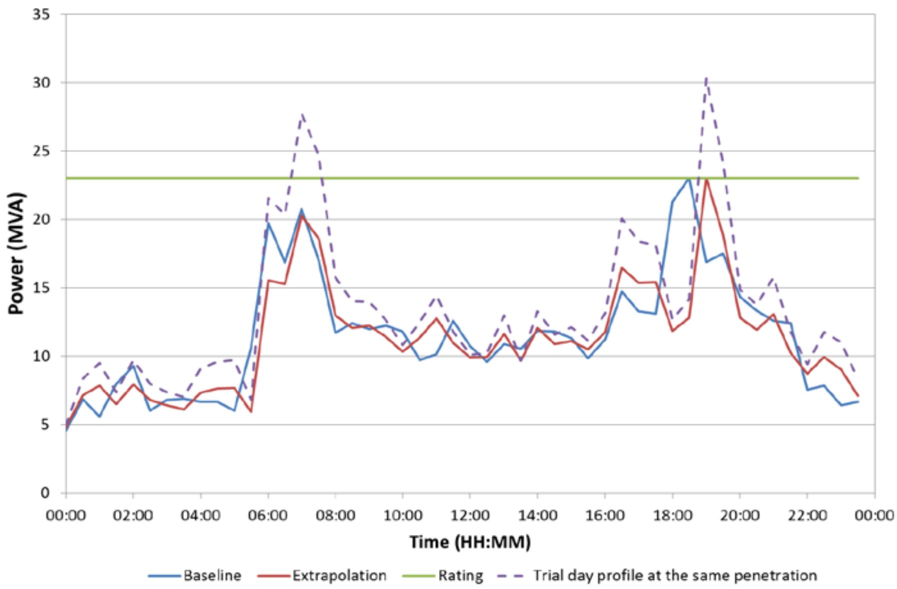

Figure 9 Baseline (*Non-trial Day*), Extrapolation (*Trial Day*) and *Trial Day* profile at the same penetration as the Baseline (Rise Carr load + trial day profile * baseline ASHP number 8478)

Considering the existing customers, the maximum number of ASHPs that can be connected is 8,478 (penetration is 85%). Considering a scenario where all these customers have an ASHP with this DSR capability, the maximum number of ASHPs that can be connected is now 5,380 (penetration is 54.1%). It can be seen that the DSR capability reduces the numbers of ASHPs that can be connected.

4.2.2 Air source heat pump - Enhancement

It can be seen in the previous section that the DSR capability reduced the capability of the network to accommodate ASHP connections. Two reasons for this are: -

1. Following completion of the DSR response an additional peak, due to rebound, is produced as all ASHP units are switched back on.
2. Heat energy consumption on the *Trial Days* is much greater than on the *Non-trial Days.* This can be seen from the higher peak during the night period (about 3am) and greater overall energy consumption by the ASHP units during the *Trial Days.* Weather conditions could be an explanation for this. This results in higher mean loads throughout the day.

It is proposed therefore to modify the profile used in the *Trial Days* element of the analysis to account for both of these factors

1. Mean power values are normalized based on total energy consumption.
2. After 19:00, consumption for each hour is the average of trial day profile between 19:00 to 23:30. This assumes the payback of ASHP DSR can be scheduled.

The modified profile *Enhancement, Normalized Profile* is illustrated in Figure 10.

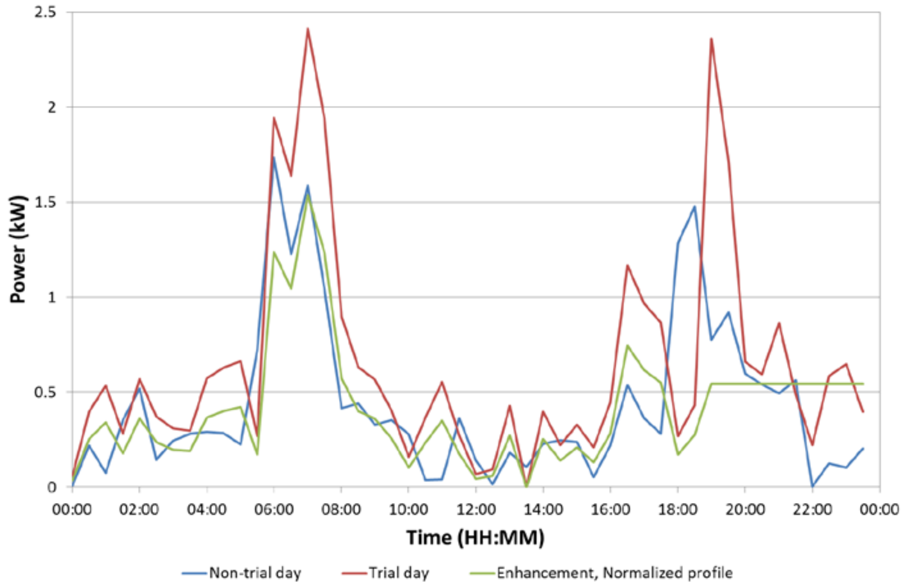

Figure 10 Mean *Trial Day*, *Non-trial day* and *Enhancement, Normalized profile*ASHP profiles

A summary of the VEEEG methodology application on the results from the ASHP DSR Trial (TC14) is presented in Table 3.

Using this modified profile, it was found that considering a scenario where all these customers have an ASHP with this revised profile, the maximum number of ASHPs that can be connected is now 10,232 (penetration is 103%)). This indicates that the capability to modulate the “bounce back” or “rebound” following the DSR event has a large effect on the ability of ASHP based DSR to connect additional units. This is illustrated in Figure 11.

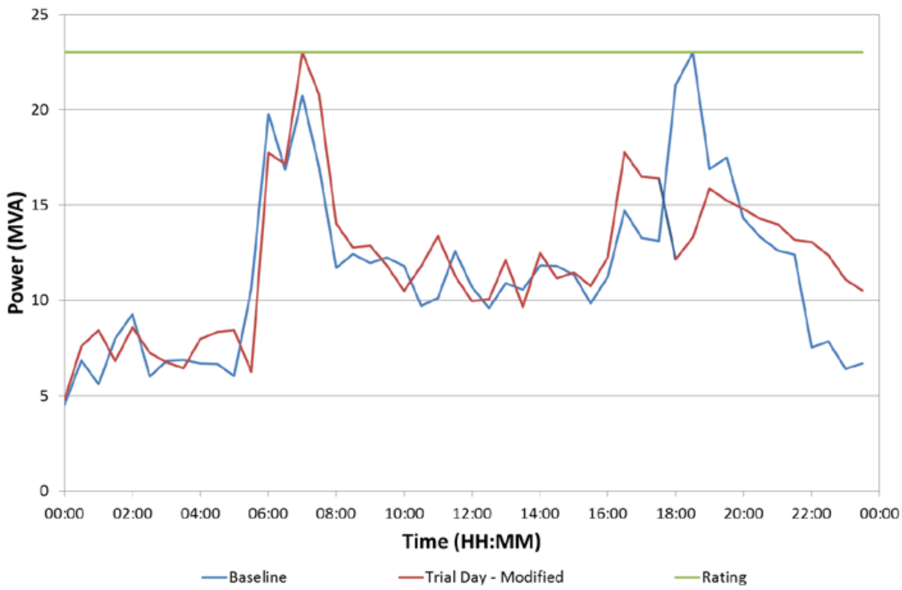

Figure 11 Baseline (*Non-trial Day*) and Extrapolation (*Trial Day*) load profile

A summary of the results for the post-trial analysis of the ASHP residential DSR trials are shown in Table 3.

Table 3 Summary of Residential DSR (ASHP) - Extrapolation and Enhancement

	No. of customers	Percentage increase
Baseline	8,478	0.0
Extrapolation	5,380	-36.5
Enhancement	10,232	20.7

4.3 Washing machine DSR trial (TC11a)

In this work the mean profiles of washing machines, with and without DSR events presented previously is used to evaluate what additional LCT can be accommodated in this network if all the downstream domestic customers with washing machines are equipped with a DSR capability.

4.3.1 Electric vehicle - Extrapolation

The winter peak demand profile detailed previously for the Rise Carr 33/6kV substation, under n-1 conditions, with EVs uniformly distributed across the downstream network under two scenarios are considered.

The first scenario is a baseline and considers the network with no intervention, with the largest number of EV customers connected without exceeding the thermal limits of the transformer.

The second scenario also considers the network, with the largest number of EV customers connected without exceeding the thermal limits of the transformer. However, this scenario also considers that all residential customers connected downstream of this substation have washing machines equipped with the DSR capability trialled in CLNR. The resultant load under the second scenario is given by the expression below.

Extrapolation Load = *Substation Load (Winter Peak) + (DSR Reduction)*Number of Customers (9,937) + Mean EV Load * No. of EV customers*

The *DSR reduction* is the difference between the mean load of the washing machine on the *Trials Days* and the *Non-trial Days*.

The load profile of the Rise Carr network connecting the largest number of EVs with and without washing machine DSR applied is shown in Figure 12.

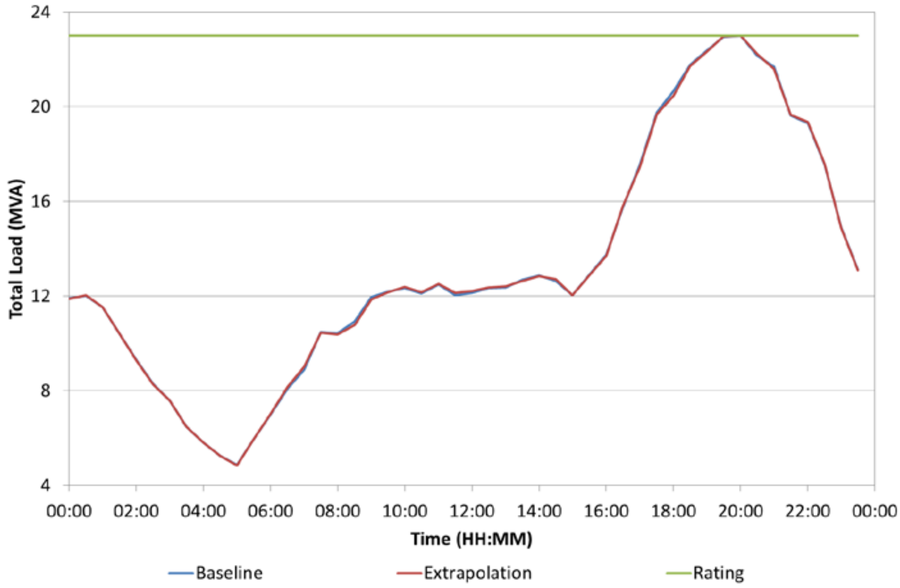

Figure 12 Baseline (*Non-trial Day*) and Extrapolation (*Trial Day*) load profile

Considering the existing customers, the maximum number of EVs that can be connected is 18,827 (penetration is 189.5%). Considering a scenario where all these customers have a washing machine with a DSR capability, the maximum number of EVs that can be connected is now 18,879 (penetration is 190.0%)). It can be seen that the washing machine DSR capability increases slightly the numbers of EVs that can be connected.

4.3.2 Air source heat pump - Extrapolation

Similarly, the use of DSR is not able to significantly increase the maximum number of ASHPs connected to the network. The load profile of the Rise Carr network capacity for accommodating EVs if washing machine DSR is applied is shown in Figure 13.

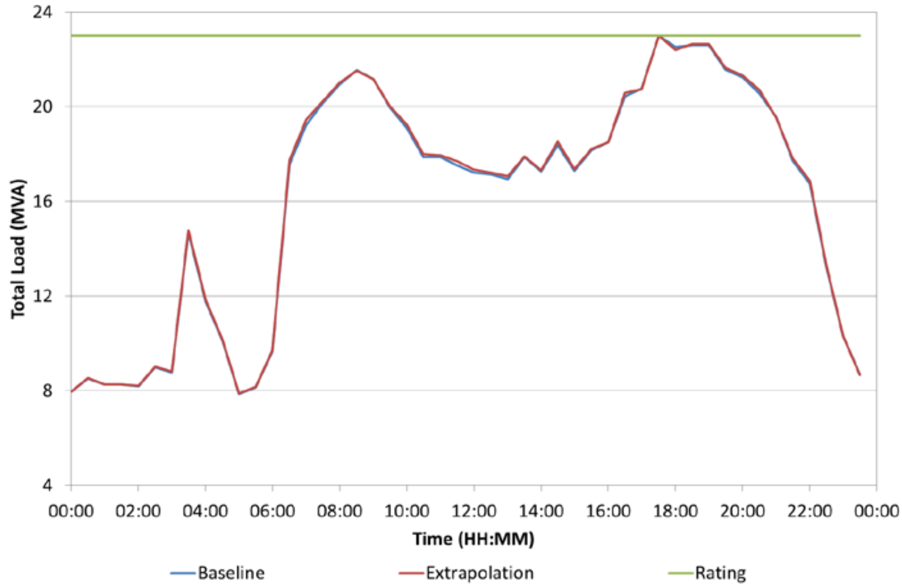

Figure 13 Baseline (*Non-trial Day*) and Extrapolation (*Trial Day*) load profile

Considering the existing customers, the maximum number of ASHPs that can be connected is 14,963 (penetration is 150.6%). Considering a scenario where all these customers have a washing machine with a DSR capability, the maximum number of ASHPs that can be connected is now 15,104 (penetration is 152.0%)). It can be seen that the washing machine DSR capability increases slightly the numbers of ASHPs that can be connected.

A summary of the results for the post-trial analysis of the washing machine residential DSR trials are shown in Table 4.

Table 4 Summary of Residential DSR (WWG) Impact

	Baseline	Enhancement	Percentage increase
EV	18,827	18,879	0.27%
ASHP	14,963	15,104	0.94%

5 Conclusions and Learning

In this report, residential DSR responses were called based on three test cells, test cell 9a time of use, test cell 11a washing machine DSR and test cell 14 air source heat pump DSR, to mitigate thermal overloads that the CLNR active network management system (ANM) observed. Data from a variety of different sources from across the CLNR project were integrated to complete this post-trial analysis.

1. Network flexibility trial data:
    a. Transformer load data from the 33/6kV substation at Rise Carr;
    b. Validated power system models.
2. Customer Flexibility trial data:
    a. Residential Time-of-Use (ToU) Trial (TC9a);
    b. Air Source Heatpump (ASHP) DSR Trial (TC14);
    c. Smart Washing Machine DSR Trial (TC11a).
3. Customer LCT disaggregated data:
    a. ASHP profile from TC3 [9];
    b. EV profile from TC6 [10].

As the distribution networks where the CLNR ANM system has been deployed have been selected to be robust, thermal overloads were highly unlikely to occur during the trial. As per the trial design methodology developed as part of CLNR the thermal limits on the item of infrastructure under investigation are tightened to stimulate the required response in order to study the entire system from detection of thermal limit violation, the decision making in the GUS system, actuation by the GUS system and the actual DSR responses observed at the appliance level. The trials therefore demonstrate how DSR can be fully integrated with a distribution network management system which utilises transformer ratings to evaluate its control actions.

This data used to test the Rise Carr network capacity to connect large quantities of low carbon technologies (electric vehicles (EV) or air source heat pumps (ASHP)) without breaking the transformer thermal limit (23MVA).

The results of the post-trial analysis, using the VEEEG methodology, from the TOU trials and the washing machine DSR trials were comparable. It was observed that the increase in capability to connect EVs and ASHPs is much greater, if all customers downstream of the Rise Carr 33/6kV substation have TOU tariffs rather than washing machines equipped with DSR. It should be noted that the TOU tariff is always in place and it therefore impacts and depends on long-term customer behavioural change. However, the impact of “tariff fatigue” on these customers is not clear. In contrast, the washing machine DSR response might only be required during periods of high load and under n-1 conditions, where the static thermal limit of the transformer is approached, which may only occur on a couple of occasions per year.

Furthermore, in CLNR, the impact of only one DSR enabled household appliance was trialled in each household. The addition of other household appliances to the DSR system would increase the capability of an actively managed distribution network to connect additional EVs or ASHPs.

Post-trial analysis of the ASHP based residential DSR, considered the capability of this system to accommodate additional ASHPs only. The initial study indicated that DSR reduced the capability of the network to accept these ASHP systems. This was due to greater energy use during the trial days and the impact of the “rebound” effect when the ASHPs restarted after the DSR event. This indicates that the capability to modulate the “bounce back” or “rebound” following the DSR event has a large effect on the ability of ASHP based DSR to enable the connection of additional ASHP units. An additional enhancement phase of post-trial analysis was carried out which considered normalised, for energy, and modified “rebound” profiles where the rebound was spread over a longer time period. These studies indicated that an additional 20%, over the baseline number of ASHP units, could be connected to the downstream Rise Carr network.

As per the washing machine DSR service this capability might only be required during periods where the static thermal limit of the transformer is approached, which may only occur on a couple of occasions per year. Moreover, for both active DSR systems the addition of RTTR on the 33/6kV transformers would reduce the frequency of these events further resulting in fewer DSR requests.

6 Reference

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