LV Network Templates for a Low Carbon Future

Stresses on the LV Network caused by Low Carbon Technologies

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Stresses on the LV network from low carbon installations

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1 Executive summary

Distribution network operators face new network challenges facilitating the connection of increased demand from low carbon technologies and increased penetration of distributed generation. Each technology brings different constraints varying from time of day to seasonal. Economic connection of these technologies is hampered by a lack of real-time LV network visibility of actual stresses on the network.

This report is one of three major reports that investigate the aforementioned challenges as part of the work undertaken by WPD in the LCN funded "LV Network Template Project":

1. Stresses on the LV network from low carbon installations
2. Use of proxy PV FiT meters to reflect local area Generation
3. Demonstration of LV Network Templates through statistical analysis

The "Stresses on the LV network from low carbon installations report" will specifically focus on demand capacity and voltage headroom in DNO networks; highlighting the effects of local low-carbon technologies and micro-generation on the existing network.

In order to gain such fundamental understanding, WPD's LV Network Template Project undertook the largest monitoring of its LV network in the UK. This approach led to the successful monitoring of over 800 substations and 3609 remote feeder ends. The data that was extrapolated from the monitors allowed the University of Bath to undertake extensive statistical and power analysis identifying 10 representative substations groups with unique voltage and demand profiles. The clustered voltage and demand profiles for each of these groups have and can be used to identify the headroom available for the application of low carbon technologies by time of day, weekday/weekends and season.

In addition to WPD and the University of Bath being able to prove that it is possible to cluster substations successfully, the following findings have also been identified:

- The maximum aggregated generation from PV within a postcode was on average only 81% of the declared capacity, consequently leading to a the voltage impact on our network approximately 36% lower than anticipated. Our findings illustrate even in locations with high PV penetration the outputs and impact to the network are relatively low. In comparison in areas where there are few heat pumps installed, there was a noticeable difference. This finding is key as current DNO network planning is based in part upon the declared capacity of registered low carbon technologies. As such there is the potential for DNO planners to more accurately assess the impact of low carbon technologies avoiding unnecessary costly network reinforcement.
- A second key output that this report highlights is that over an 11 month period, 96 million voltage measurements at remote feeder ends were taken. From this WPD have been able to identify that for those monitored points, 99.62% of the voltage readings were within statutory voltage limits. The analysis shows that in

the minority of cases the proportion of excursions associated with a single site was extremely small. If the UK were to adopt EU voltage limits, 99.998% of voltage readings would be within limits.To put a scale of value to the adoption of the EU voltage limits, a 1.5% fall in energy use through voltage reduction of 2.5% across only half of the 230,000 UK ground mounted distribution transformers, at an average of 150 domestic customers per transformer would save some 850,000 MWh p.a. The value of that saving to DNO customers would be over £100M p.a. If voltage reduction were more widespread and included pole mounted connected customers, through adjustment of primary substation target voltages, the savings would be even higher

As identified above and throughout this report, the Clusters identified as part of this Project deliver real value, cost and potential carbon savings to DNOs, their customers and the wider industry.

Moving forward the insight gained can and has already begun to be applied within WPD in the form of policy changes and the ability to help make more informed decisions about the networks effective operation/design of its LV network. WPD have taken proactive steps in immediately addressing statutory voltage excursions and hope to use the Projects findings to deliver greater GB saving by with Ofgem the potential for the UK to adopt European standards. Finally, WPD will continue to collect, monitor, analyse and share our findings with the industry in order to continue understanding the impact low carbon installations have on the LV network.

2 Introduction

The UK government has committed to reducing the greenhouse gas emissions by at least 80% by 2050 relative to the 1990 emission levels. Supporting this commitment is the "UK Renewable Energy Roadmap" that applies targets for 30% of electricity, 12% of heat and 10% of the energy generated for transport to come from renewable sources [1]. In its December 2012 update, DECC confirmed that by 2020, 15% of UK energy demand is to be supplied by renewable distributed generation.

It also recognised that the uncertain nature of deployment across the portfolio of technologies as well as relative cost effectiveness means that generation may end up at the high end of one technologies deployment range therefore requiring less deployment of others. Solar PV is now included as a key technology.

As the UK transitions to a low carbon economy, the energy sector faces significant challenges, both in the generation mix, the patterns and type of consumption seen (Demand). As a consequence DNOs will be impacted in the way they need to design and operate the electricity distribution networks in order to maintain security and quality of supply [2-3].

A key question that a DNO therefore needs to be able to answer is 'how and to what extent the LV network is impacted by the adoption of low carbon technologies and distributed generation'.

Some collaborative works involving DNOs and academia have sought to answer the aforementioned question. Such as the study by Centre for Sustainable Energy and Distributed Generation- Imperial College [4], concluding that the impact from electric vehicles, heat pumps has the greatest impact the LV network (specifically HV & LV transformers) Other studies have identified that the maintenance of voltages is further impacted by the introduction of LV connected intermittent renewable generation technologies such as Photovoltaic cells (PV).

This report aims to understand the actual demand and voltage headroom available on areas of the network with and without distributed generation and low carbon technologies connected to it. This will allow us to understand in detail the related time of day and seasonal performances of low carbon technologies versus the capacity and voltage headroom available. In addition, this report examines whether low carbon technologies are likely to cause issues with voltage levels being outside of statutory limits.

Finally the key findings of this Project will help DNOs to make more informed cost-effective investment, and operational decisions for the management of the low voltage distribution network; as the UK transitions to a low carbon economy.

2.1 The LV networks project

As identified in our LCNF submission the "LV Network Template Project" sought to explore;

- The degree of headroom available across differing types of LV system topology and customer mixes
- The effect of stresses on the network from low carbon installations
- The ability to identify low carbon stresses through templates and the associated voltage profiles

The major challenges facing the DNOs network development and operation are thus to timely accommodate the expected increase in intermittent low carbon generation and the heat and transport demand, and at the same time deliver value to customers. Work done by others, notably the DECC / Ofgem, ENSG and Imperial College has pointed to the role of demand side management and voltage optimization in partial mitigation of the network impacts. There are however, significant gaps in our understanding on the headroom or the margin of the current system, as there are marked differences in network topographies and customer mixes, and the degree of stress that might be imposed by the low carbon technologies

A second key challenge could as a result of voltages being above or below statutory limits potentially leading to adverse consequences on end customers' energy use, power quality, and equipment life. Whilst not initially the intention of this Project, the Expert Panel were also advised that in checking the actual voltages measured across wide parts of the LV system, valuable insight could be gained into the headroom that might, or might not exist, within the existing 230v+10%/-6% limits set out in the UK legislation.

Furthermore, if it were to be demonstrated that there was a valid case that compliance was maintained throughout daily and seasonal voltage changes, then there could be a strong case to argue for a change in legislation to move to the EU 230v +10/-10% voltage range. (White goods have, for many years, been manufactured to be compliant with the wider EU voltage limits). If the Project demonstrated very limited numbers of non-compliant voltage excursions against the -6% limit then a wholesale drop in network voltage by a 2.5% tap on distribution transformers, or by lowering target voltage at primary substations could achieve measurable drop in both UK peak power and to a lesser extent overall UK energy demand and the potential deferment of network reinforcement.

3 Monitoring

Two types of monitoring were undertaken as part of the LV Network Template Project, substation and at the remote feeder end usually within the customers premise. This was to understand substation demand and the voltages at both ends of the LV network.

In total circa 800 substations provided data for analysis, the exact number depending on the time period of study. Each substation monitor captured 13 channels of data including:

- L1, L2, L3 Voltage
- L1, L2, L3 Current
- Real Power import/export
- Reactive Power lag/lead
- Total Harmonic Distortion (3 phases)

Measurements of each comprised of the average values over 10 minute intervals providing us with the granularity and confidence of being able to clearly develop load and voltage profiles needed to understand the impact of the stresses to the network

3.1 Remote feeder end monitoring

In addition to the voltage monitored on each phase within the substation, there are 3609 individual phase monitors on remote feeder ends measuring voltage. Recorded measurements are again the averages over ten minute intervals. The majority of these are in customer homes with some monitored on cable ends and LV poles.

4 Network headroom

Whilst DNOs will frequently have the facility to determine simultaneous annual maximum demand information on ground mounted HV/LV substations through use of so called Maximum Demand Indicators "MDIs", these will also capture increased demand imposed on a substation during occasional transfers of demand when responding to network faults or planned shutdowns. By the end of 2019 it is planned that "smart meters" will have been installed in all UK households, and this would enable the aggregation of their individual demands to arrive at an annual maximum. However such aggregation would not provide the full picture of HV/LV transformer loading as it would not include for the network losses on the LV system or so called "unmetered demand" from un-metered street lighting, street furniture such as traffic lights, bus shelters and bollards and advertising hoardings. Nor will it provide as standard phase related or real time voltage information.

The accommodation of low carbon technologies onto the LV network not only requires knowledge of the existing peak demand, but also the variation of the shape of the demand curve through the day and how that varies over the week and seasons. The identification of periods during the day when demand is significantly below its peak represents the unutilised demand "headroom" that can be occupied by low carbon technologies imposing network demand, such as electric vehicle (EV) charging or ground / air source heat pumps. Conversely demand profiles that peak coincident with the output of low carbon generation technologies afford opportunity for absorption of higher levels of such generation. Parallel considerations on the maintenance of voltage within statutory limits also apply, and periods of time when there is latitude for further voltage rise or drop within those limits represent the "voltage headroom".

The cluster analysis has identified ten distinct groups or clusters of substations. Statistically, the demand profiles of substations within a particular cluster are more similar than those in the other clusters. Voltage profiles for each cluster were obtained by linking measurements at remote feeder ends associated with substations in each of the different clusters and calculating average profiles for each cluster. In order to further illustrate the impact of system loading level, voltage profiles are calculated by phase and both load and voltage profiles for each cluster have been assessed for weekdays, Saturday and Sundays.

The detailed reporting of work on the clustering analysis will be set out in another report, to be published in July. However, here we use results from the clustering analysis in order to demonstrate the potential of effects of low carbon stresses on the network. Specifically, results from the analyses for high summer, which would be expected to most reflect the effects of the significant LV PV penetration imposed by the Arbed and FiT initiatives, are presented (see Section 5 for details).

It should be noted that a separate report on Proxy PV FiT meters, published coincident with this report, contains significant findings in relation to aggregate local PV power output versus aggregate declared installed rating.

4.1 Demand and voltage profiling

The following sections provide the following information for each of the ten clusters (based on real power delivered)

- Power profiles over time for weekdays and weekends (Saturday and Sunday separately)
- Voltage profiles using data measured at the remote feeder ends
- A summary of the ability to accommodate low carbon stress

The demand profiles are, as normal practice in establishing load and loss load factors normalised to the respective peak within the time period under consideration.

4.1.1 Cluster 1

Cluster 1 is largely commercial dominated with a relatively high flat demand during day time and lower demand overnight, its demand profiles for weekday and weekends are shown in figure 1.

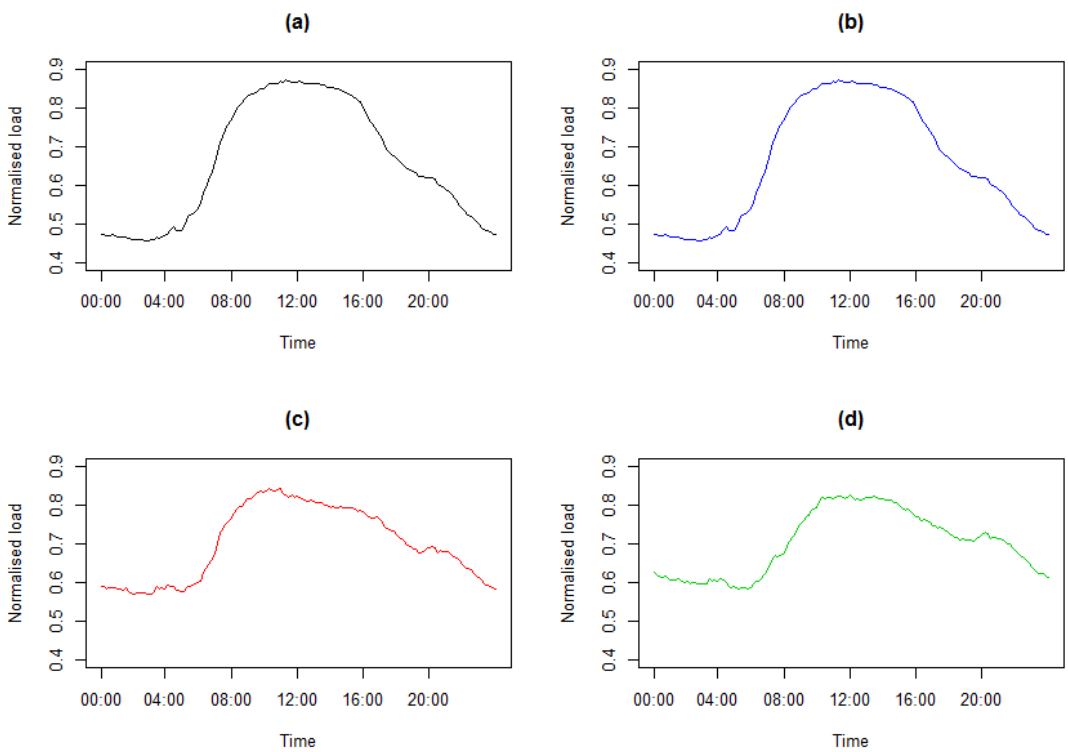


Figure 1: Substation demand profiles for cluster 1. Panels show results for (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The voltage profiles (at remote feeder ends) are shown in figure 2. During weekdays, all three phases have similar patterns with higher voltages when demand is lower and vice-versa.

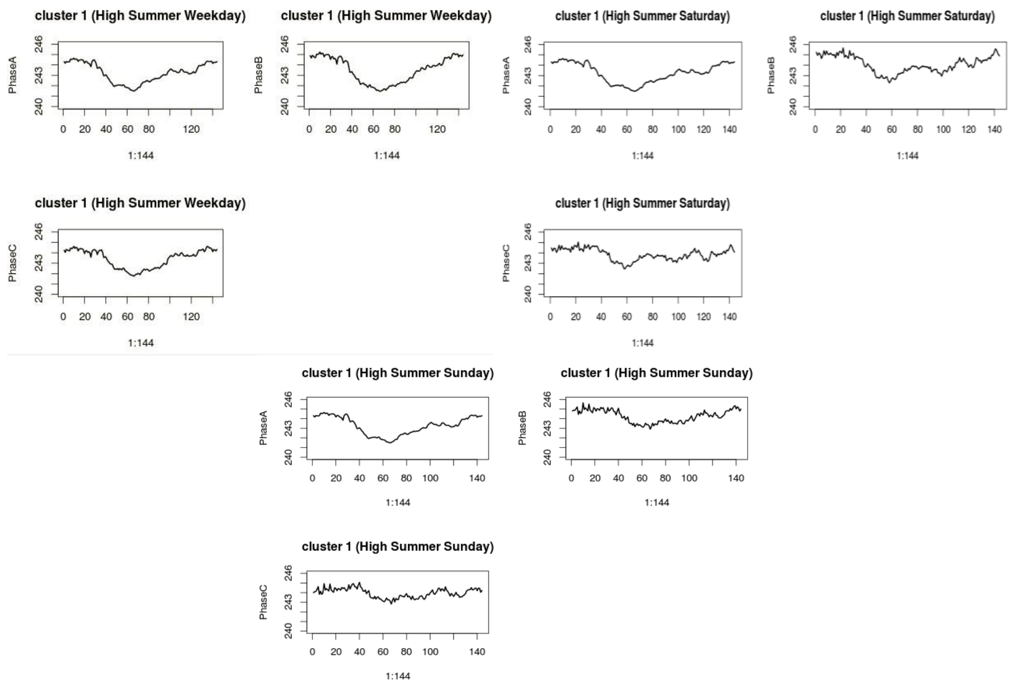


Figure 2: Voltage profiles at remote feeder ends for cluster 1. Clockwise, the figures represent the three-phase voltages in weekdays, Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 1 substations to absorb low carbon stresses introduced by differing low carbon technologies is detailed in Table 1.

Type	Comment
Workplace / Retail EV charging	Unsuitable time of day pattern as need is coincident with prevailing peak
Overnight EV charging	Very suitable
Heat Pump	Only if linked with insulation or heat storage to permit off peak operation
PV	Suitable - complimentary to both power and voltage curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 1: Cluster 1: ability to absorb low carbon stress

4.1.2 Cluster 2

Cluster 2 comprises predominately of substations dominated by domestic customers, its demand profiles for weekday and weekends are shown in figure 3. The associated voltage profiles are depicted in figure 4.

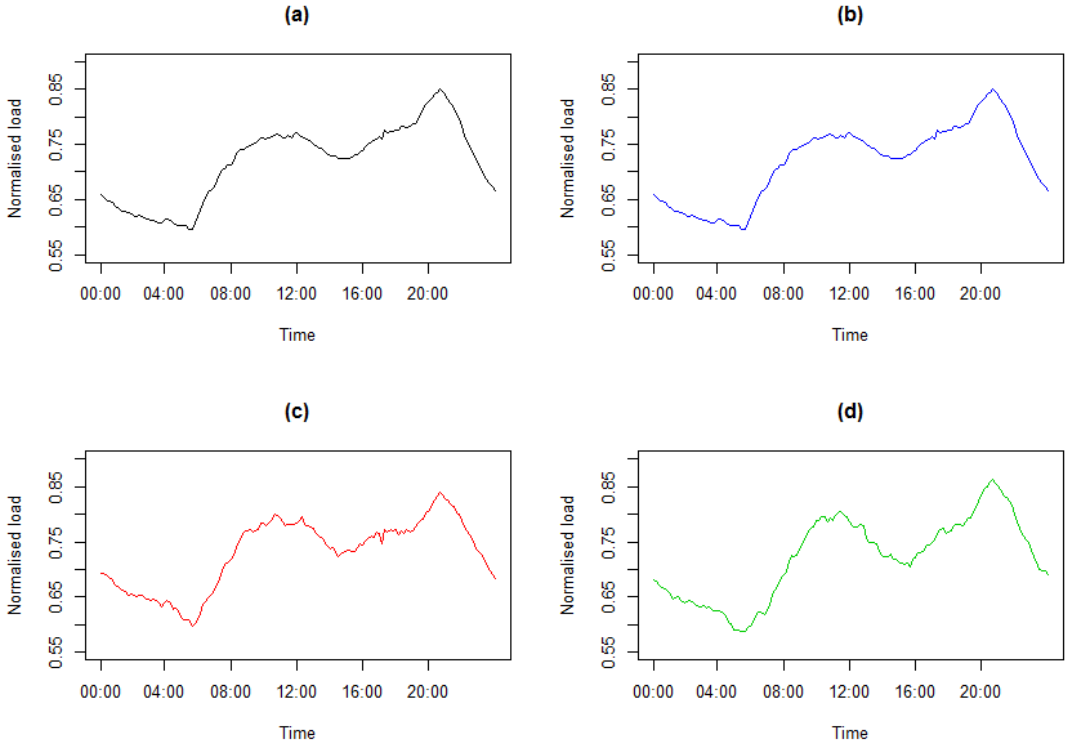
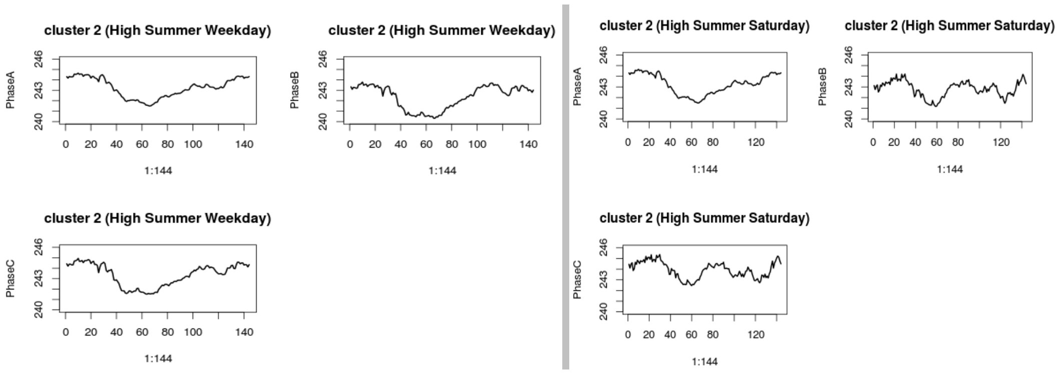


Figure 3: Substation demand profiles for cluster 2. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The three-phase feeder end voltage profiles during weekdays differ slightly from each other, all showing a minimum demand around 10am where phase B has a lower minimum (240V at 10am) than phases A and C, suggesting that phase B is more heavily loaded at this time than the other two phases., Compared to weekdays, the voltages are higher for all three phases over weekends. In contrast, profiles and magnitudes of phase A do not change as much compared to weekdays, probably because of its demand is not greatly affect by day of the week.



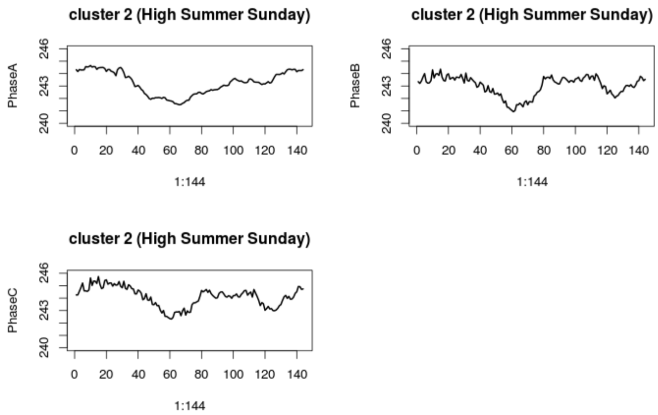


Figure 4: Voltage profiles at remote feeder ends for cluster 2. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 1 substations to absorb low carbon stresses is detailed in Table 2.

Type	Comment
Workplace / Retail EV charging	Suitable time of day pattern with limited need to curtail charge rate around 1730 peak - for workplace potentially not an issue if staff travelling then anyway, but possible minor constraint on commercial for shopping malls etc being visited at that time en-route from work.
Overnight EV charging	Suitable
Heat Pump	Suitable with insulation or heat storage with limited time of day constraint
PV	Suitable - complimentary to power and voltage curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 2: Cluster 2: ability to absorb low carbon stress

4.1.3 Cluster 3

The patterns observed for cluster 3 are similar to those observed in cluster 2 but here there are more commercial customers . The substation demand and voltage profiles are shown in figures 5 and 6 respectively.

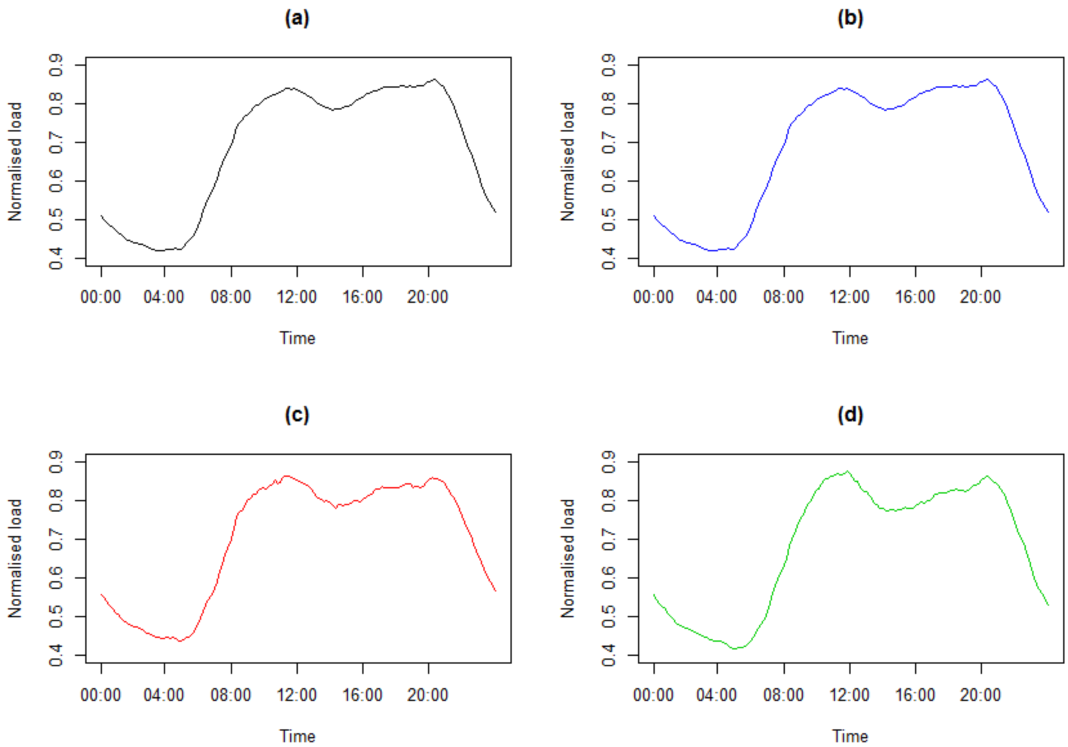


Figure 5: Substation demand profiles for cluster 3. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The voltages at remote feeder ends conform well to the load cluster profile, with lower voltages when demand is high and vice versa.. During weekends, the three-phase voltage profiles follow similar patterns of weekdays, with higher magnitudes due to light loading.

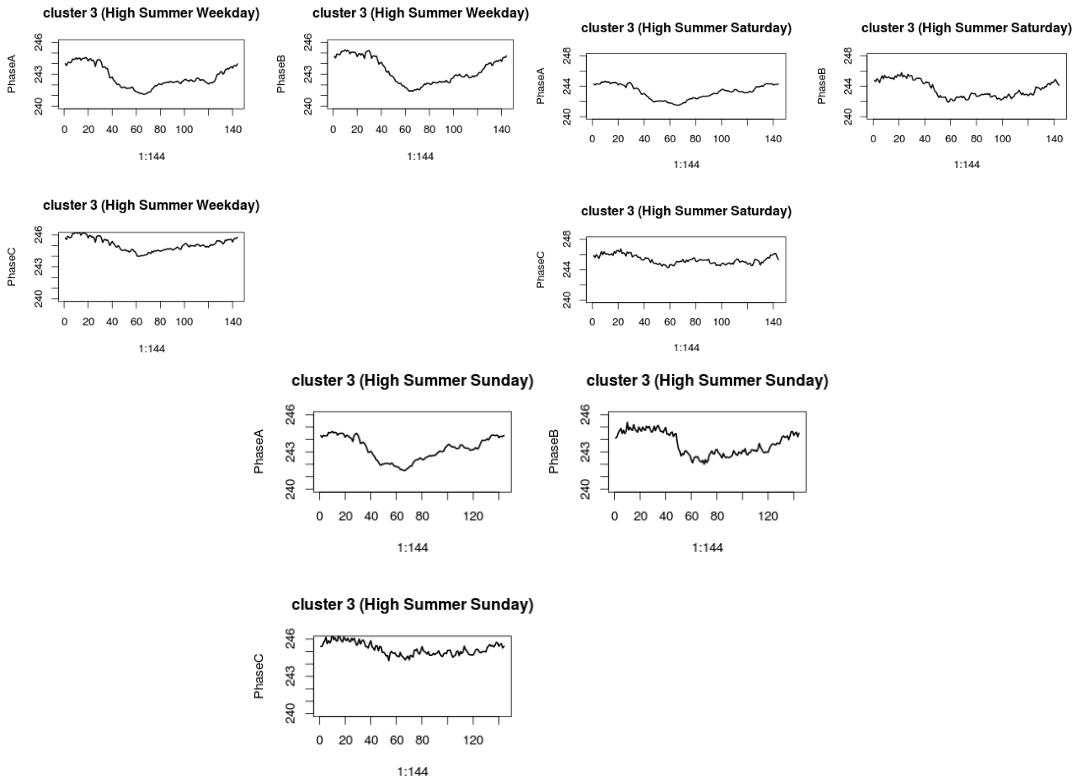


Figure 6: Voltage profiles at remote feeder ends for cluster 3. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 3 substations to absorb low carbon stresses is detailed in Table 3.

Type	Comment
Workplace / Retail EV charging	Less unsuitable time of day pattern as load curve shows limited drop off during working hours
Overnight EV charging	Suitable
Heat Pump	Suitable if linked with insulation or heat storage to permit off peak operation
PV	Suitable - complimentary to both power and voltage curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 3: Cluster 3: ability to absorb low carbon stress

4.1.4 Cluster 4

Cluster 4 comprises largely of domestically dominated substations. The substation demand and voltage profiles are shown in figures 7 and 8 respectively.

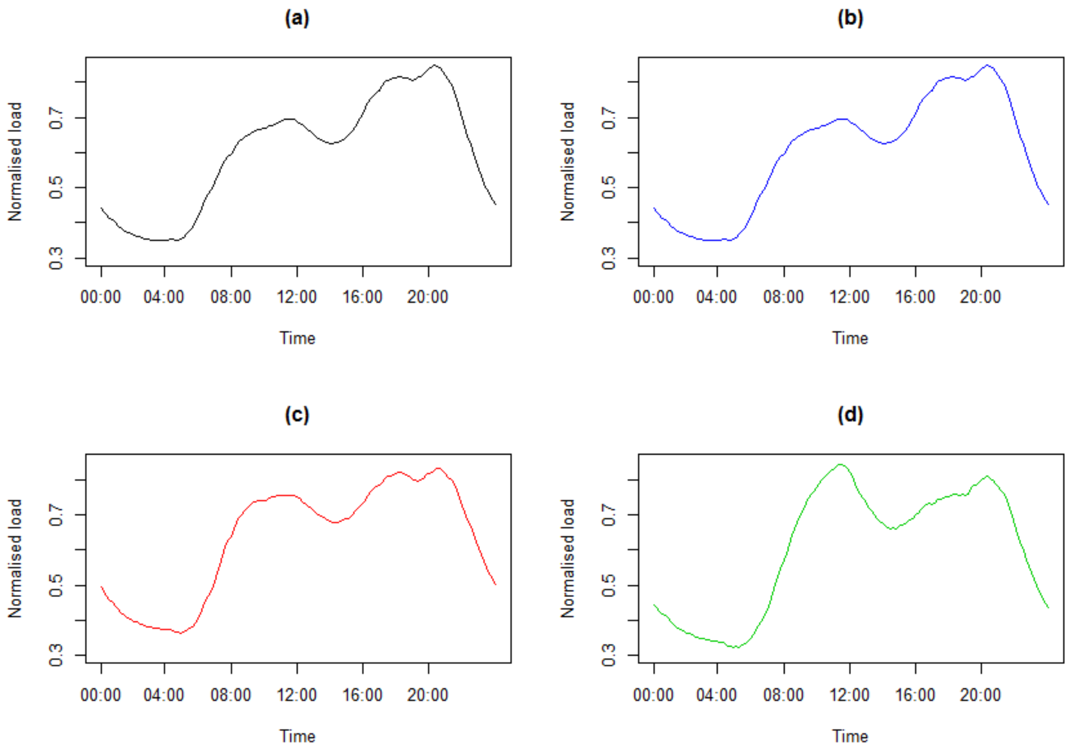


Figure 7: Substation demand profiles for cluster 4. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The three-phase remote feeder end voltages linked to cluster 4 are very similar in terms of both magnitude and profiles.. The voltages are as high as 244-245V during the night, dropping to 241-242V during the day. The weekend three-phase voltage profiles are also similar, but the Sunday's profiles have more variation.

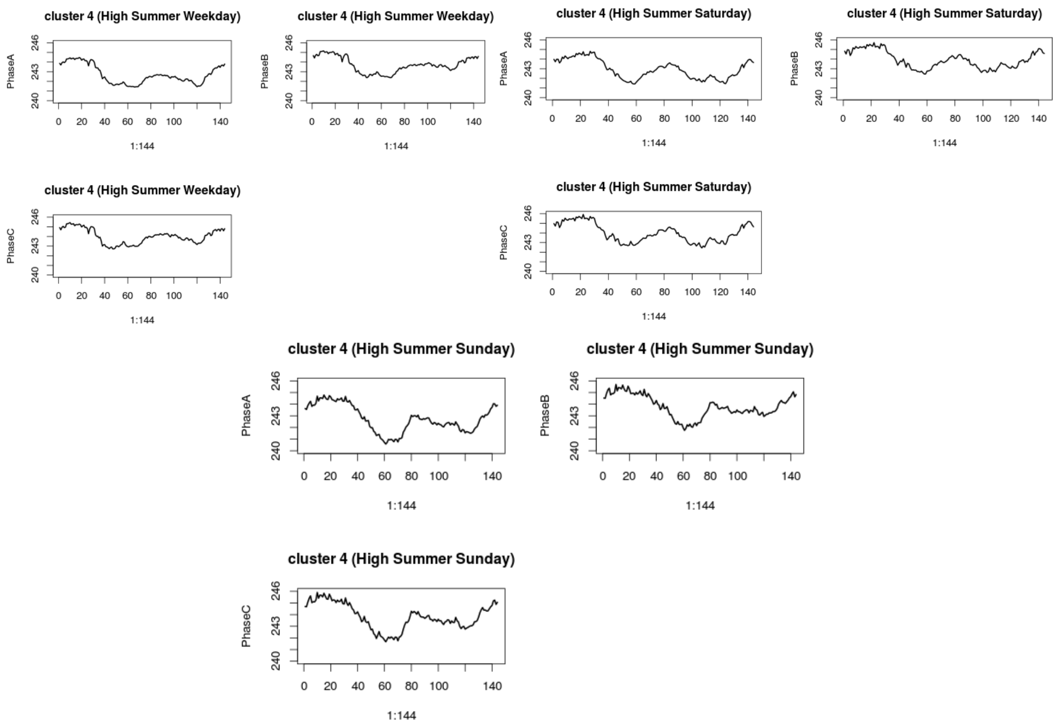


Figure 8: Voltage profiles at remote feeder ends for cluster 4. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 4 substations to absorb low carbon stresses is detailed in Table 4.

Type	Comment
Workplace / Retail EV charging	Unsuitable time of day pattern as need is coincident with prevailing peak
Overnight EV charging	Suitable
Heat Pump	Only if linked with insulation or heat storage to permit off peak operation
PV	Suitable - complimentary to both power and voltage curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 4: Cluster 4 - ability to absorb low carbon stress

4.1.5 Cluster 5

As with clusters 2 and 4, cluster 5 represents domestic dominated substations. The substation demand and voltage profiles are shown in figures 9 and 10 respectively.

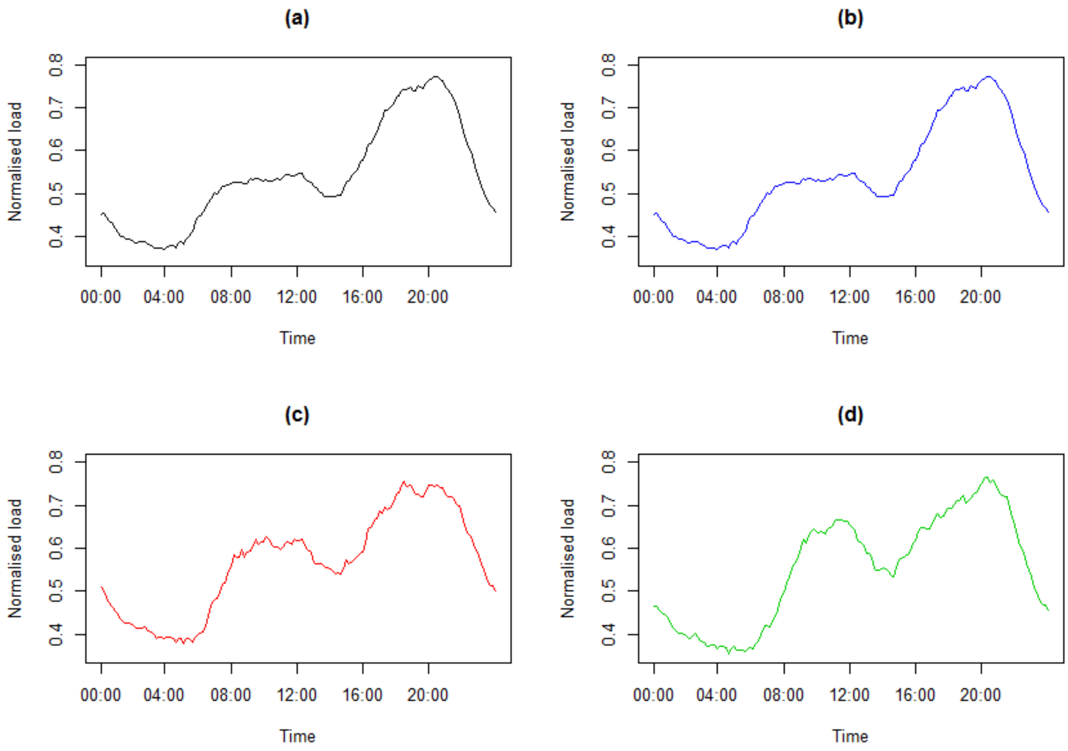


Figure 9: Substation demand profiles for cluster 5. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

This cluster consists entirely of substations that are single phase. The voltage profiles show the inverse pattern to demand with a minimum of 242V at 20:00pm. The profiles for weekends show an apparent rise during the middle of the day together with more variation than is seen for weekdays.

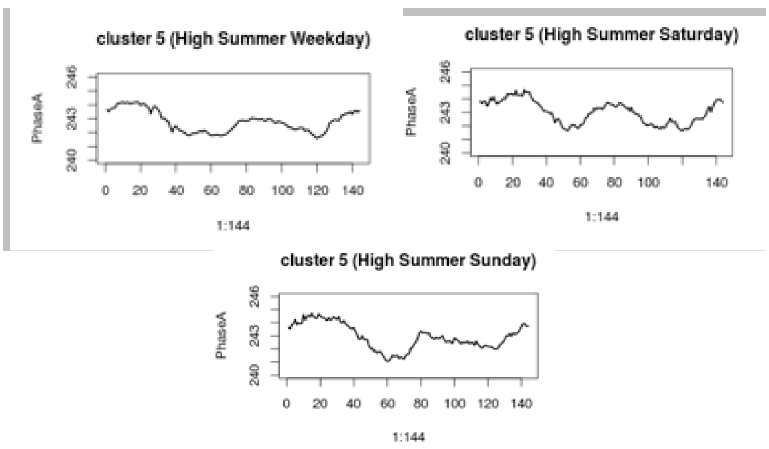


Figure 10: Voltage profiles at remote feeder ends for cluster 5. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 5 substations to absorb low carbon stresses is detailed in Table 5.

Type	Comment
Workplace / Retail EV charging	Suitable providing that work / sole operating hours are not coincident with peak
Overnight EV charging	Suitable
Heat Pump	Might require link with insulation or heat storage to permit off peak operation
PV	Less suitable - as not complimentary to power curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 5: Cluster 5: ability to absorb low carbon stress

4.1.6 Cluster 6

As with clusters 1 and 3, cluster 6 represents commercial dominated substations. The pattern observed for cluster 6 is very similar to cluster 1 but with a higher magnitude due to these substations serving mainly large-size industrial and commercial customers. The substation demand and voltage profiles are shown in figures 11 and 12 respectively.

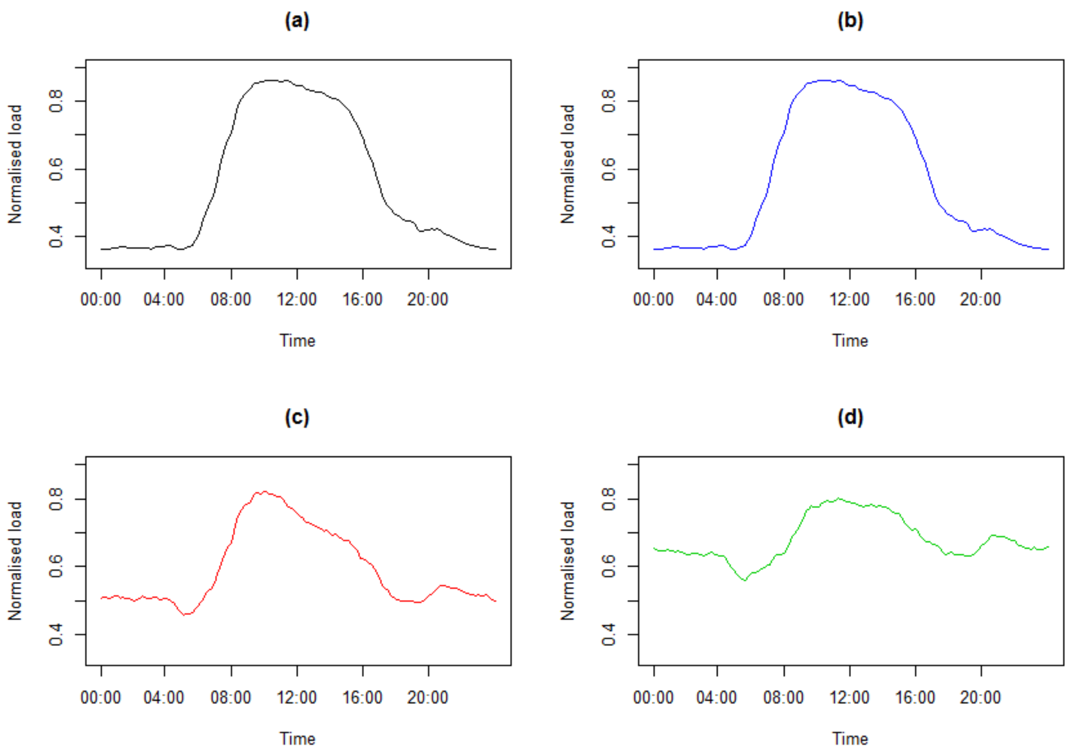


Figure 11: Substation demand profiles for cluster 6. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The remote feeder end voltage profiles on the three phases are nearly identical and reflect the demand. At weekends, higher magnitudes are observed when compared to weekdays.

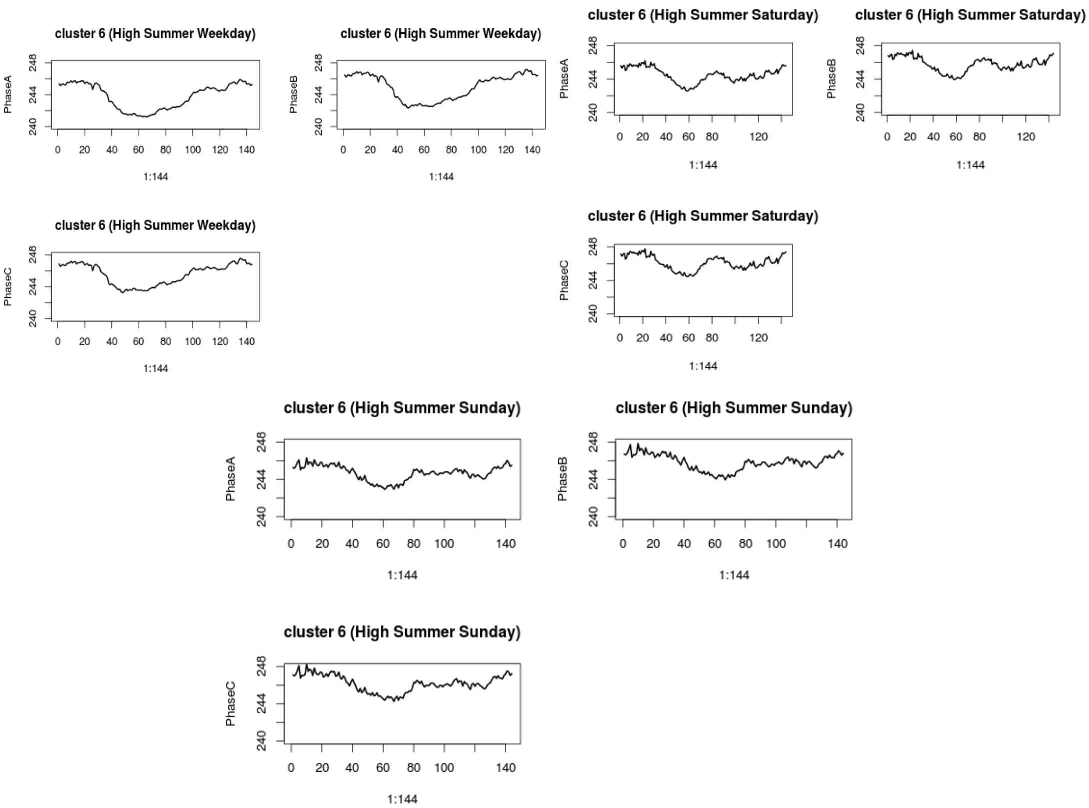


Figure 12: Voltage profiles at remote feeder ends for cluster 6. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 6 substations to absorb low carbon stresses is detailed in Table 6.

Type	Comment
Workplace / Retail EV charging	Unsuitable time of day pattern as need is coincident with prevailing peak
Overnight EV charging	Very suitable
Heat Pump	Only if linked with insulation or heat storage to permit off peak operation
PV	Suitable - complimentary to both power and voltage curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 6: Cluster 6: ability to absorb low carbon stress

4.1.7 Cluster 7

Cluster 7 largely contains substations of a mix of domestic customers and small commercial customers in rural areas with low demands. There are two obvious peaks, the first of which appear around 12:00 pm driven by commercial customers and the second of which happens at approximately 20:00 pm triggered by domestic customers. The substation demand and voltage profiles are shown in figures 13 and 14 respectively.

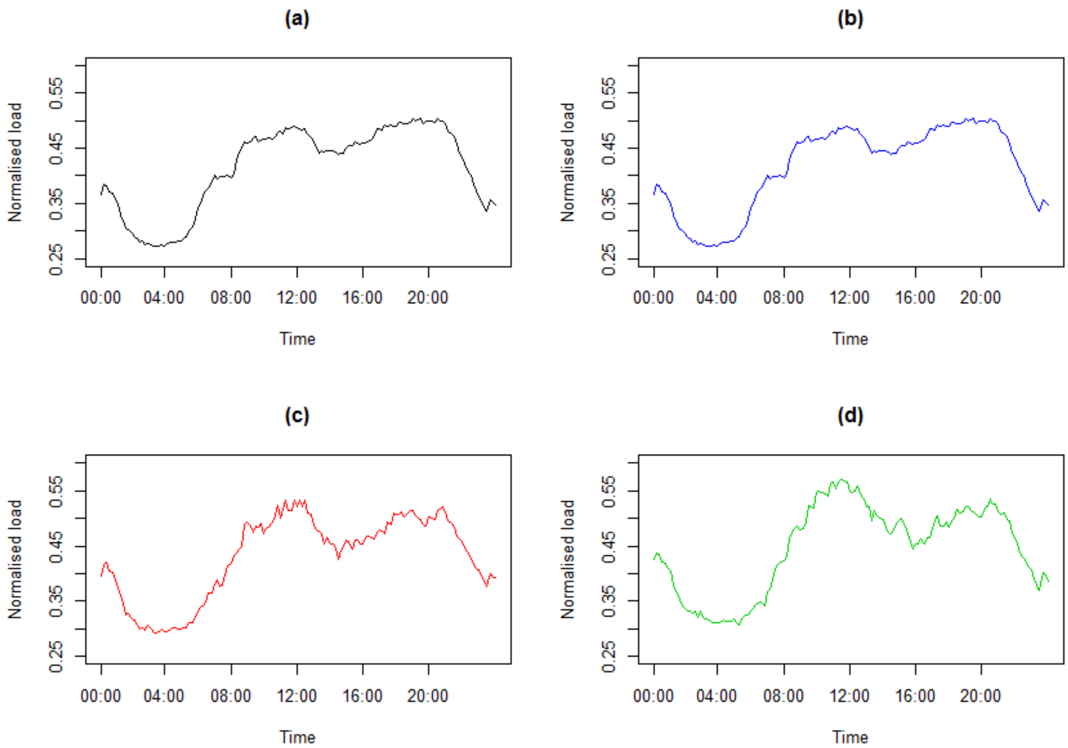
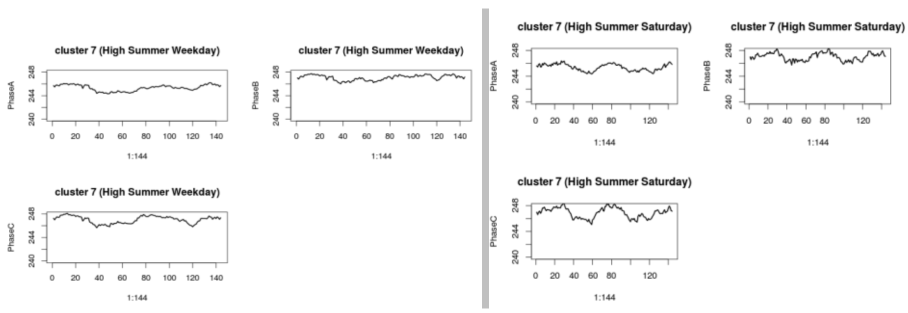


Figure 13: Substation demand profiles for cluster 7. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The voltage profiles at remote feeder ends show that weekdays are relatively steady, fluctuating within a small range (245V-248V). The magnitude of phase A is smaller than those of phases B and C, indicating relatively higher loads. For the weekend profiles, phase A's are comparably steady, while phases B and C exhibit larger variation.



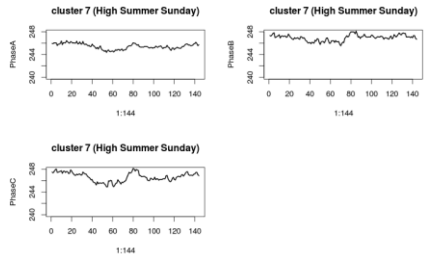


Figure 14: Voltage profiles at remote feeder ends for cluster 7. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 7 substations to absorb low carbon stresses is detailed in Table 7.

Type	Comment
Workplace / Retail EV charging	The wider variability within this cluster precludes firm conclusion though the tendency is a curve that is not complementary to workplace EV charging
Overnight EV charging	Suitable
Heat Pump	Only if linked with insulation or heat storage to permit off peak operation
PV	The wider variability within this cluster is less suitable for PV-
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 7: Cluster 7 : ability to absorb low carbon stress

4.1.8 Cluster 8

Cluster 8 comprises of a mix of commercial and domestic customers. At the time of writing, there no remote feeder end voltage monitors were associated with this group of substations. The substation demand profiles are shown in figure 15.

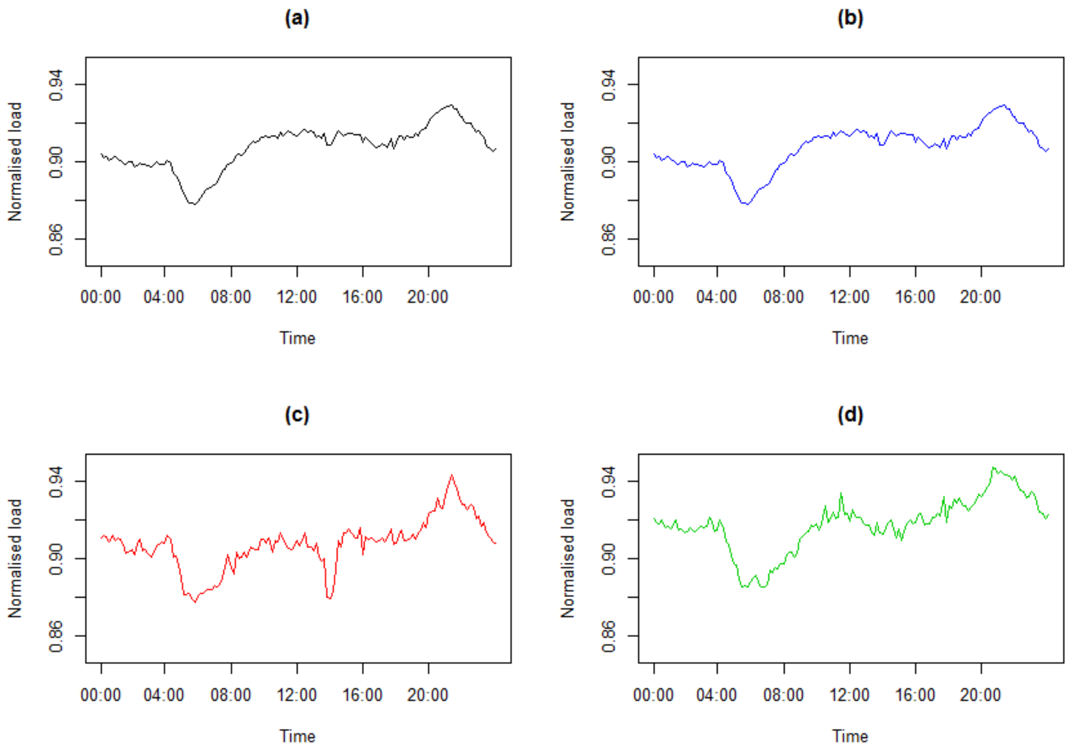


Figure 15: Substation demand profiles for cluster 8. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

From the load and voltage profiles, the ability of cluster 8 substations to absorb low carbon stresses is detailed in Table 8.

Type	Comment
Workplace / Retail EV charging	Unsuitable time of day pattern as need is coincident with prevailing peak
Overnight EV charging	less suitable
Heat Pump	More limited capability due to lack of depth and duration of off peak demand
PV	Suitable - complimentary to power curves
CHP, AD, Hydro, Wind	More suitable than most given that generation is not naturally limited to time of day and demand curve has reduced depth and duration of off peak period

Table 8: Cluster 8: ability to absorb low carbon stress

4.1.9 Cluster 9

Cluster represents domestic dominated substations with significant Economy 7 customers. The substation demand and voltage profiles are shown in figures 16 and 17 respectively.

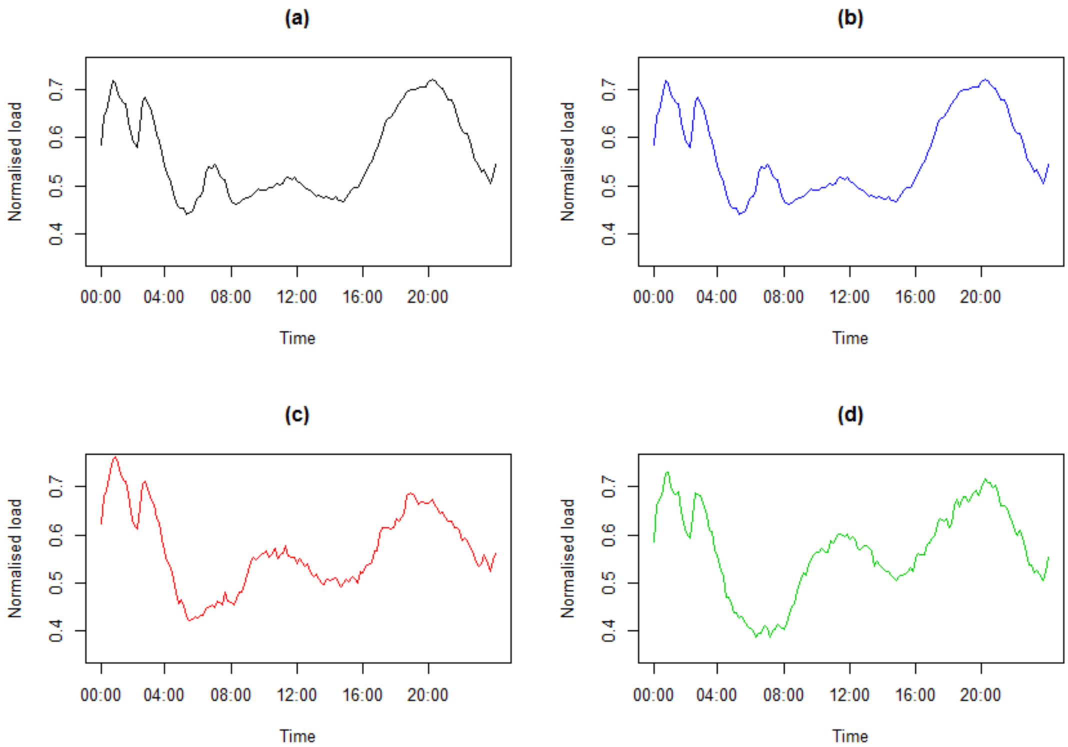


Figure 16: Substation demand profiles for cluster 9. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

The remote feeder end voltage profiles are relatively flat, without any apparent voltage dip, with more variation being observed in the weekend profiles.

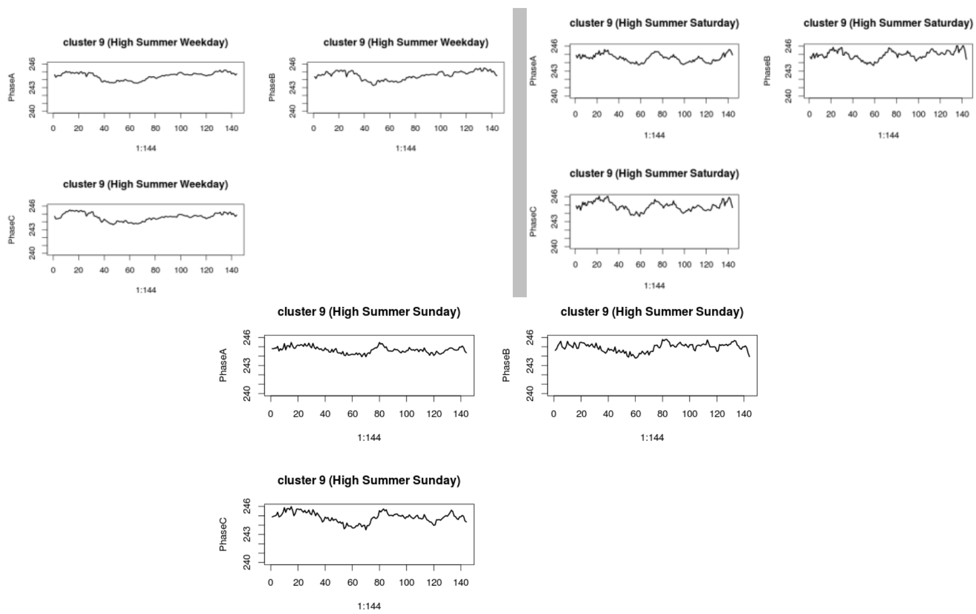


Figure 17: Voltage profiles at remote feeder ends for cluster 9. Clockwise, the figures represent the three-phase voltages in weekdays Saturday and Sunday.

From the load and voltage profiles, the ability of cluster 9 substations to absorb low carbon stresses is detailed in Table 9.

Type	Comment
Workplace / Retail EV charging	Suitable providing that work / sole operating hours are not coincident with peak
Overnight EV charging	Not suitable
Heat Pump	Requires further examination of nature of activity - might require link with insulation or heat storage to permit off peak operation
PV	Less suitable - as not complimentary to power curves
CHP, AD, Hydro, Wind	Since generation is not naturally limited to time of day, potential need for constraint for voltage reasons off peak

Table 9: Cluster 9: ability to absorb low carbon stress

4.1.10 Cluster 10

Cluster 10 comprises exclusively of substation for motorway communication/ lighting pillars. There are no remote feeder voltage end monitors associated with these substations. The substation demand profiles are shown in figure 19.

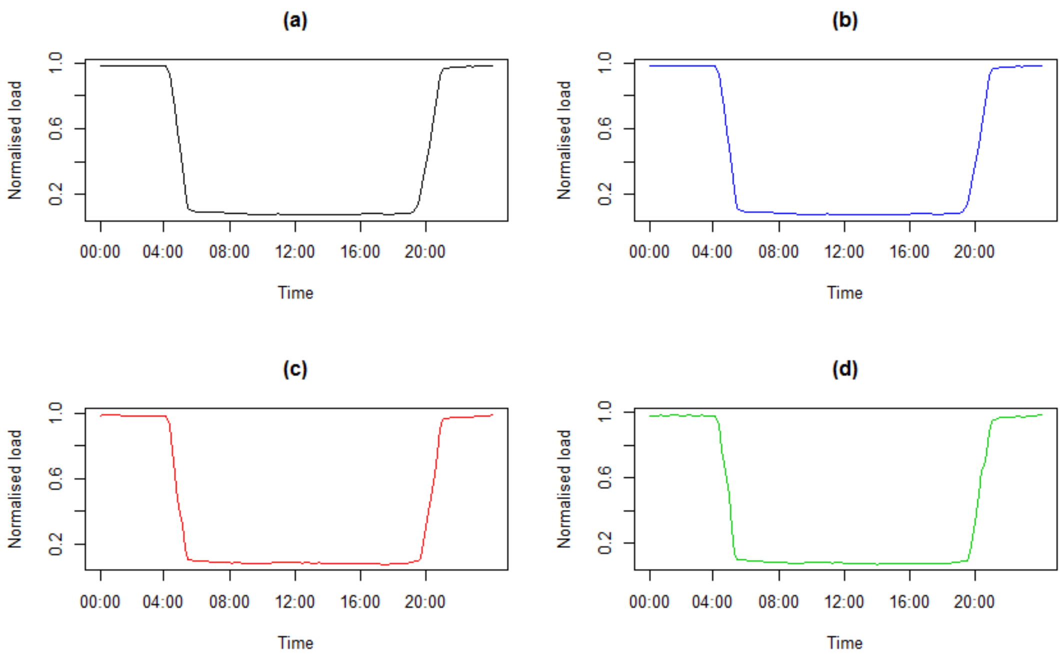


Figure 18: Substation demand profiles for cluster 10. Panels show results for; (a) all days, (b) weekdays, (c) Saturdays and (d) Sundays.

Only from the load profiles, the ability of cluster 10 substations to absorb low carbon stresses is detailed in Table 10.

Type	Comment
Workplace / Retail EV charging	Suitable, complementary with power profiles
Overnight EV charging	Unsuitable time of day pattern as need is coincident with demand
Heat Pump	Suitable
PV	Unsuitable, demand is not there when PV radiation is at peak
CHP, AD, Hydro, Wind	Suitable

Table 10: Cluster 10 - ability to absorb low carbon stress

5 The effect of local low carbon installations.

The low carbon stress analyses draw heavily from Wales Strategic Energy Performance Investment Programme – Arbed initiative, aiming for increasing 'domestic energy efficiency, community-scale renewables and alleviating fuel poverty'. The initiative is set out in "A Low Carbon Revolution –The Welsh Assembly Government Energy Policy Statement part of Welsh government", as part of the Welsh government's ambitious energy plan - 'making low carbon energy a reality' [5].

The total number of properties registered with Arbed at the time of analysis was 4036. At these properties 912 PVs, 616 SHWs (Solar Water Heaters), 2198 EWI (External Wall Insulation), 539 fuel switching, 213 boiler replacements and 62 ASHPs (Air Source Heat Pumps) were installed. These installations were associated with 115 substations of which ca. 100 were monitored as part of this study. We now compare profiles of power and voltage profiles between two groups of substations: (i) those with registered low carbon initiatives that might be expected to have an effect on the network and (ii) those without. The creation of these two groups and the numbers of substations available for analysis can be seen in Figure 19. In order to perform as direct a comparison of the possible effects of the installations as possible, demand and voltage (at remote feeder ends) were obtained for the substations in cluster 4. Cluster 4 is dominated by domestic customers and has the highest penetration of low carbon installations of any of the clusters.

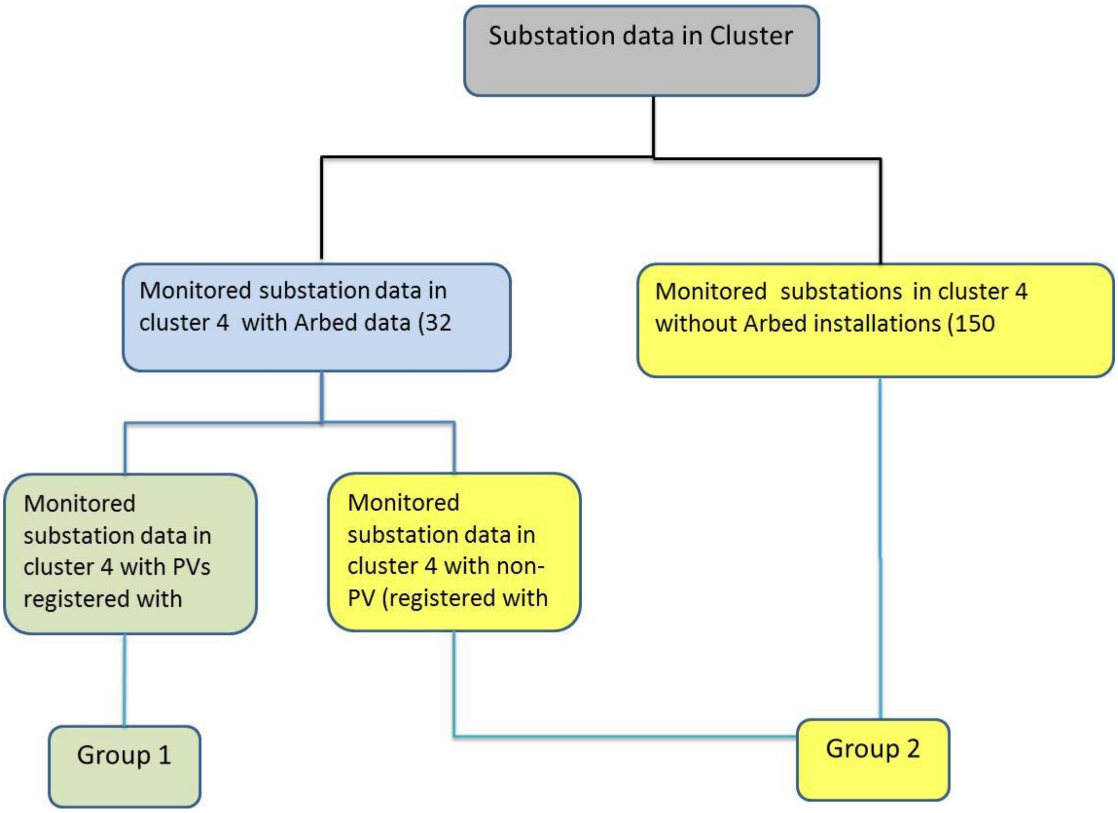


Figure 19: Schematic of the creation of two groups for analysis of the effects low carbon installations on demand and voltage profiles. Groups 1 and 2 contain substations in cluster 4 with and without Arbed registered PV installations respectively.

5.1 Assessing differences in demand and voltage profiles due to PV installations

5.1.1 Comparison of substation demand profiles

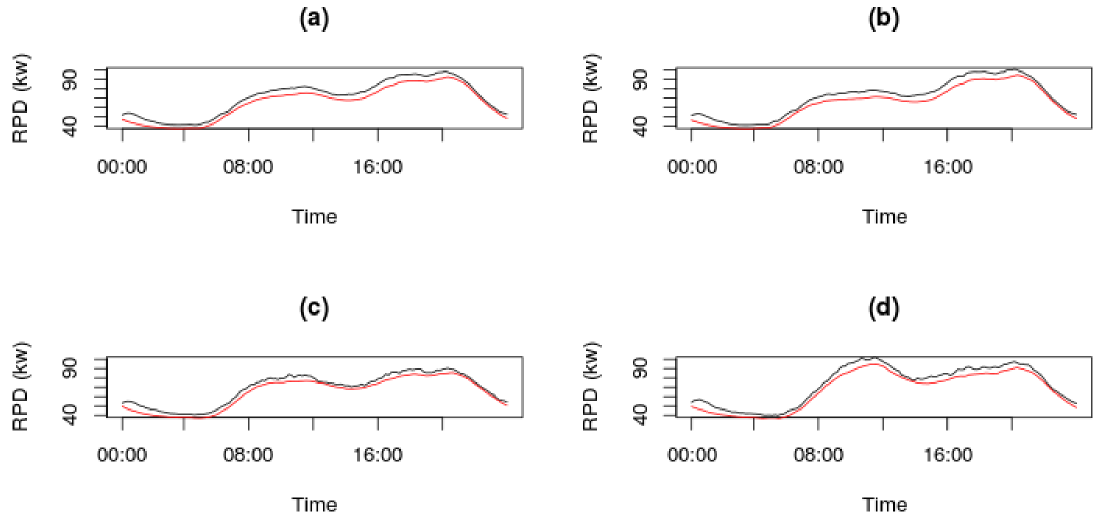


Figure 20: Substation load profiles (real power delivered) for Group 1 (black line) and Group 2 (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

5.1.2 Comparison of substation voltage profiles

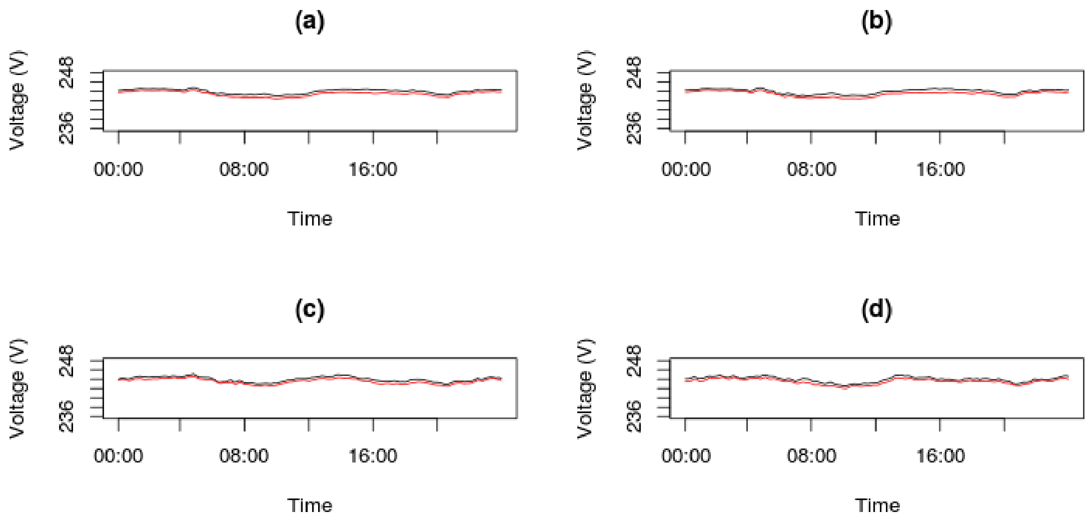


Figure 21: Substation voltage profiles (Phase A) for Group 1 (black line) and Group 2 (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

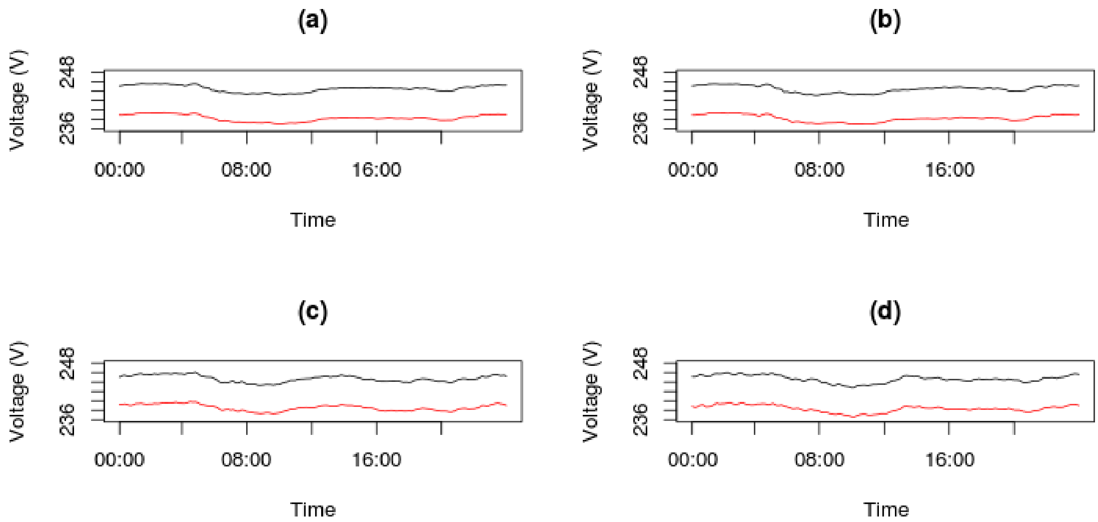


Figure 22: Substation voltage profiles (Phase B) for Group 1 (black line) and Group 2 (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

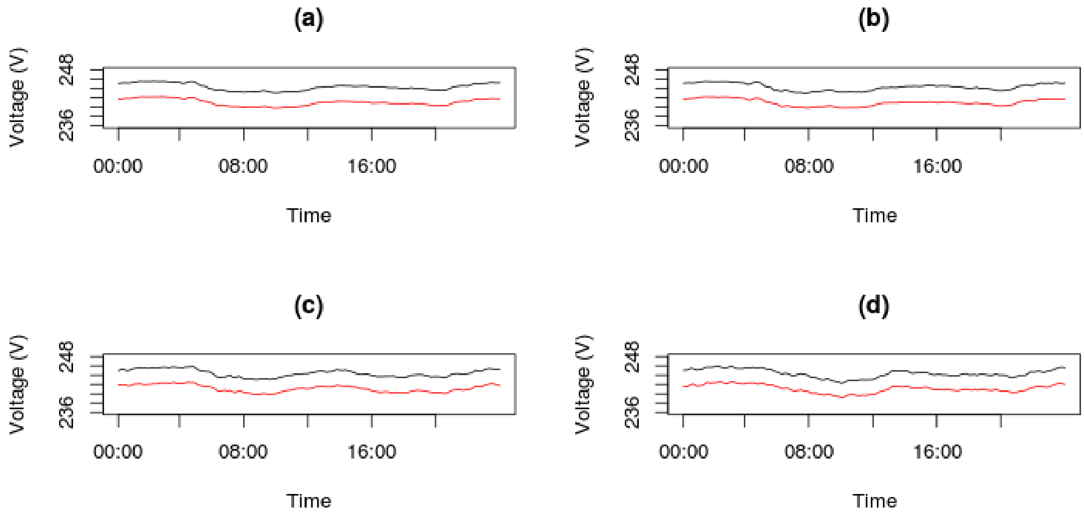


Figure 23: Substation voltage profiles (Phase C) for Group 1 (black line) and Group 2 (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

5.1.3 Conclusion on comparison between groups of substations with and without PV installations

- The above groups with and without PV clearly exhibit the same voltage and demand profiles. This is not as anticipated, as significant installations of PV would be expected to show a relative increase in voltage during daylight hours.
- In seeking to understand this, the findings of the PV FiT report have demonstrated that the maximum aggregate output generated from multiple PV installations within a postcode was only 81% of the declared capacity.

Consequently, since the associated voltage rise / drop is related to the square of the current, the voltage impact of the PVs is at least 36% lower than at full rated output.

- The current analysis suggests that the level of PV installed at the monitored substations had little impact on the network. This may be due to a combination of system design, assuming 100% efficiency, and possible overstatement of maximum rated output by installers. It is proposed to undertake further analysis to compare individual similar substations with or without PV and also compare individual substations on high and low solar radiation days. These findings will be disseminated.

5.2 Assessing differences in power profiles due to heat pumps

In assessing the potential effects of air source heat pumps, two substations had substantially more Arbed registered installations than all others. Two substations had 23 each (out of the total of 62 over all Arbed substations). These two substations were in clusters 5 and 6). In the following analysis, the demand profiles of the two substations in comparison to the others in their respective clusters are presented. Results are initially presented for the same period as that chosen to maximise the potential for observing difference due to PVs, i.e, high summer. As it might be expected that there might be little evidence of any effect of air source heat pumps during this period, results are also presented for winter.

5.3 Substation with 23 registered air source heat pumps compared to other substations in cluster 5.

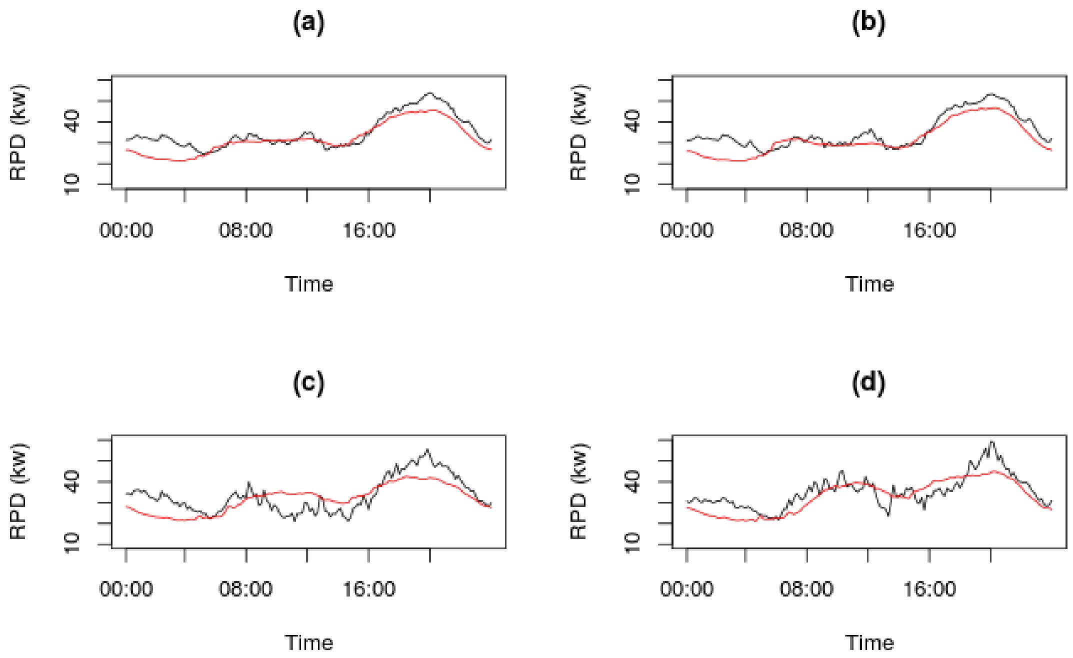


Figure 24: Substation load profiles (real power delivered) for substation in cluster 5 with 23 Arbed registered air source heat pumps (black line) and remaining substations in cluster 5, excluding substation with 23 Arbed registered air source heat pumps (red line). Results are for High summer. Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

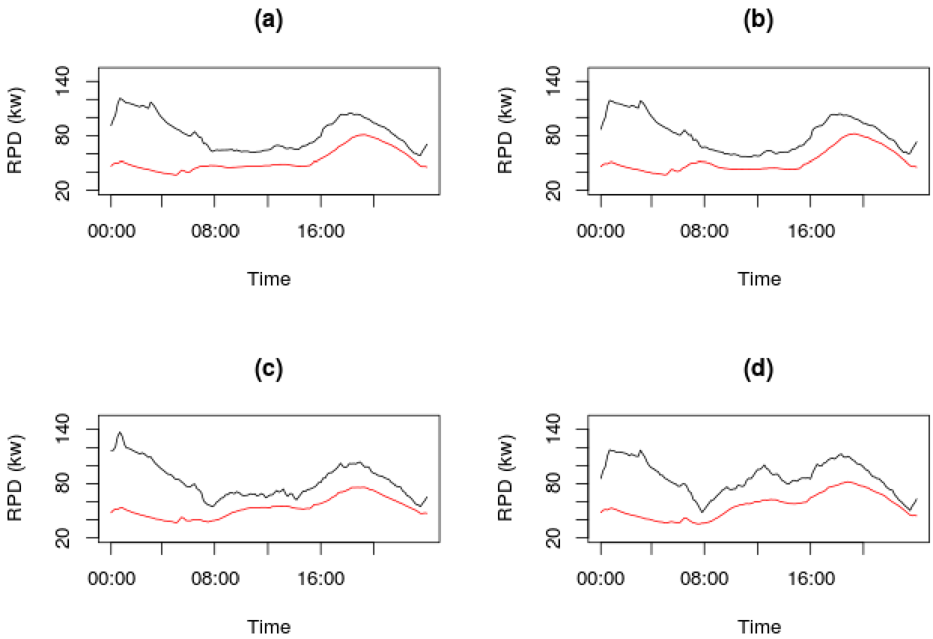


Figure 25: Substation load profiles (real power delivered) for substation in cluster 5 with 23 Arbed registered air source heat pumps (black line) and remaining substations in cluster 5, excluding substation with 23 Arbed registered air source heat pumps (red line). Results are for winter. Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday.

5.4 Substation with 23 registered air source heat pumps compared to other substations in cluster 6.

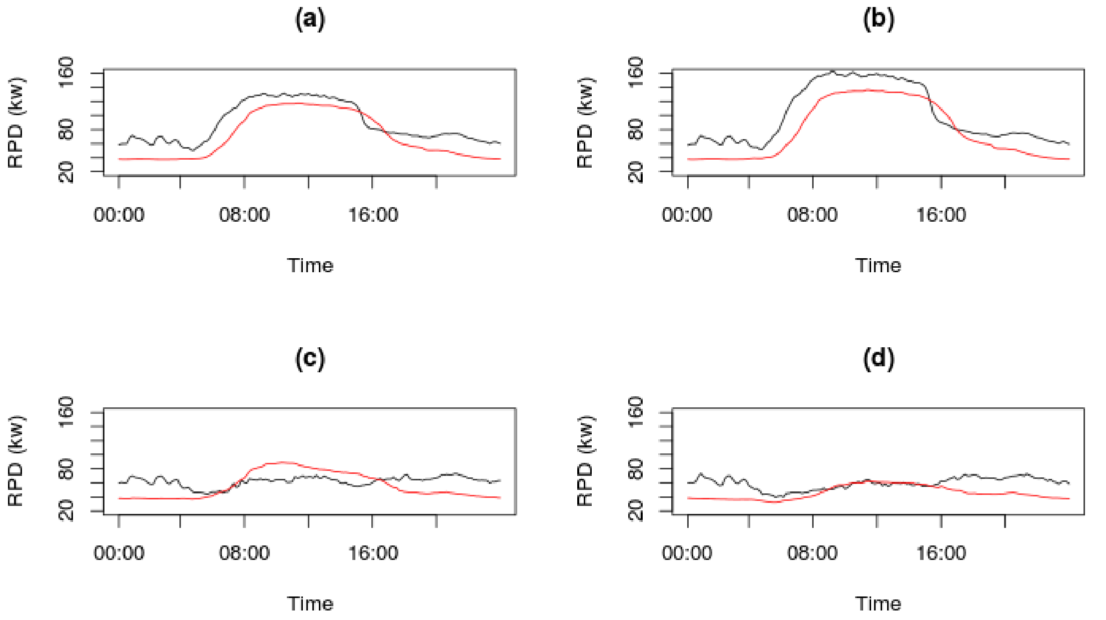


Figure 26: Substation load profiles (real power delivered) for substation in cluster 6 with 23 Arbed registered air source heat pumps (black line) and remaining substations in cluster 6, excluding substation with 23 Arbed registered air source heat pumps (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday. Results are for High Summer.

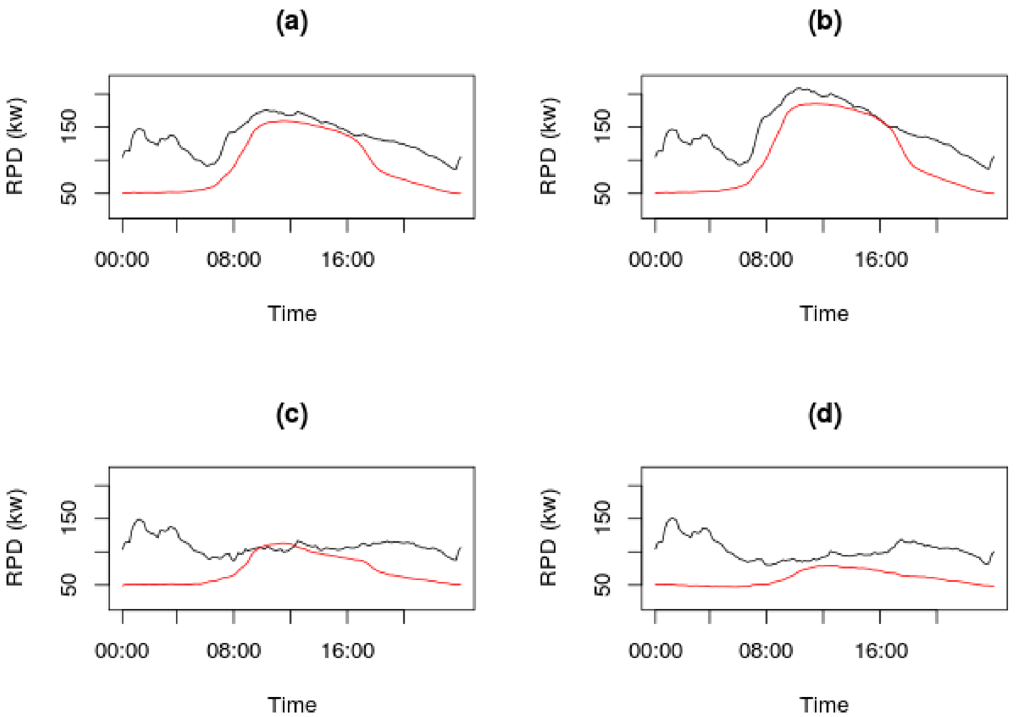


Figure 27: Substation load profiles (real power delivered) for substation in cluster 6 with 23 Arbed registered air source heat pumps (black line) and remaining

substations in cluster 6, excluding substation with 23 Arbed registered air source heat pumps (red line). Panels show results for (a) all days; (b) Weekday; (c) Saturday; (d) Sunday. Results are for winter.

5.5 Conclusions

- Amongst other things, these figures show the ability of the clusters to discriminate between substations with differing customer mixes. Cluster 5 is dominated by domestic customers, the demand profile for which can clearly be seen in Figure 24 (excluding the substation with the 23 heat pumps) and the substation with the Arbed registered heat pumps in this cluster has 100% domestic customers. Cluster 6 comprises of substations that are commercially dominated as is demonstrated by the demand profiles shown in Figure 26 that shows the profiles averaged over substations excluding the one with the Arbed registered heat pumps. Relative to the majority of substations in cluster 6, this substation has a higher proportion of domestic customers, the effect of which can be seen in the different profiles observed at weekends during which the commercial load drops off, leaving the domestic load as dominant.
- In high summer there is little evidence of the effect of ASHP's within the profiles of substations, with and without ASHP's. With both Clusters 5 & 6 adopting a very similar pattern.
- In winter however there is a clear increase in demand from around 00.00hrs to 07.00hrs, which is believed to be the effect of ASHP's. This is clearly evident in cluster 5, but can also be seen in cluster 6, when the domestic load is dominating.
- It would appear that the ASHP's are operating coincidentally with Economy 7 type time of use tariff. What is evident is that, if the increased demand from ASHP's was shifted to coincide with the tea time peak (Cluster 5) or the daytime peak (Cluster 6) there could well be some network issues as a result.
- There is reduced capacity for EV overnight charging on Cluster 5 if ASHP's are connected their use would coincide with the peak overnight demand, but they could be accommodated during the working day (08.00hrs to 16.00hrs)
- When the headroom identified with this project has been exploited by the connection of greater densities of low carbon technologies there will clearly be a need to examine the case for updated or new templates

6 Adherence to voltage limits

Networks are designed to operate within UK statutory voltage limits set out over many years in the Electricity Supply Regulations and most recently in the Electricity Safety Quality and Continuity Regulations 2002(as amended). (ESQCRs) These require (Reg 27 (2)) for low voltages to be maintained between 230v +10%/-6%.

In the 2002 issued Guidance to the ESQCRs, UK Government also stated "in 1993 the UK government committed to harmonisation of low voltage tolerances across the

European Community in accordance with CENELEC document HD 472 S1. In July 2001 the CENELEC Technical Board decided to extend the existing tolerance for low voltage systems (see regulation 27(3)(b)) to 2008, at which time it is possible that further consolidation of voltage tolerances across Europe will take place".

Whilst there has not yet been a change to the wider EU LV tolerances of 230v +/- 10% - i.e an extension from -6% to -10%, it was clearly within UK Government consideration. In the event that this Project were to reveal that in practice there was widespread evidence that networks were consistently performing at or close to the lower limits, there would be a weaker case to argue for adoption of the EU limits as there would be less confidence that wholesale voltage reduction would not adversely affect larger numbers of outliers.

In this section, we present an analysis of over/under voltage problems at substations and remote feeder ends using the real-time monitored voltage data from April 2012 to end of February 2013. This project provided for long term and very widespread monitoring of voltages across ca. 800 substations, mostly with 3 phase outputs, and ca. 3600 ends of LV feeders, every 10 minutes. An individual measurement of a single phase and location is termed "an instance". This currently provides a database of ca. 180, 000, 000 measurements with monitoring still on-going. It is understood to be the largest ever check of LV network voltages in UK.

The purpose of making these measurements was threefold; to verify that the actual performance was consistently within UK statutory limits, to understand how voltage varied with daily load patterns and clusters, and to see what headroom was left relating to opportunities / constraints on installation of low carbon technologies

The monitored voltages are the averaged voltage values at 10-minitue intervals; a measurement recognised in EN 50160. Analysis has been undertaken to verify compliance with UK voltage limits and to understand the frequency, duration, magnitude, and distribution of voltages across the voltage monitors. Where instances have been identified that pass threshold criteria set near but within statutory limits, those have been subject to further detailed analysis as described below. Finally, there is discussion into the potential for adopting the EU voltage standards.

The analyses comprises of the following components:

1. Sense checking to filter out suspect data
2. Identifying patterns of lower / higher voltages; times, duration and magnitude both between substations and over time.
3. Further investigation of these patterns over seasons, days of week , hours and locations
4. Assessing the potential for adopting EU voltage standards; extending the lower boundary from -6% to -10% (with the upper boundary unchanged).

6.1 Sense checking

It is recognised that there is a potential for problems in data acquisition, transfer and storage and consequently the analysis undertaken has had sense checking inbuilt to the process. Given that voltages measured are 10 minute averages, as recognised by EN 50160, a fault or loss of supply impinging within that 10 minute period will be reflected as a lower average voltage; it is thus necessary to set some boundaries that are wide enough not to exclude genuine under or over voltage problems that would clearly generate a customer contact. Measurements above 276V and below 184V at both substations and remote feeder ends were deemed to fall into this category and were excluded from the following analyses. Figure 28 shows the limits used for this sense checking

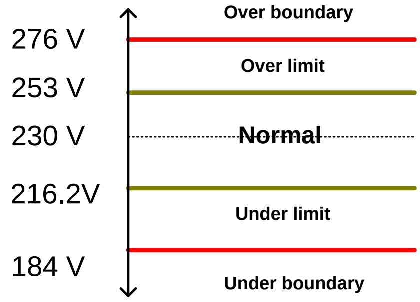


Figure 28. Criteria for sense-checking voltage measurements. Upper boundary for inclusion in analysis, 276V, lower limit 184V. The UK limits of 216.2-253V are shown together with EU lower limit of 207V.

6.2 Network pressures under the UK standards

6.2.1 Voltages measured at substations

Out of the 84,300,929 measurements of voltage made at 828 substations during this time period, 81,105,726 were within the range 184-276V and are used in the following analysis. Out of these, 99.31% (80546257 measurements) were within the UK limits of 216.2-253V and 0.69% outside. The split of those outside limits were 0.0078% below the lower limit and 0.69% above the upper limit

Table 11 shows the distribution of the magnitude of the measurements that were outside the limits. Figure 29 shows the distribution of measurements above the UK limit of 253V by substation that shows that the majority of substations have very few occurrences. Figure 30 shows the corresponding information for the small number of measurements that were under the limit of 216.2V.

Range: 230 V+/- given percentage	Percentage
>10% (>253V)	0.69%
8 to 10% (248.4V, 253V)	6.98%

6 to 8% (243.8V, 248.4V)	49.17%
-2 to -4 % (220.8V, 225.4V)	0.00076%
-4 to -6 % (220.8V, 216.2V)	0.00025%
-6 to -10% (216.2V, 207V)	0.00025%
<-10% (207V<)	0.00053%

Table 11: Distribution of the magnitude of voltage measurements measured at substations.

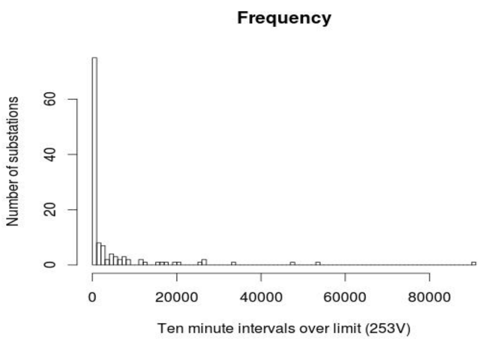


Figure 29: Distribution of measurements above the UK limit of 253V by substations

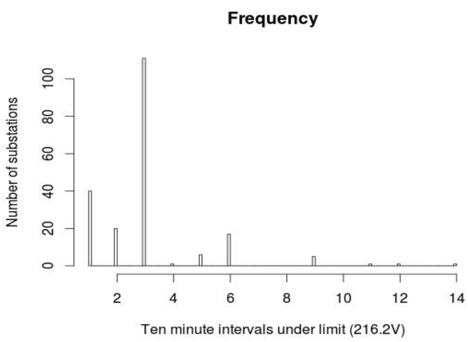


Figure 30: Distribution of measurements below the UK limit of 216.2V by substations

6.2.2 Voltages measured at remote feeder ends

There were 96,407,984 measurements from remote feeder ends which were inside the sense checking boundaries (97.7% of the total of 98,663,154 ten minute interval measurements). Of these, 99.62% were within the UK limits 216.2-253V and 0.38% outside. The split between those outside these limits was 0.021% below the lower limit and 0.35% above the upper limit.

Table 12 shows the distribution of the magnitude of the measurements respective to 230V. Figure 31 shows the distribution of measurements above the UK limit of 253V by remote feeder end monitor which shows that the majority of substations have very few occurrences. Figure 32 shows the corresponding information for the small number of measurements that were under the limit of 216.2V.

Range: 230 V+/-	Percentage
>10% (>253V)	0.35%
8 to 10% (248.4V, 253V)	5.22%
6 to 8% (243.8V, 248.4V)	32.30%
-2 to -4 % (220.8V, 225.4V)	0.1234%
-4 to -6 % (220.8V, 216.2V)	0.0437%
-6 to -10% (216.2V, 207V)	0.0187%
<-10% (<207V)	0.0022%

Table 12: Distribution of the magnitude of voltage measurements measured at remote feeder ends.

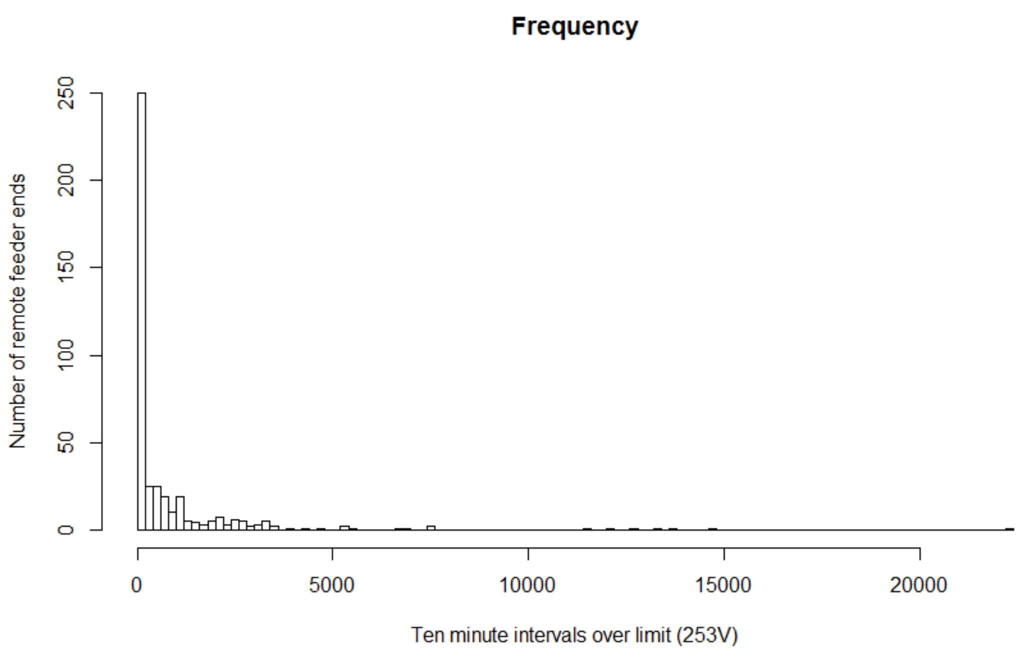


Figure 31: Distribution of measurements above the UK limit of 253V by remote feeder ends.

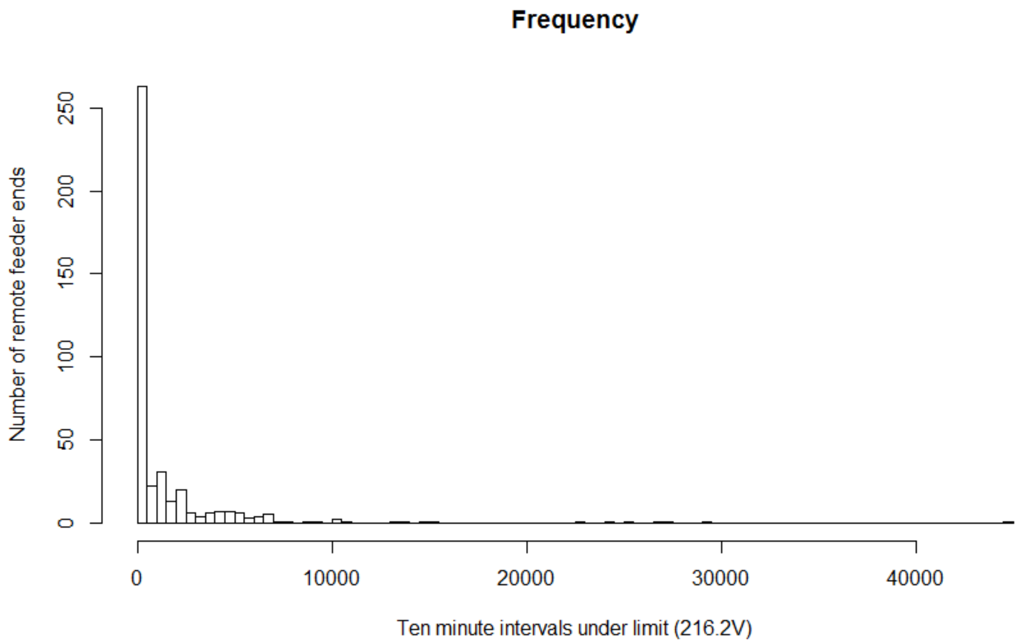


Figure 32: Distribution of measurements below the UK limit of 216.2V by remote feeder ends

6.3 Network Pressure Analysis under EU Standards

This section examines the difference that would be made by moving to the wider EU voltage standard, 230 +/-10%.

Had the preceding analysis revealed a widespread problem with multiple locations at the limit or in breach of the current UK lower voltage limit, it would suggest that the additional "headroom" which would be afforded by the move to the lower EU limit was already being exploited (in breach of current UK ESQCRs). Since that has not been the case, there is an argument that a reduction of some 2.5%, which is a tap step on ground mount transformers, could be applied without danger of substantial numbers of LV connected customers actually experiencing voltages under lower EU limit. A similar level of voltage reduction could be applied by re-setting target voltages at primary substations.

The benefits to UK and Customers would arise from the demand reduction associated with lower supply voltage. For purely resistive load a 2.5% reduction in voltage amounts to a 2.5% reduction in instantaneous demand (kW). In practice some types of demand, e.g. heating, may still use the same amount of energy (kWh), but over a longer time period. A midline estimate would be that 2.5% voltage reduction would produce around 1.5% reduction in demand. This would benefit

- network capacity,
- need for reinforcement,

- headroom to deploy low carbon demand technologies reduction in network losses
- reduction in peak UK demand, meaning displacement of low merit and least efficient generation
- reduction in UK CO2 emissions

The following paragraphs illustrate the different numbers of instances of out of limit voltage instances that would have applied in this Project had the EU lower limit been in place. The results for the upper limits remain as before given that UK and EU limits are the same.

In this scenario, the total number of measurement locations (remote feeder ends) that have under voltage drops from 152 to 32 and the total voltage instances reduce to 2019, accounting for 0.0022% of all voltage measurements, as can be seen in Figure 33.

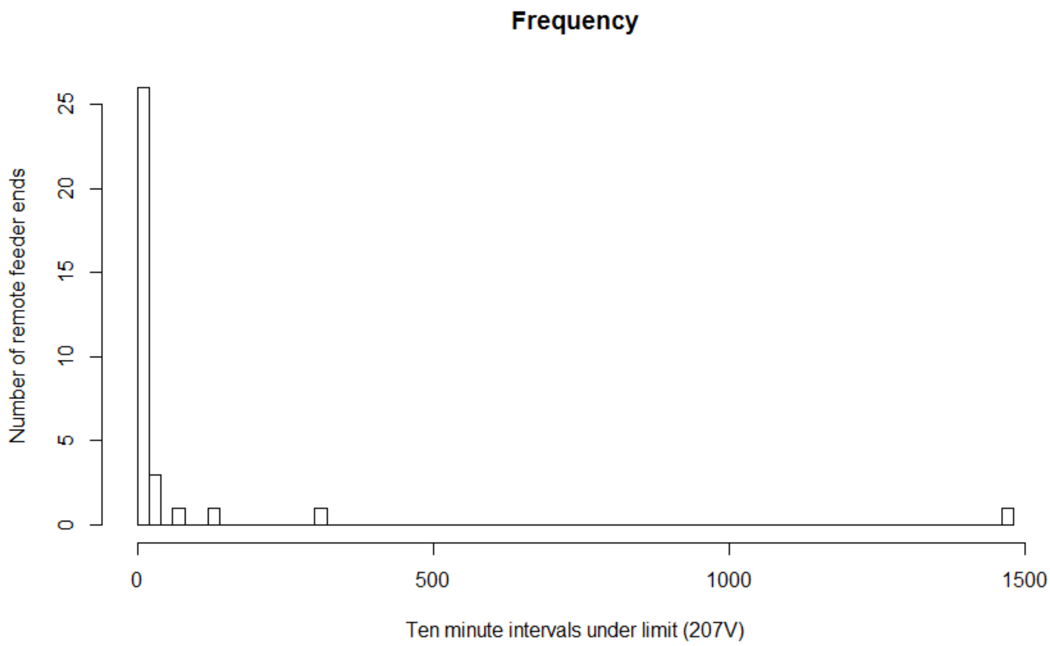


Figure 33: Distribution of measurements below the EU limit of 207V by remote feeder ends

6.4 Conclusions

The above analysis leads to the following observations

- The current system behaves extremely well with only 0.38% of some 96 million voltage measurements being outside the range 216.2-253V over the eleven month period considered here (April 2012-February 2013)
- The data shows that in the few cases where the LV networks do have out of limit voltages the majority of incidents are over limit voltage problems rather than under limit problems; 0.35% of remote feeder ends were

observed to be over-limit compared to 0.0187% 230V -6 to -10% and 0.0022%below -10%;

- There are very few measurement locations (feeder ends) that have a persistent over/under limit problems,
- Most of the Measurement locations have only limited time of over voltage problems, and only very small number of Measurement locations have prolonged over voltage problems
- Of the small number of cases of under voltage, 90% fall within the EU voltage limits.
- To put a scale of value to adoption of the EU voltage limits, a 1.5% fall in energy use through voltage reduction of 2.5% across only half of the 230,000 UK ground mounted distribution transformers, at an average of 150 domestic customers per transformer would save some 850,000 MWh p.a. (Using Ofgem factsheet 96, 2011, average UK domestic electricity customer of 3,300kWhr). Using the cost per unit valuation from the same factsheet, at 12.8p / unit), the value of that saving to domestic end customers is over £100M p.a If voltage reduction were more widespread and included pole mounted connected customers, through adjustment of primary substation target voltages, the savings would be higher.
- Statistical analysis has identified 10 cluster types, having differing capabilities to absorb low carbon generation or demand technologies. A detailed report on these clusters is to be published, in line with the Ofgem Project Direction, in July. Use of these clusters will aid network design planning and loss reduction. Findings from the Proxy PV FiT meter report have identified significant capacity headroom for LV PV installations.

8. References

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