SP ENERGY NETWORKS

Flexible Networks for a Low Carbon Future

Improved Characterisation of PV Capacity at LV

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Author:	Jorge Acosta, Sarah Weatherhead and Charlotte Higgins
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TNEI Services Ltd

Bainbridge House	Milburn House	Queens House	Chester House
86 – 90 London Road	Dean Street	19 St Vincent Place	76-86 Chertsey Road
Manchester	**Newcastle Upon Tyne**	**Glasgow**	**Woking**
M1 2PW	NE1 1LE	G1 2DT	Surrey
Tel: +44 (0) 161 233 4800	Tel: +44 (0) 191 211 1400	United Kingdom	GU21 5BJ
Fax: +44 (0) 161 233 4801	Fax: +44 (0) 191 211 1432	Tel : +44 (0) 141 428 3184	United Kingdom

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Executive Summary

To facilitate a future flexible network, it is critical to develop improved network planning and operations tools and processes that enable a more appropriate techno-economic response to load growth and distributed generation. These will be supported by more detailed and extensive monitoring of the network that provides insights into the underlying HV and LV network behaviour and trends. Network monitoring data has traditionally been deployed and analysed consistent with a fit and forget network. This will be inadequate as increasing amounts of low carbon technology including PV, electric vehicles, heat pumps and energy storage connect to the distribution network and with the growth of dynamic rating, network automation, active network management, demand side response and network/generation ancillary services.

As the uptake of embedded PV generation on LV networks increases, new techniques and tools are required to understand the implications of embedded PV on network power quality and security. The main constraint to embedded PV generation uptake is the increase in voltage towards the end of the feeder rather than reaching asset thermal limits. For example, the voltage can approach and exceed statutory limits when "PV clustering" is present in the LV network. A more optimised assessment of future PV generation capacity across the LV network and identification of suitable network solutions needs an improved understanding of the network behaviour of existing embedded PV clusters. This can be obtained through analysis and interpretation of the detailed LV network monitoring available from the Flexible Networks trial sites. Improved analysis tools and more general learning such as generic "rules-of-thumb" can then be developed. Ongoing analysis of LV networks with high PV uptake will be carried out during RIIO-ED1 to provide further verification of this approach facilitated by the SPEN RIIO-ED1 LCT Network Monitoring Strategy.

Improved approach to characterising the behaviour of embedded PV generation and residential load

As part of this study, we developed the following methodology to improve the characterisation of PV generation and identification of available capacity headroom, based on monitoring data collected;

- Use of detailed irradiance data measured over the summer period to provide an accurate representation of actual PV output. A maximum PV generation of 90% of rated capacity was derived based on our simple PV resource assessment model which correlates irradiance with PV generation output. This is based on a nominal rated power output at 1000 W/m^2. Regional peak solar irradiance differences between the SP Manweb licence area (North Wales) and the SP Distribution license area (Southern Scotland) were found to be limited.

A peak PV generation load factor of 90% is appropriate for both North Wales and Southern Scotland

Installation of a simple low-cost solar irradiance measurement device in network areas with high PV uptake will enable an accurate characterisation of solar irradiance distribution.

- A generic minimum demand profile was defined for domestic properties in the Ruabon LV network. This is based on the number of customers along an LV feeder and an average measured peak domestic summer demand (teatime peak around 6pm). Minimum daytime demand was found to typically occur during the morning with morning demand generally lower during the week compared to weekends, and was approximately 333W. Based on this analysis, minimum demand at peak PV generation will be defined as 300W in PV connection SPEN policy in future to consider variation in minimum daytime demand between LV networks. WPD's LV Network Templates classification tool could be used to enable wider applicability of our methodology to a range of LV network types.

Minimum demand for domestic customers during periods of peak PV generation will be defined as 300W in SPEN policy

- Remaining PV generation capacity headroom was estimated by scaling the existing embedded PV in the model until statutory voltage limits were exceeded at the ends of LV feeders.
- In future, the maximum PV generation capacity factor along with the generic minimum daytime demand could be input into a simple LV feeder model to improve calculation of voltage and thus remaining generation capacity headroom, at LV feeder end.

Experimental verification of the PV generation resource assessment model and generic minimum demand profile was achieved through comparison of measured load and voltage profiles with results from a power systems model of the Ruabon LV network developed in IPSA. This indicated strong to medium correlation with LV feeder load profiles in the main. Representation of embedded PV generation size and location within the network was based on connections data accessible through the SPEN GIS database. Validation was carried out for load and voltage profiles on a number of LV feeders with low and high PV uptake and on high and low irradiance days. Further model verification was carried out based on measurements of LV customer voltage along LV feeders.

The impact of diversity on PV generation e.g. varying roof pitch and direction, did not appear to have a significant influence on model validation when compared to consideration of measured peak irradiance on PV generation output per LV feeder. However, most of the PV installations were oriented East-West and house types were generally similar in the Ruabon LV network analysed so underlying diversity may be fairly minimal. The aim here was to create a simple model that represented the most influential variables.

Key metrics for characterisation of PV generation are peak solar irradiance and minimum average weekday daytime demand

PV generation installed on industrial and commercial properties was not assessed in this study as it was not prevalent in the network trial site assessed. However we recognise that in some LV networks, this may be the dominant source of embedded generation.

One of the wider challenges for characterising embedded PV generation is that often the DNO is not notified of all connected PV generation. This is expected to improve during RIIO-ED1 with the rollout of an online PV connection notification form and improved linkages with Ofgem FiT data for the purposes of verification.

Improved characterisation of PV phase imbalance

Phase imbalance due to the varying connection of PV generation across LV feeder phases can erode generation capacity headroom and lead to increased voltage rise compared to an LV feeder where PV generation is distributed relatively equally across phases.

Our analysis suggests that PV generation uptake approaches approximately 800W per customer on a typical residential LV feeder, before generation phase imbalance is likely to result in marginal overvoltage, if it is present to any significant extent. In related analysis as part of the Flexible Networks project, our findings suggest that the load on LV feeders with large numbers of residential customers is more likely to be balanced compared to LV feeders with rural or mixed industrial, commercial and residential loads due to increased customer numbers **providing more diversity.**

A generic individual LV feeder should generally have a PV hosting capacity of at least 800W per customer given potential phase imbalance

Network voltage reduction can provide significant additional generation capacity headroom for the LV network. A 2% reduction in voltage enables PV hosting capacity on a generic individual LV feeder basis to increase to approximately 1300W per customer. Given that After Diversity Maximum Demand for a residential customer is typically around 2kW, this should not result in a thermal loading issue if this level of uptake was replicated across all feeders in an LV network. However, it may lead to reverse power flow and thus voltage issues further up the network.

On a generic individual LV feeder, a 2% voltage reduction should generally increase PV hosting capacity to 1300W per customer

Northern Power Grid (NPG) LCNF Tier 2 project "Customer Led Network Revolution" found in a case study that included consideration of phase imbalance, network voltage issues were experienced once customer solar PV penetration levels exceeded 30% or 1100W per customer[1]. Minimum daytime demand at peak PV generation was higher than in this analysis and the levels of phase imbalance modelled appear to be lower than in the example test case presented in this report.

Greater consideration of phase imbalance will be required for rural networks with PV generation uptake although sometimes customers are connected on single phase feeders. Rural LV networks were not analysed in detail here.

Improved characterisation of PV generation capacity headroom at Ruabon

Application of this approach enabled us to identify further generation capacity headroom at the Flexible Networks trial site of Ruabon which had no available headroom based on application of the existing SPEN PV connection policy.

Approved PV generation connections were modelled for Ruabon and further PV connections were modelled consistent with currently unapproved PV connections. Approved PV generation equates to a total customer uptake of 21% across the secondary substations analysed for an average rated capacity of 1.6kW or 336W per customer on average. Taking phase imbalance and other considerations such as voltage control deadband into account both generally and specifically for the LV feeders analysed, it should be possible to connect an additional 38% of PV by kW in Ruabon without exceeding statutory voltage limits or 464W per customer on average. This gives a total of 439kW of PV generation at rated capacity and equates to the currently unapproved PV generation volumes, with a maximum LV feeder PV hosting capacity of 900W per customer.

An additional 38% of PV generation can be connected at Ruabon based on improved PV characterisation

Network voltage reduction can provide significant additional generation capacity headroom for the LV network. A 2% reduction in voltage enables a further 124% of (approved) PV generation by kW to be connected or 885W per customer.

A voltage reduction of 2% will allow an additional 124% of PV generation to be connected at Ruabon

[1] Northern Power Grid, Customer-Led Network Revolution - Optimal solutions for smarter distribution businesses, January 2015.

http://www.networkrevolution.co.uk/wp-content/uploads/2015/03/OSR-Final.pdf

Improved characterisation of generic network PV generation capacity headroom

Learning from monitoring, modelling and verification of the Ruabon LV network enables the development of more generic "rules-of-thumb" to inform future PV connections policy. Based on a minimum demand of 300W per customer, assuming that demand and PV clustering characteristics at the six secondary substations analysed at Ruabon are broadly representative of other GB LV networks, the following PV hosting capacities are obtained for a generic LV network;

- Improved PV characterisation should enable the connection of approximately 430W per customer,
- Furthermore, a 2% network voltage reduction should increase PV hosting capacity to 850W per customer.

Improved characterisation of distribution of PV generation output and corresponding LV network behaviour

This study explored the distribution of solar irradiance and LV busbar and feeder voltage measurements to better understand the probabilistic behaviour and dependencies of peak events.

On an annual basis, 5 minute average solar irradiance is above 1000 W/m^2 for 0.1% of the time, thus the probability of achieving sustained rated power output for PV generation in Ruabon is very small. During summer, 5 minute average solar irradiance is above 900 W/m^2 for about 2% of the time for generally short durations of less than 20 minutes. Our methodology for modelling of PV generation at Ruabon is based on a peak solar irradiance of 900 W/m^2 which takes a practical engineering approach to characterising peak solar PV output for the purposes of network planning.

The characteristics of the LV busbar voltage profile for substations with a high and low PV uptake on a representative high solar irradiance day suggest that variations in loading of the LV network due to embedded PV generation i.e. reverse power flow, or demand do not influence LV busbar voltage significantly. The LV busbar voltage profile is however highly correlated with the upstream primary transformer HV busbar voltage profile. Careful consideration of the impact on downstream voltage should be made for the connection of HV generation on a feeder connected to an LV network with high levels of embedded PV generation.

On an annual basis, LV voltages on secondary substation LV busbars were within statutory limits 99.6% of the time. Voltage excursions generally appear to be associated with the primary transformer tapchanger operations. Variations in loading of the LV network due to embedded PV generation or demand **do not** influence LV busbar voltage characteristics visibly.

In terms of wider LV network voltage management partly to enable further PV uptake and more generally to reduce existing voltages, there is a case for voltage reduction. This should be unlikely to lead to undervoltages during observed peak demand winter conditions. There is generally about 6% voltage legroom during typical high demand conditions based on LV customer voltage measurements towards the ends of LV feeders. The bandwidth of the primary voltage relay should also be considered when reviewing voltage distribution characteristics and potential benefits of voltage management techniques.

There is sufficient voltage legroom in the Ruabon LV network to apply a seasonal or permanent voltage reduction

Better consideration of LV feeder voltage profile

In order to provide further validation of the modelling approach, modelled voltage drop/rise was compared to voltage drop/rise derived from concurrent LV customer and secondary substation LV busbar voltage measurements. This was to ensure that voltage rise due to PV uptake was being captured.

The verification results suggest that when modelling voltage rise it may be prudent to leave some margin of voltage near LV feeder ends to account for stochastic customer load variations, generation phase imbalance and model simplification of demand/generation sources.

In future, smart meters should enable voltage measurements to be extracted at key network locations to support more active evaluation and response to the effects of high embedded PV generation uptake.

Summary of new generic "Rules-of-thumb"

- **Peak PV generation load factor of 90% is appropriate for both North Wales and Southern Scotland.**
- **Minimum demand for domestic customers during periods of peak PV generation can be defined as 300W.**

PV Hosting Capacity "Rules of Thumb"	Generic LV Feeder (W/customer)	Generic LV Network (W/customer)	Ruabon LV Network (W/customer)	% Capacity Gain for Ruabon
Base Case	580		336	-
Improved PV Characterisation	800	430	464	38%
Improved PV Characterisation + 2% Voltage Reduction	1300	850	885	~260%

Customer Benefits

The application of this new approach can provide significant benefits to network customers:

- Facilitation of the connection of greater amounts of PV generation
- Facilitation of faster customer generation connections based on assessment of specific LV network characteristics e.g. geographic location (solar irradiance), PV generation size, customer type – minimum demand profile, and application of network voltage reduction.

Glossary

DNO	Distribution Network Operator
GIS	Geographic Information System
HALB	Hampden Arms Link Box feeder
HV	High Voltage
LV	Low Voltage
LCNF	Low Carbon Network Fund
LCT	Low Carbon Technology
MD	Maple Drive Feeder
PV	Photovoltaics
SPD	SP Distribution
SPEN	SP Energy Networks
SPM	SP Manweb
WPD	Western Power Distribution

1 Learning Outcomes

A new methodology was developed for improved characterisation of embedded PV generation on the LV distribution network based on extensive LV network monitoring data from the Flexible Networks project. This has achieved the following learning outcomes;

- Identification of additional generation capacity headroom at Ruabon for further PV connections based on an improved understanding of the behaviour of PV generation and customer demand during peak generation periods, and impact on the LV network.
- Improved and validated simplified assessment approach for determining available PV generation headroom across the LV network to facilitate greater numbers of embedded PV connections.
- Improved understanding of the benefits of network voltage reduction that can be deployed to manage the impact of increasing embedded generation to within statutory voltage limits.
- Development and application from the outset of successful internal stakeholder engagement strategies to achieve user buy-in and fast-tracking of the improved processes into business-as-usual.

1.1 Existing Approach

There has been some uncertainty in relation to the impact of increasing PV generation connection on LV networks. The limited measured network data available at this voltage level has inhibited a full understanding and assessment of existing and future network behaviour with high PV uptake.

Currently, a simple spreadsheet tool is used by SPEN network planners to understand the impact of PV on the LV and HV network. This is used to identify any potential voltage rise issues beyond the statutory limits and thermal overloading. Minimum summer midday demand is modelled as 200W.

This analysis tool was validated with more detailed feeder models in DigSilent and IPSA, further details are included in Appendix A. There was also limited validation with measured data from an LV network in Wales with PV uptake.

Main limitations of the tool were identified as follows;

- The PV generation is assumed to be operating at rated output, without consideration of actual irradiance conditions and PV diversity (e.g. panel direction, orientation etc.)
- The network planner is able to assign loads and PV generation to specific phases. However this data is not typically available so assumed values are used. Thus, the designation of loads and generation to phases can be arbitrary and there is potential to be overly conservative.

1.2 Improved modelling of PV generation

The availability of detailed HV and LV network monitoring data as part of the Flexible Networks project enables PV generation characteristics to be more fully explored. A new approach has been developed that addresses the limitations of the existing approach outlined above, allowing incorporation of more detailed network monitoring data. This enables an improved characterisation of embedded PV generation impact and generation capacity headroom identification. The graphic below illustrates the various inputs that have been used to achieve this.

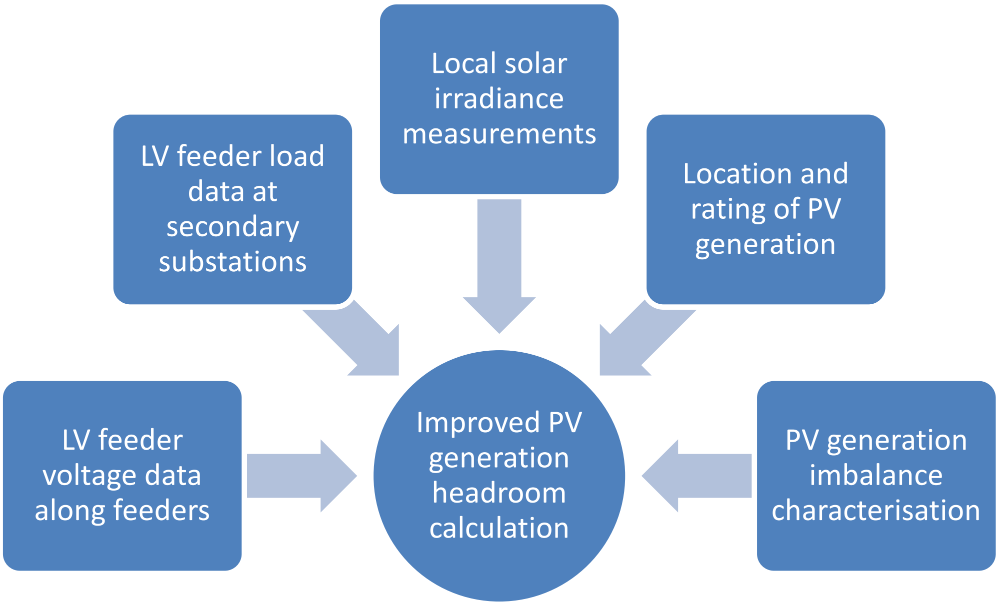


Figure 1-1 Data Inputs to Improved Characterisation of PV generation capacity headroom

This also enables identification of key measured data required as well as development of improved simplified modelling techniques based on generic "rules-of-thumb" to better assess generation capacity headroom on LV networks, where either limited or detailed network monitoring data is available.

Improved PV generation characterisation enables a more efficient approach to generation connections and network planning

1.3 Benefits

1.3.1 Network Planning

- More accurate and rapid assessment of capacity for new generation connections

- Improved characterisation and modelling of the LV network and understanding of uncertainties
- Enhanced network reinforcement prioritisation and proposal design

2 Experimental Design

An analysis approach was developed to characterise the behaviour of embedded PV generation in the LV distribution network and the available generation capacity headroom. This is based on monitoring data collected from secondary substations and along LV feeders within the Ruabon network in 2013 and 2014.

In order to develop a robust and experimentally verifiable methodology, the following activities were carried out;

- Power systems network model build using available circuit parameters and asset rating data, with assumptions based on similar and/or adjacent equipment where specific data is not available.
- Development and testing of demand profile assumptions for a generic residential minimum demand profile on a per customer basis.
- Development and testing of a PV generation resource assessment model based on measured solar irradiance data.
- Comparison of modelled and measured network loading and voltage on key LV feeders (with both high and low PV penetration) over the summer of 2014, for a range of PV generation output.
- Comparison of modelled and measured voltage drop/rise along key LV feeders (with a range of PV penetration uptake).
- Assessment of interactions with the HV network e.g. correlation of secondary substation LV voltage with primary substation HV busbar voltage.
- Comparative assessment of the impact of LV imbalance for PV generation connections.

The secondary substations and LV feeders studied were selected to include a range of PV generation uptake levels and residential load types e.g. terraced housing, semi-detached. The limited number of commercial and industrial properties connected to the Ruabon LV network area studied did not have PV generation and were not considered specifically in the assessment.

This approach should ensure that the learning outcomes are robust and reproducible for other similar LV network types. As levels of LV monitoring increase throughout the RIIO-ED1 period, additional data will be available to verify and refine our simplified PV generation characterisation approach.

3 Modelling of PV Generation

3.1 Introduction

In order to understand the impact of PV on the LV feeder voltage profile and power flows, an LV network model was developed and verified with extensive monitoring data from LV feeders connected to Ruabon HV/LV secondary substations.

The measured data is from the 18th of July 2013 to the 28th of July 2014. The months of June and July 2014 were selected as the highest solar irradiance is generally experienced during these two months. Current data is available at a resolution of 10 minutes and is recorded as a one second "snapshot", rather than a ten minute average. Voltage data is available at a resolution of 1 minute and is also recorded as a one second snapshot.

3.2 LV Network Modelling

A power systems model of part of the Ruabon LV network was constructed in IPSA. This is a radially operated LV network with some capacity to be run interconnected. Seven secondary substations, Peris, Plas Madoc, Dinas, Idwal, Hampden Way, Bodlyn and Leisure centre, were modelled with their respective LV feeders. Conductor length, type and material data was extracted from the SPEN GIS database with very little missing data. In the limited cases where data was not available, cable type was assumed based on the surrounding cables. The number of LV customers and PV installations along with rated generation capacity were defined in the LV network model, as recorded in the SPEN GIS database.

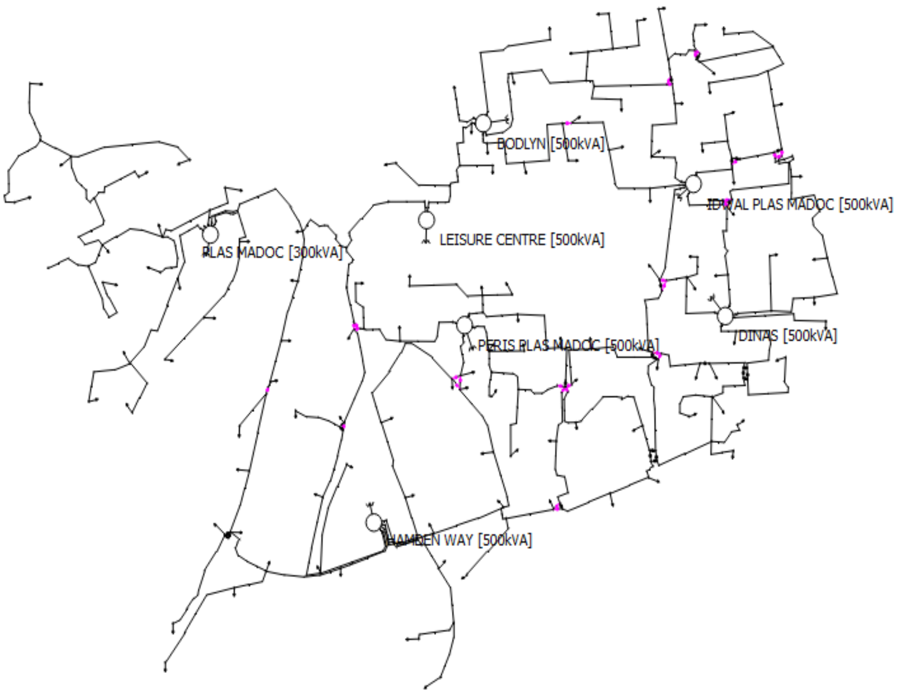


Figure 3-1 IPSA Model of the Ruabon LV Network Analysed (link boxes shown in pink)

The IPSA model is shown in Figure 3-1 with the seven secondary substations denoted. A three phase LV network was modelled; individual phases were not represented.

3.2.1 LV Load Modelling

Domestic demand and PV generation were aggregated along LV feeders in the network model in order to simplify the analysis. Typically between 2 to 4 lumped loads were modelled depending on the length of the cable. This enables an efficient network modelling approach without compromising accuracy. The generation was added to the demand by assuming it to be a negative load offsetting the demand. A power factor of 0.98 was applied to demand and a power factor of 1 was applied to the PV generation.

The total rated PV generation in each aggregated load was calculated based on the number of installations reported by the council (or private resident). This was added to the appropriate LV feeder with an average rated maximum generation of 1.6 kW per installation and power output defined by the measured solar irradiance throughout the day. A value of 1.6kW was found to provide a good representation of the limited range of PV generation rated capacity within the Ruabon LV network, as shown in Figure 3-2.

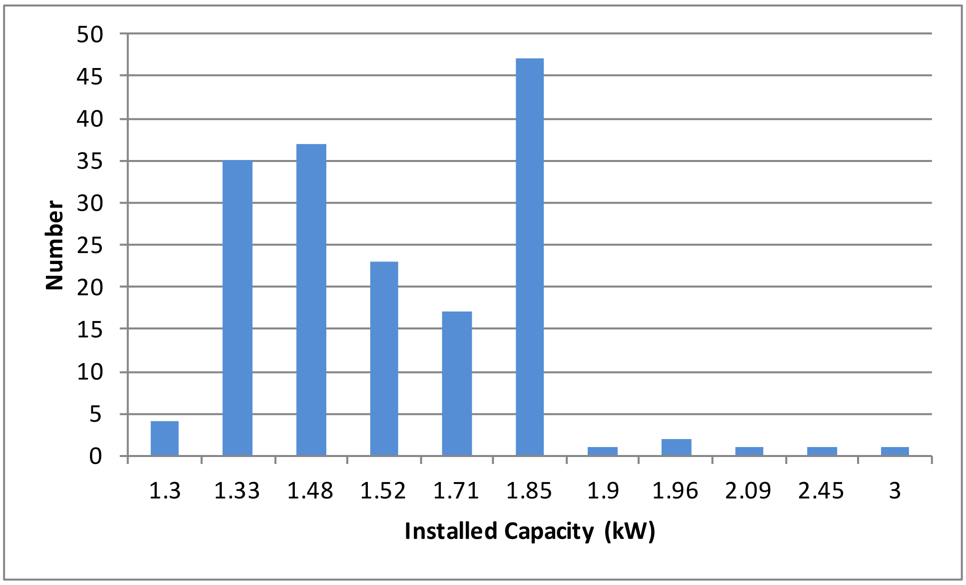


Figure 3-2 Distribution of Embedded PV Generation Installed Capacity at the Ruabon Secondary Substations analysed

LV feeders with commercial and industrial customers were not modelled. PV generation in Ruabon is generally due to domestic customer connections.

3.2.2 Modelling Challenges

There is known to be poor visibility of the PV connected to the LV network across the UK. Although installers have an obligation to notify the DNO of small-scale G83 (less than 3.68kW) PV installations, this is often not done. SPEN has compared the PV recorded on its GIS system with the government installations register (used for the Feed-in-Tariff program) and found that only 48% of the installed PV has been registered with SPEN. Recommendations are provided in the SPEN RIIO-ED1 business plan to address this.

In Ruabon, the proportion of reported PV is likely to be much higher than 48% as the majority stems from a single council-run project in close communication with SPEN. We have assumed that the registered PV is 100% of the installed PV in the Ruabon network. This was tested and verified through comparison of modelling results and monitoring data as part of this study.

The configuration of the link boxes around the interconnected Ruabon LV network was available; however, the validation of the model was done without the aid of the link box connection diagrams. These diagrams for the network may change over time depending on the needs of the network and the approach was to validate the model according to measured power and voltage, mainly due to the operation of link boxes is manual and changes are typically not recorded. Comparison of modelling results with measured load data was used to adjust the configuration of the link boxes in the network model to obtain a better match. This process was trial and error and no patterns relating to optimisation of LV feeder length or number of customers was identified. The validation was then compared to the default diagrams of the configuration of the network. The test network has 19 link boxes; the model has the same configuration for 16 of them. Even though the model does not agree with 3 link boxes, the load is balanced and will not change the model outputs.

Initially the network model was run using the nominal SPEN tap setting of secondary substation transformers however, this may not be the case for all transformers and it is possible that a tap setting was changed but not noted in maintenance records. It is usually not possible to confirm this without a site visit. This is explored further in assessment of the results.

3.3 Network monitoring

Measured phase voltage and current for all LV feeders connected to the secondary substations in the Ruabon LV network is available. The files have a 10 minute resolution from the 18th of July 2013 to the 28th of July 2014. The months of June and July 2014 were selected as the highest solar irradiance is generally experienced during these two months. The apparent power was calculated using the three single phase currents for every feeder and voltage (voltage across phases was found not to vary significantly) to calculate the three phase measured power output to be compared with the IPSA network model results.

Maximum, minimum, average and standard deviation solar irradiance was measured with a resolution of 5 minutes at the Ruabon primary substation.

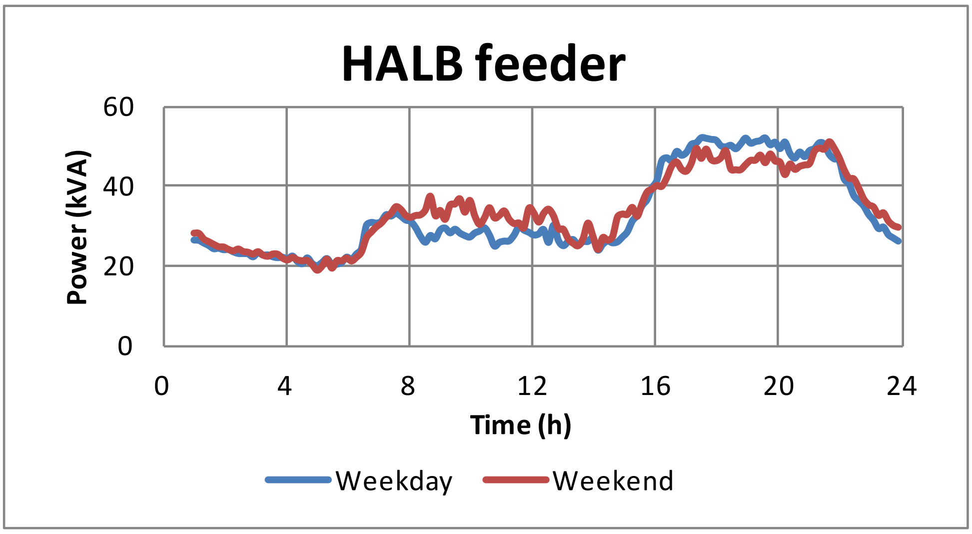
3.4 Characterisation of Minimum Demand Profile

In order to define domestic customer demand in a representative and consistent manner in the network model, a 'generic' average minimum daily demand profile was derived from analysis of the measured current and voltage data for selected LV feeders in the network area under consideration. This was over the summer period of June and July, where irradiance and thus PV generation is at peak.

This was carried out as follows;

- Calculate average minimum daily demand profile for several LV feeders with high and low PV uptake. Feeders with low PV uptake were of particular importance to disaggregate the effect of PV generation on the demand profile.
- Calculate average minimum daily demand profile for LV feeders on a high irradiance and low irradiance day.
- Consider weekday and weekend separately to capture variations in customer behaviour. The profile with lowest demand during peak PV generation was weekdays so this was selected as representative of the "worst-case".
- Normalise the minimum demand profile in per unit based on the number of customers and average daily maximum summer demand per customer to enable application to other LV feeders.

The selected LV feeders considered are tagged as Maple Drive (MD) and Hamden Arm Link box (HALB) connected to Plas Madoc secondary substation. The Maple Drive feeder contains 3.7 kWp of installed PV and 26 customers (142 W/customer). Hampden Arms link box feeder contains 20.6 kWp of installed PV, however there are 94 customers so the PV generation per customer is still fairly low (<220 W/customer). LV feeders with low PV uptake were selected to minimise the effect of PV generation on the average daily load profile. For comparison, LV feeders with high PV uptake had up to 820 Wp/customer.



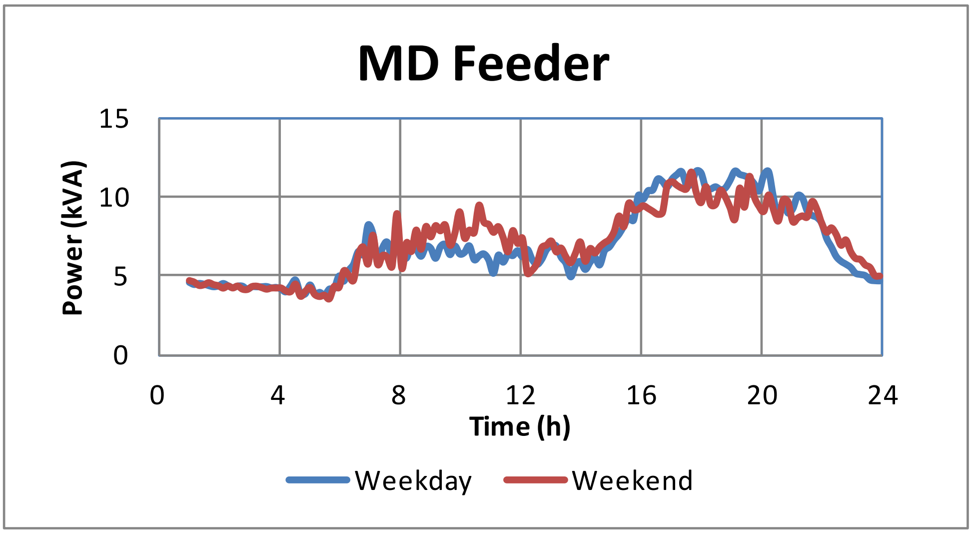


Figure 3-3 Selected LV Feeder Average Daily Summer Load Profile

The measured average minimum demand profiles for weekdays and weekends over the summer period (June/July) are shown in Figure 3-3. These minimum demand profiles are expected to be representative of other LV network feeders with similar characteristics e.g. residential customers. Customer behaviour over weekdays and weekends can be seen to vary. For weekdays, demand is lower during the day and the evening peak is slightly higher compared to the weekend (small amount of load shift). This indicates that PV generation will have the most impact on feeder voltage and loading during a weekday when demand is generally lower during the day.

The minimum demand profile was normalised in per unit based on the number of LV domestic customers to enable application to other LV feeders. The average daily peak demand for the summer was calculated to be approximately 555 W per customer. The generic minimum demand profile used in the IPSA model is shown in Figure 3-4.

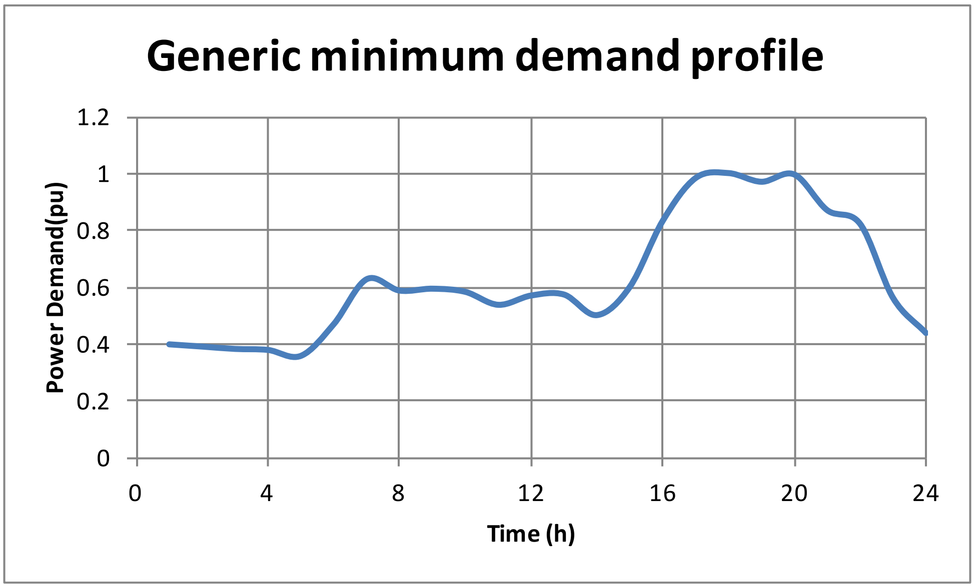


Figure 3-4 Generic Minimum Demand Profile

This profile is assumed to be representative of LV feeders with residential properties across the Ruabon network. It does not consider socio-economic differences between customers that could cause some differences in demand requirements and it also does not consider the interrelated effect on demand of different housing stock. However, the validation process will demonstrate that the model is fairly robust and can be used confidently to assess the voltage profile and impact of the PV across the Ruabon network and other similar LV networks.

This element of the work shares some similarities with work carried out for the LCNF Tier 2 Western Power Distribution project LV Network Templates. A network classification tool developed as part of LV Network Templates can produce seasonal generic load profiles for an LV network depending on its characteristics and thus, classification. The LV Network Templates tool could be applied here to enable wider applicability of our methodology to a range of LV network "types" including those with some commercial and industrial load that were not studied here.

Minimum demand for domestic customers during periods of peak PV generation will be defined as 300W in SPEN policy to consider potential variation in minimum daytime demand across LV networks.

3.5 Characterisation of PV Generation

Table 3—1 shows the PV installed capacity and the number of customers connected at the secondary substations analysed: Peris, Plas Madoc, Dinas, Idwal, Hampden Way and Bodlyn where kWp is peak power output. Individual feeders in the LV network have up to 51% existing PV uptake (816kW per customer) by customer. This will increase to a maximum of 56% PV uptake (900W per customer) on an individual LV feeder basis with currently unapproved PV generation.

Table 3—1 Demand/Generation Characteristics Per Substation

Secondary Substation	No. Of Customers	Installed PV	kW of PV/customer	Unapproved PV
Plas Madoc	172	42 kWp	0.244	3.2 kWp
Idwal	127	36.24 kWp	0.285	6.4 kWp
Dinas	254	51.3 kWp	0.2	72 kWp
Peris	79	54.46 kWp	0.689	9.6 kWp
Hampden Way	213	76.8 kWp	0.36	25.6 kWp
Bodlyn	99	59.2 kWp	0.6	3.2 kWp

Figure 3-5 gives an indication of the differences in the average daily summer load profile for secondary substations with high PV uptake per customer compared to secondary substations with low PV uptake per customer based on aggregation and analysis of the LV feeder monitoring data. The profiles for secondary substations with a relatively high PV uptake (i.e. Peris and Bodlyn) generally have a similar shape compared to secondary substations with a low PV uptake such as Dinas and Plas Madoc. The average early morning demand for Bodlyn is somewhat higher than other substations; this may be attributable to different customer behaviour although the houses are terraced similar to most of the other LV networks, or a commercial or industrial load. Apart from this, the average load profiles outside of the hours of high PV generation compare well.

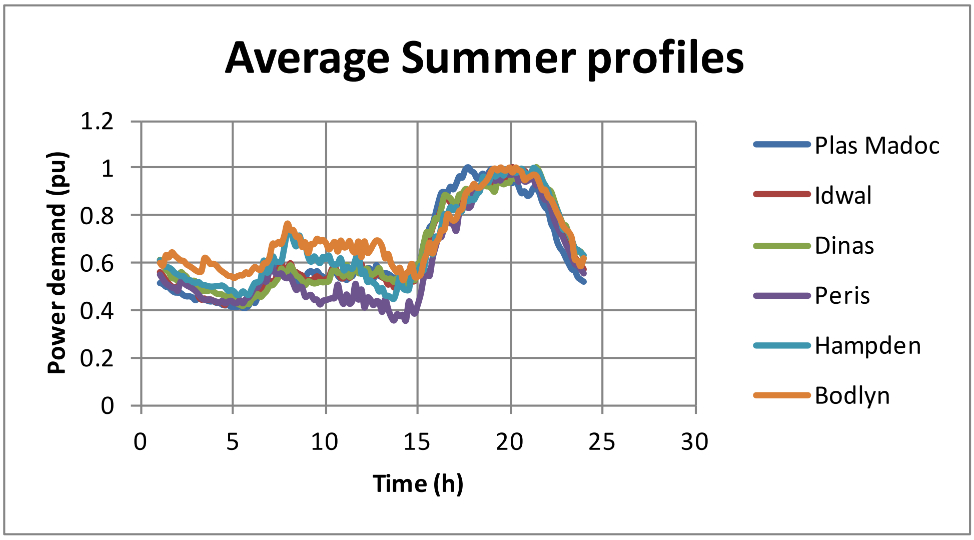


Figure 3-5 Average Daily Summer Load Profiles for Secondary Substations (normalised by number of customers and maximum average daily load)

3.5.1 Generation Resource Assessment

The maximum instantaneous solar irradiance that occurs across the UK is 1000W/m^2, at sea level with the sun at its apex. However, the frequency of this and thus average solar irradiance, varies greatly depending on regional climate e.g. typical cloud cover. Refracted light can increase solar irradiance to over 1000W/m^2, this can be due to cloud reflection or reflections from nearby objects.

PV generation power output can be correlated to the solar irradiance measurement of the weather station within the vicinity. Typically the rated power output of a PV installation is reached at 1000 W/m^2 irradiance[2].

Using the solar irradiance data measured for June and July 2014 and PV installation location and rated capacity, the generation load profile for PV at Ruabon can be constructed with a reasonable level of certainty. PV generation output is added to the customer demand as a negative load at the customer point of connection (i.e. offsetting the demand) and included as part of the aggregated LV loads in the network model. The average 5 minute solar irradiance was used for modelling. The maximum 5 minute value lasts for only a short period of time and would produce an overly conservative representation of PV generation hosting capacity.

Two high irradiance days and one low irradiance day were selected for model validation and analysis. The high solar irradiance days selected are the 23rd of June and the 10th of July with a peak irradiance of approximately 900 W/m^2, the day with low solar irradiance is the 4th of July with a peak irradiance of about 250 W/m^2. The solar irradiance profiles for these days are plotted below in Figure 3-6 with the average irradiance shown for the summer months (June/July 2014) with a peak of 450 W/m^2.

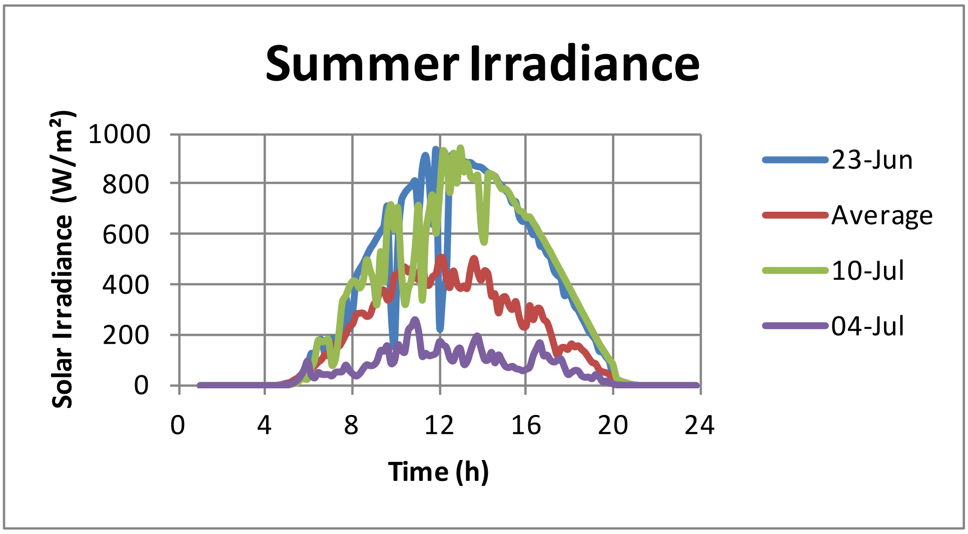


Figure 3-6 Ruabon Solar Irradiance for High and Low Irradiance Days

Use of these profiles enabled the network model to be validated over the range of PV generation output.

[2] British Standard (EN/IEC) 60904-3:2008 “Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data”

3.5.1.1 Regional variance of peak solar irradiance

The solar irradiance measured in Ruabon has been compared to solar irradiance measured in St Andrews, Scotland to explore regional differences. A peak solar irradiance of 768W/m^2 was measured at St Andrews between September 2013 and end of March 2014. This compares to a peak solar irradiance of 745 W/m^2 measured at Ruabon during the same period. Whilst the available data period does not cover high summer solar irradiance conditions, a qualitative assessment of solar irradiance peak values over the measurement period indicates that generally, these are similar at the two locations.

3.6 PV Imbalance

There are two related load imbalance issues to be considered;

- demand phase imbalance due to domestic properties connected unequally across the three phases along an LV feeder.
- generation phase imbalance due to embedded PV generation units connected unequally across the three phases along an LV feeder.

It is assumed that PV generation for a domestic property will be connected to the same phase as the domestic customer. Thus, existing demand phase imbalance is likely to be reflected to an extent through generation phase imbalance. Whilst significant amounts of demand phase imbalance were found on the SPEN LV network (7640-07 Flexible Networks HV and LV Phase Imbalance), our findings suggest that suburban residential networks are less likely to be imbalanced due to the higher number of customers providing some increased diversity.

Figure 3-7 provides an example power profile for a typical LV feeder in the Ruabon LV network with high PV uptake and reverse power flow, indicating some generation phase imbalance on a high solar irradiance day.

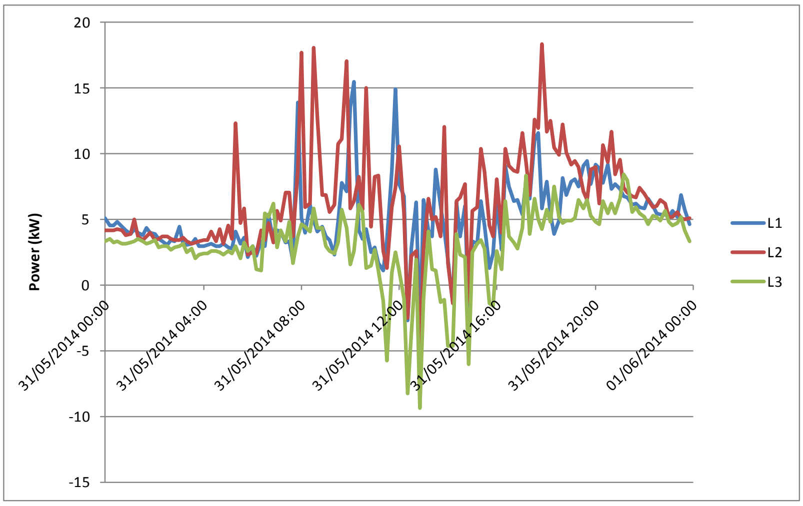


Figure 3-7 Power Profile of Typical LV Feeder at Secondary Substation showing Generation Phase Imbalance on High Solar Irradiance Day

To analyse the potential impact of PV generation imbalance on LV feeder voltage profile, a representative LV feeder was analysed using the simple SPEN PV analysis spreadsheet described in Appendix A. The following input data was used;

- The LV feeder has 50 customers on a 500m cable with 25 PV installations. This equates to a PV uptake by customer of 50% and for a PV generation capacity of 1.6kW, 800W per customer, consistent with PV generation uptake levels expected towards the end of the RIIO-ED2 regulatory period in the SPM licence area[3].
- Secondary substation LV busbar voltage is set to a nominal 250V.
- Maximum PV output was defined as equivalent to a generation load factor of 90% with an installed customer capacity of 1.6kW, consistent with the resource assessment for Ruabon.
- Minimum daytime demand was set to 300W from the generic minimum demand profile.

Figure 3-8 shows the voltage profile along the feeder assuming PV generation is connected equally across the three phases and resultant voltage is well within statutory limits.

Work carried out as part of the Flexible Networks project found that based on secondary substation LV feeder measurements, for LV feeders that were identified as persistently unbalanced (about 15% of the total 233 LV feeders analysed and 11% of LV feeders in the Ruabon LV network), the average phase imbalance under high loading conditions in terms of phase current divided by average current was a factor of approximately 2.

Figure 3-9 provides voltage profile results for the case where customer connections are unbalanced to result in a phase imbalance factor of 2 (26 customers are connected to phase A, 12 to phase B and 12 to phase C). PV installations are also distributed consistent with this level of phase imbalance (13, 6, 6). This suggests that phase imbalance (if present) may result in an overvoltage at the end of the LV feeder at this level of PV uptake, affecting approximately 20% of customers. This is for a total PV hosting capacity of 800W per customer. Reducing this to a PV hosting capacity of about 770W per customer removes the overvoltage condition from the LV feeder phase so it is marginal.

A network voltage reduction of 2% will provide significantly more generation headroom as shown in Figure 3-10, allowing the connection of 1300W per customer.

[3] TNEI Services Limited for SP Energy Networks, RIIO-ED1 HV and LV Network Investment Analysis – Phase 2, March 2013.

http://www.spenergynetworks.co.uk/userfiles/file/201303_TNEI_HVLVNetworkInvestmentAnalysis.pdf

If higher numbers of PV installations are connected to more lightly loaded phases with less customer connections, this may also result in a slight overvoltage at the end of the LV feeder. The likelihood of this occurring will depend entirely on the feeder configuration e.g. customers on the south facing side of the street mainly connected to one phase.

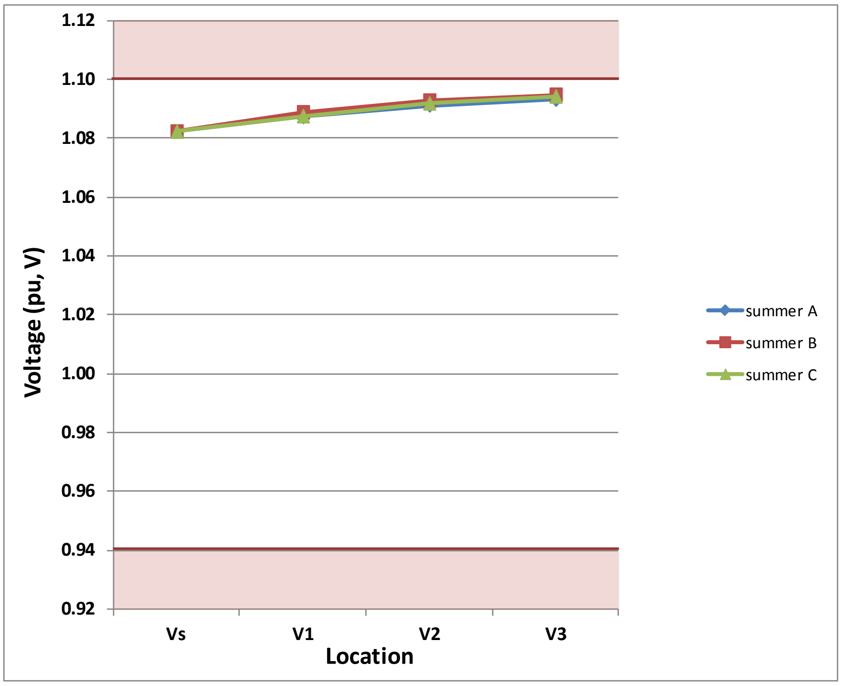


Figure 3-8 Voltage Along LV feeder, Balanced Demand/Generation Case

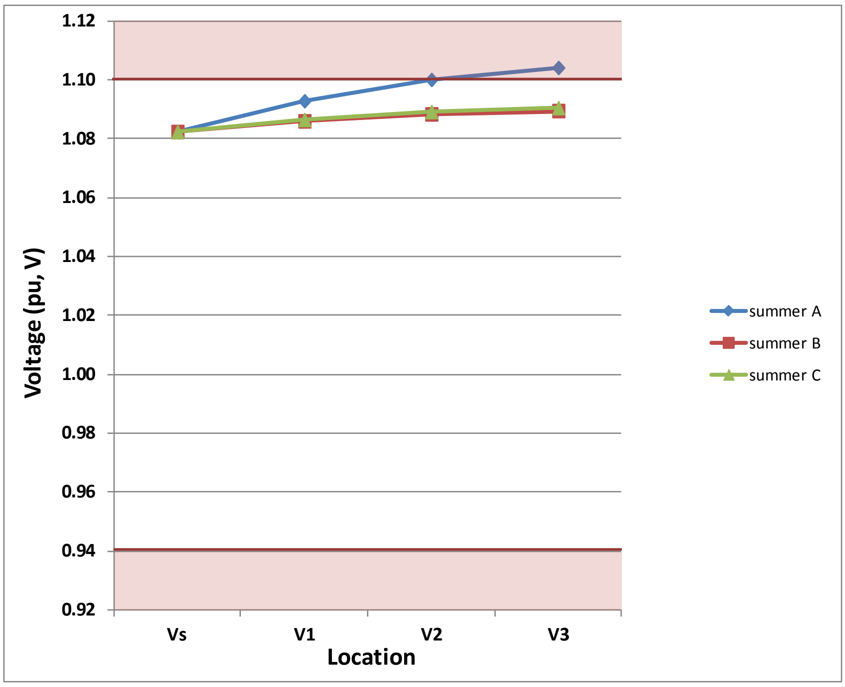


Figure 3-9 Voltage Along LV Feeder, Unbalanced Demand/Generation Case

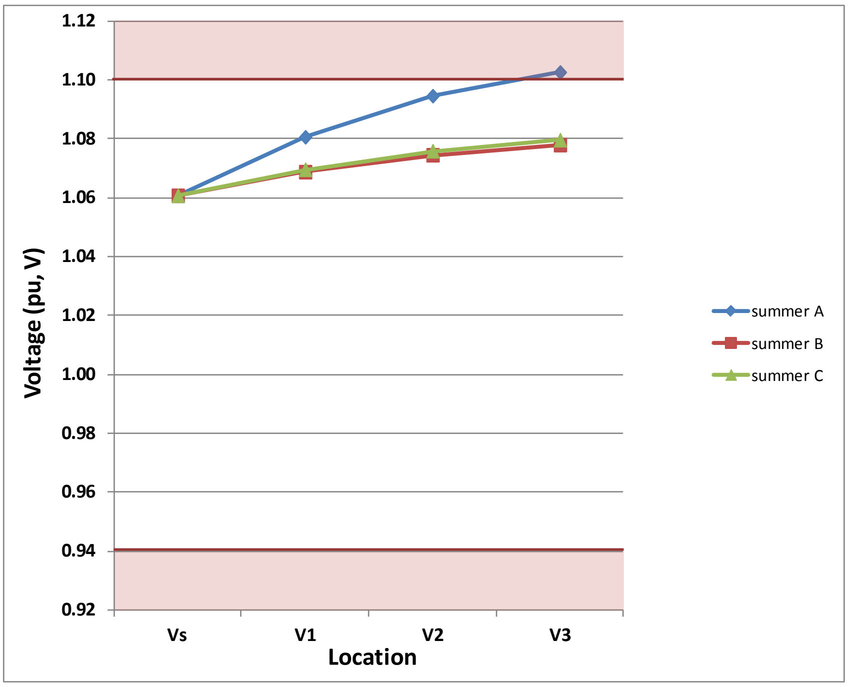


Figure 3-10 Voltage Along LV Feeder, Unbalanced Demand/Generation Case with 2% Voltage Reduction)

A probabilistic Monte Carlo simulation for LV feeders with varying length, impedance, demand, PV generation capacity and phase imbalance was carried out for the LCNF Tier 2 Electricity Northwest project Smart Street on radial LV networks[4]. Findings suggest that at 50% uptake of PV by customer, consideration of phase unbalance leads to voltage issues being experienced by up to 10% of customers. Our generalised analysis results are fairly consistent with this.

For the LV feeders in the Ruabon network with the highest PV generation uptake, generation phase imbalance was generally low in comparison to a phase imbalance factor of 2.

3.7 Validation of LV feeder loading

In order to validate the network model and modelling approach developed, LV feeder loading and voltage in the IPSA model (defined by the "generic" minimum daily demand profile and the PV resource assessment model) was compared with measured data. The network model was set up to perform a load flow every hour over a 24 hr period. Load results were then compared to three phase apparent power calculated from the monitoring data for two high irradiance days and one

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[4] Electricity North West Limited, Smart Street - An Introduction and Overview of Technology, February 2015.

http://www.enwl.co.uk/docs/default-source/sustainability/an-introduction-and-overview.pptx?sfvrsn=0 low irradiance day. The network model is based on input data with 10 minute resolution consistent with the measured data so the comparison was appropriate.

Figure 3-11 gives two examples where the modelling approach was shown to validate well against the measured LV feeder load profiles. For the two high solar irradiance days assessed, there is a strong correlation between modelled and measured data for 8 to 11 feeders and a medium correlation for 13 feeders, leaving 4 to 7 feeders with weak correlation, giving confidence in the developed methodology.

Further details of the validation of modelled and measured load and voltage profiles for a full set of LV feeders are given in Appendix B and C.

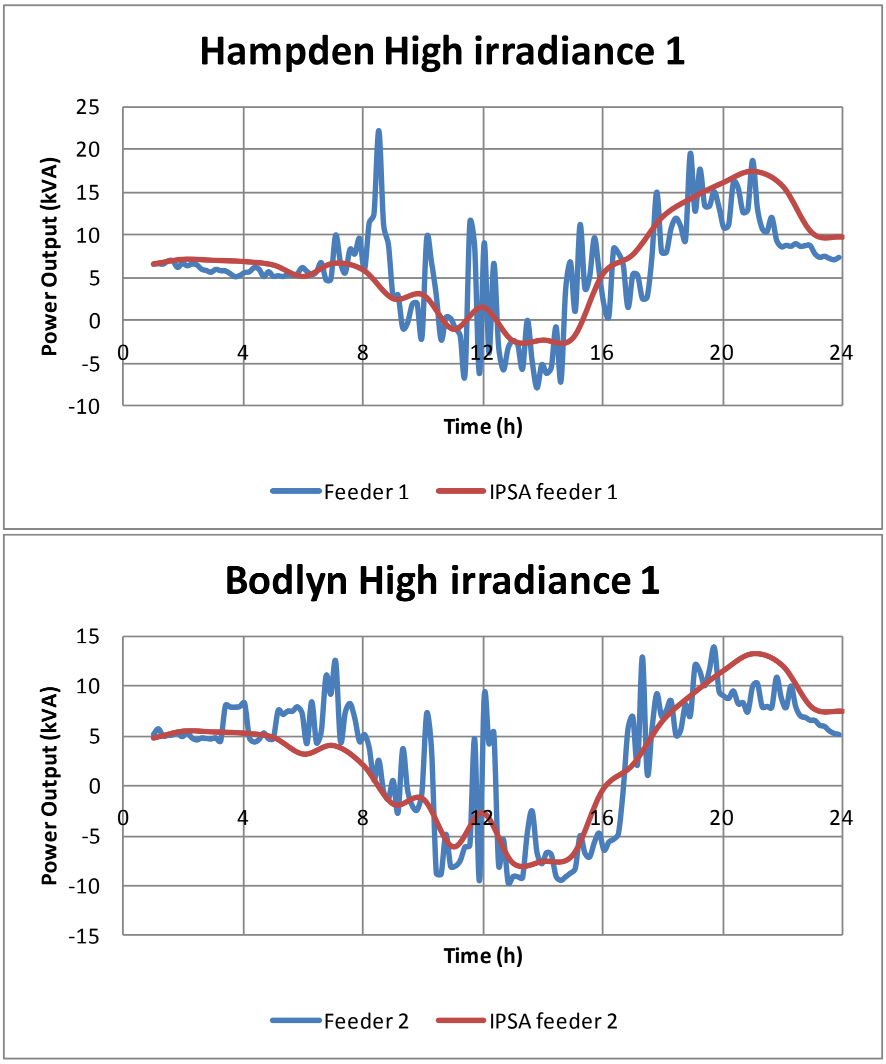


Figure 3-11 Validation of LV Feeder Modelled and Measured Loads

Figure 3-12 gives an example of an LV feeder where the load profile could not be reproduced by the model. The shape of the load profile suggests that this is a feeder with high commercial demand during daytime hours. As there is no PV generation present and commercial demand was not modelled, this LV feeder was discounted from the validation process. A total of 4 out of 28 LV feeders were identified as having some commercial demand, consistent with a review of GIS data. Thus, it should be noted that this approach is not so suitable for LV networks with high commercial and industrial load.

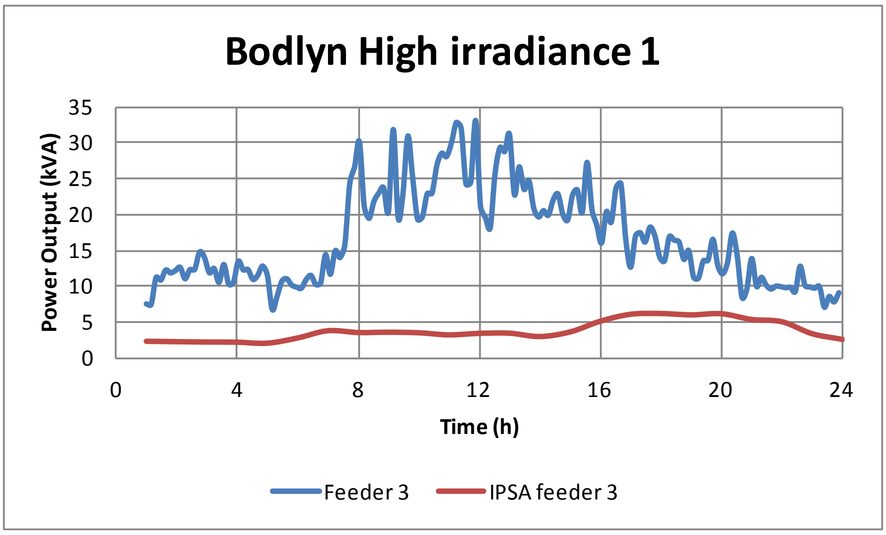


Figure 3-12 Validation of LV Feeder Modelled and Measured Loads (with high commercial demand)

It can be seen that the measured load is generally highly stochastic, especially for feeders with low number of customers (such as Dinas feeder 2 with 20 customers connected). This is in comparison to LV feeders with large numbers of customers (such as Plas Madoc Feeder 4 with 94 customers connected). It should also be noted that only one hourly results for the IPSA network model are calculated and plotted to minimise calculation time (although these have an underlying resolution of 10 minutes for PV generation and demand inputs).

Another interesting load profile characteristic that was observed for several of the LV feeders is shown in Figure 3-13 for Dinas Feeder 3. It can be seen that the demand increases significantly overnight and this is likely attributable to Economy 7 tariff heating. This behaviour is not modelled hence the divergence however the modelled PV and load characteristics during the day agree well with measurements.

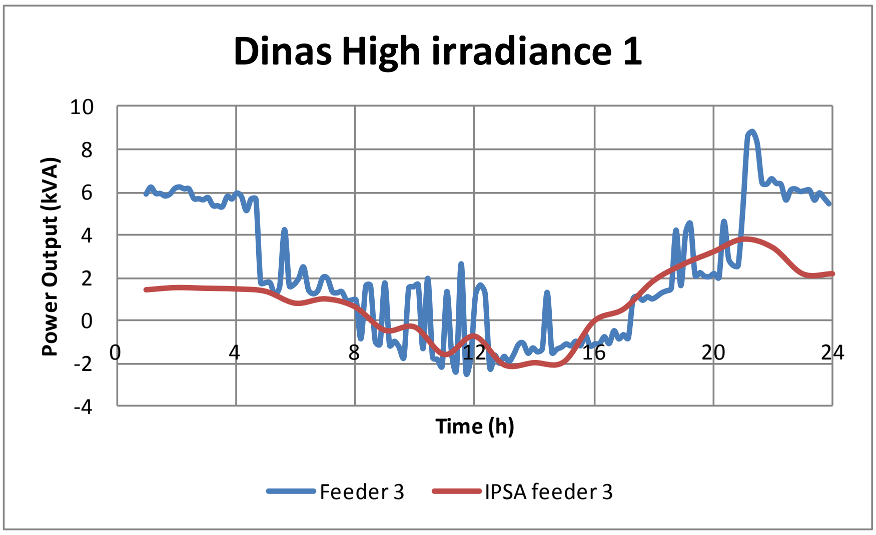


Figure 3-13 Economy 7 LV Feeder Load Profile Behaviour

One of the key areas of modelling uncertainty was the link box connections. These were adjusted to improve agreement with measured data however, in some cases, there were still material differences between modelled results and measured data. Also, commercial and industrial loads were not modelled which resulted in less agreement between modelled and measured load profiles where these loads were connected.

However, modelling results for the majority of the LV feeders with a high penetration of PV compared well with monitoring data.

4 PV Generation Capacity Headroom Assessment

4.1 Introduction

In order to assess the available generation headroom at Ruabon in more detail based on the network model validated with monitoring data, a number of representative LV feeders were assessed in detail. These are;

- Plas Madoc Feeder 1 (with no PV installed)
- Plas Madoc Feeder 3 and Dinas Feeder 1 (medium PV uptake)
- Idwal Feeder 5 (with high PV uptake)

These feeders enable characterisation of LV feeder voltage rise for a range of PV uptake in Ruabon, from little to no PV to high PV uptake. The main objective of this assessment is to determine the generation headroom available by reviewing the resultant voltage profiles in relation to the statutory voltage limits. These limits are -6% and +10% on 230V for the LV network. A voltage rise of 0.4V was included in the calculation of results to represent voltage rise on the customer service cable. Phase imbalance was not modelled.

We note that the Peris Plas Madoc voltage monitor is known to not be calibrated correctly however this should not affect results as the IPSA model was run with a uniform secondary substation of 250V. We assume that the correct Peris Plas Madoc voltage would be consistent with the voltage behaviour of the other secondary substations.

4.2 Scenarios

Using the IPSA network model, seven scenarios were defined and modelled (including the validation scenarios). The scenarios are as follows;

- Scenario 1: High irradiance day 1, approved PV
- Scenario 2: High irradiance day 2, approved PV
- Scenario 3: Low irradiance day 1, approved PV
- Scenario 4: High irradiance day 2, approved and unapproved PV
- Scenario 5: High irradiance day 2, approved and unapproved PV increased output by 20%
- Scenario 6: High irradiance day 2, approved and unapproved PV and a 2% decrease in network voltage
- Scenario 7: High irradiance day 2, approved and unapproved PV increased output by factor of 1.9 (55% uptake by customers on average) and a 2% decrease in network voltage.

The first three scenarios were used to validate the modelling approach with comparison of resultant modelled and measured load and voltage profiles shown in Appendix B and C. Scenario 4 explores the impact of connection of the currently unapproved PV to the network. Scenario 5 investigates the impact of a further increase of 20% in PV generation volumes based on existing clustering patterns. Scenarios 6 and 7 explore the effect of reducing the network voltage by 2%.

4.3 Results

The first three scenarios model the current state of the network with installed PV and measured solar irradiance on three different days. Comparison with measured data as part of the modelling validation process was discussed in detail in Section 4.7. The remaining scenarios assess the impact of a higher penetration of PV than at present and network voltage reduction.

Figure 4-1, Figure 4-2, Figure 4-3 and Figure 4-4 provide results for the voltage profile at the end of the LV feeders where it is expected to be highest due to PV uptake for Scenarios 4, 5, 6 and 7. The statutory voltage upper limit is represented by the dotted red line at 253 V.

It can be appreciated that the LV feeders with PV uptake should experience some voltage rise at peak solar irradiance in the middle of the day and all LV feeders experience voltage drop in the late afternoon/evening at peak demand times. For the Idwal LV feeder with high PV uptake, the voltage rise is higher compared to the LV feeders with medium PV uptake, whereas the Plas Madoc LV feeder with no PV experiences minimal voltage rise.

This indicates that the currently unapproved PV generation and up to approximately 20% additional PV generation can be connected in the Ruabon LV network without exceeding statutory voltage limits. This assumes that future uptake follows existing clustering patterns (due to favourable street orientations for example) however, some diversification is likely to occur. Taking generation phase imbalance into consideration for the LV feeders modelled in the Ruabon network as well as voltage control deadband suggests that connection of the currently unapproved PV generation is reasonable but not the additional 20%.

The application of voltage reduction techniques can significantly increase generation capacity headroom. This is illustrated in Figure 4-3 and Figure 4-4, where an additional 124% of PV generation (as a percentage of approved) can be feasibly connected in the Ruabon network for a voltage reduction of 2%, resulting in a total increase of PV generation of 162%.

Typically highly urban distribution networks are able to absorb high levels of distributed generation without causing voltage problems due to the higher demand and the limited space for small-scale PV installations. On the other hand rural distribution networks are less likely to be able to accept distributed generation due to the lower demand and larger space available for generator installation, which can cause higher voltages at the end of the feeders.[5] Often

[5] J.L. Acosta, Micro and Small-scale Generation in Urban Distribution Networks, PhD Thesis, School of Engineering, The University of Edinburgh, UK, 2012

rural LV feeders have shorter LV distributors/services as the 11kV feeder is routed closer to customers (e.g. along a main rural thoroughfare), which to an extent mitigates the resultant voltage rise.

The Ruabon network is considered to be a semi-urban area with medium capacity for PV uptake due to residential loading and limited space for small-scale generation installation.

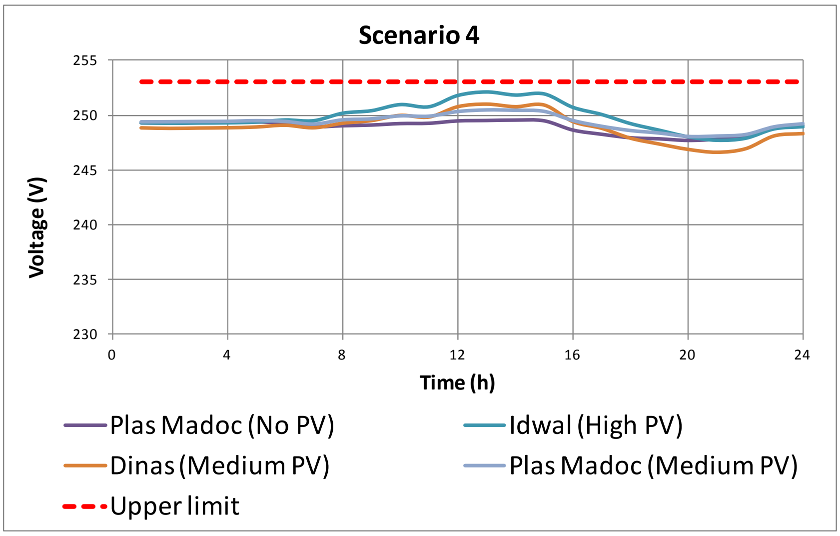


Figure 4-1 Voltage Profile for Scenario 4

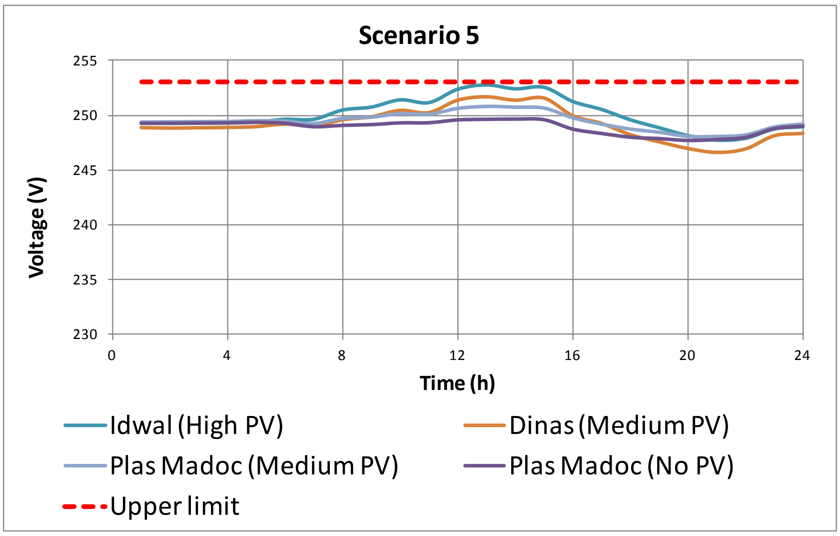


Figure 4-2 Voltage Profile for Scenario 5

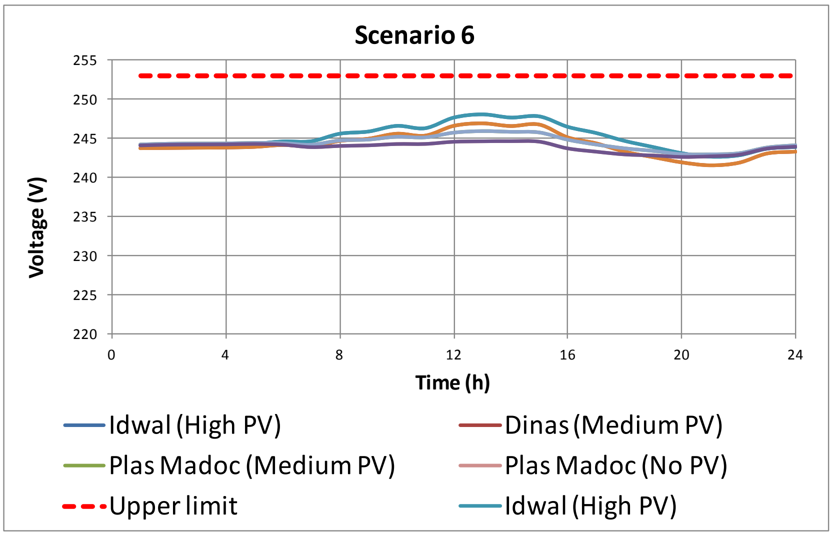


Figure 4-3 Voltage Profile for Scenario 6

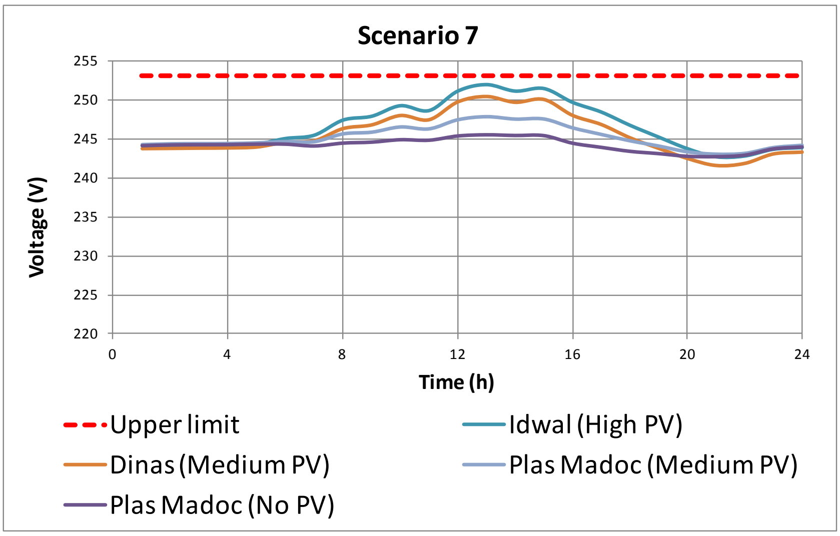


Figure 4-4 Voltage Profile for Scenario 7

5 Probabilistic Characterisation of PV Generation

5.1 Introduction

The distribution of voltage measurements for the secondary substations in the area of the Ruabon LV network investigated provides an insight into probabilistic voltage characteristics when PV generation is highest and in general.

The probabilistic distribution of measured solar irradiance data is also assessed. The frequency of high solar irradiance events when PV generation will be close to or at rated output gives some perspective on the impact of PV generation on the Ruabon LV network.

5.2 Voltage

The measured data for secondary substations LV voltage busbars was analysed to understand the current performance of the network and the impact of a future increase in PV uptake.

Figure 5-1 shows the average 10 minute snapshot voltage at each secondary substation, measured over June and July 2014. The voltage profiles suggests that variations in loading of the LV network due to embedded PV generation or demand **do not** influence voltage characteristics visibly. This is further explored in Figure 5-2 to Figure 5-3 which indicate that for Bodlyn, Dinas and Peris Plas Madoc secondary substations on high solar irradiance days, there is little coupling between phase voltages at the secondary substation and solar irradiance, and thus PV generation output. These secondary substations all have higher levels of PV uptake and Peris Plas Madoc experiences reverse power flow on the day investigated. We note that the Peris Plas Madoc voltage monitor is known to not be calibrated correctly however this should only affect the magnitude of the monitored values rather than general voltage characteristics.

Table 5—1 shows the correlation of secondary substation LV busbar phase voltage with corresponding total LV phase current as well as correlation with the Ruabon Primary HV busbar phase voltage, for three secondary substations with PV uptake on a high solar irradiance day. This correlation is replicated for a representative high demand loading winter's day and verifies the strong coupling of voltages between primary and secondary substations. It can also be seen that the correlation between LV busbar phase voltage and phase current is very weak. It should be noted that there is a biomass generator with declared generation export of 2.24MW and an actual generation export of 0.43MW in the Ruabon primary network on the HV feeder named "Ruabon School". Measured data from the SPEN load database (this feeder was not monitored as part of Flexible Networks) on the yellow phase of the HV feeder indicates the occurrence of some minimal reverse power flow on this feeder on occasions, although it is possible that this generation is in fact connected to another phase. The level of output is material when compared with the minimum demand at Ruabon (in the order of 1MW) and will have some impact on the primary voltage particularly if generating during low demand.

Table 5—1 Correlation of Secondary LV Phase Voltage with Secondary LV Phase Current and Primary HV Phase Voltage

Secondary Substation	Dinas			Bodlyn			Peris Plas Madoc		
Phase	**L1**	**L2**	**L3**	**L1**	**L2**	**L3**	**L1**	**L2**	**L3**
Secondary LV Busbar Phase Voltage with Secondary LV Phase Current	0.15	0.15	0.23	0.13	0.12	0.19	0.06	0.37	0.23
Secondary LV Busbar Phase Voltage with Primary HV Busbar Phase Voltage	0.91	0.95	0.94	0.93	0.97	0.92	0.88	0.96	0.92

In order to assess the probabilistic likelihood of overvoltage in the Ruabon LV network in general, Figure 5-6 shows Dinas secondary substation voltage distribution for all three phases from 29th of July 2013 to the 28th of July 2014 at 10 minute intervals. The voltage values on the x axis represent the **upper** value of each band. For Dinas, voltage is within the statutory limit for at least 99.85% of the time. Voltage excursions generally appear to be associated with the primary transformer tapchanger operations.

Results for other secondary substations are broadly similar, apart from Peris Plas Madoc which is known to not be calibrated correctly, and can be found in Appendix E.

In terms of wider LV network voltage management, there is a case for reducing the voltage based on the existing voltage distributions. This is unlikely to lead to undervoltages during peak demand winter conditions assuming a typical LV distributor/service cable voltage drop of 7%.

It is understood that Electricity North West have proposed an innovation project 'Customer Voltage & Power Quality Limits' which aims to review a combination of quantitative network data and qualitative customer data to determine whether short duration or lower level excursions outside statutory limits cause any noticeable effects for customers.

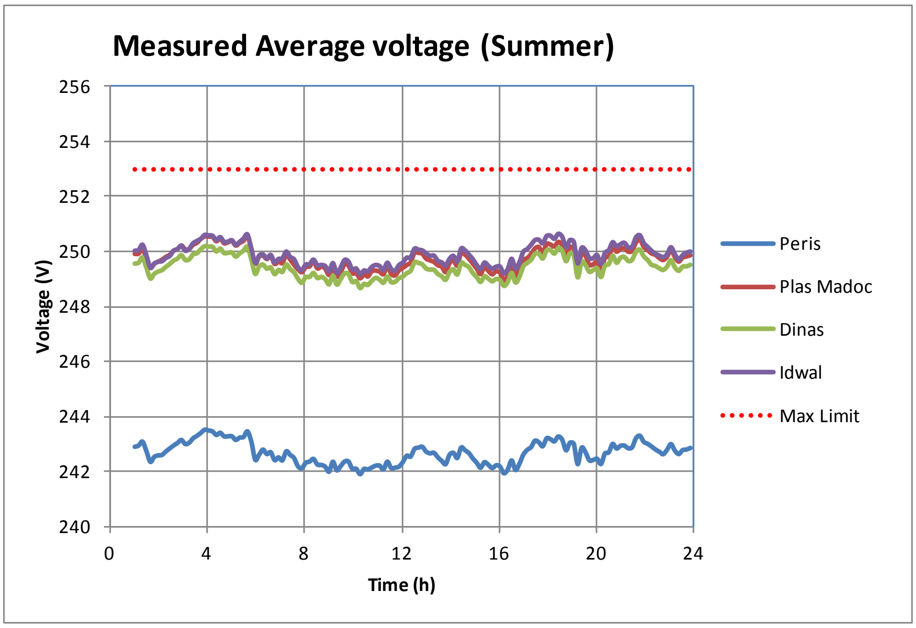


Figure 5-1 Measured Average Voltage

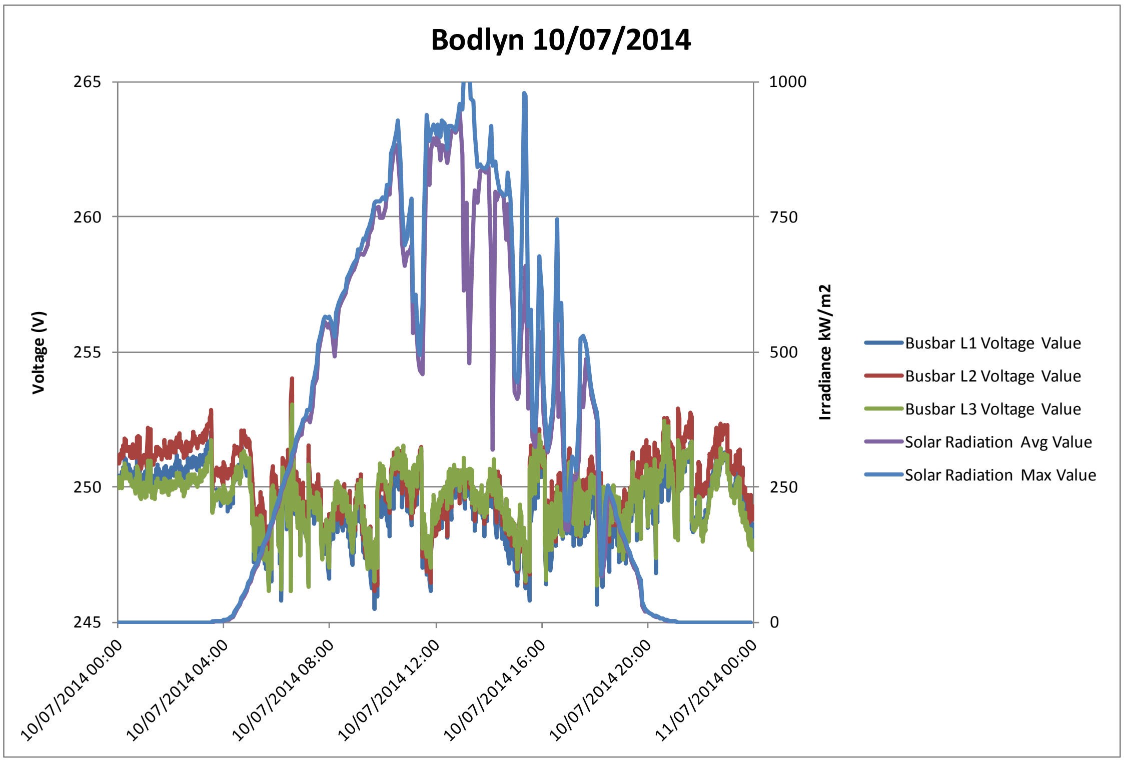


Figure 5-2 Bodlyn Measured Voltage and Solar Irradiance (10/07/2014)

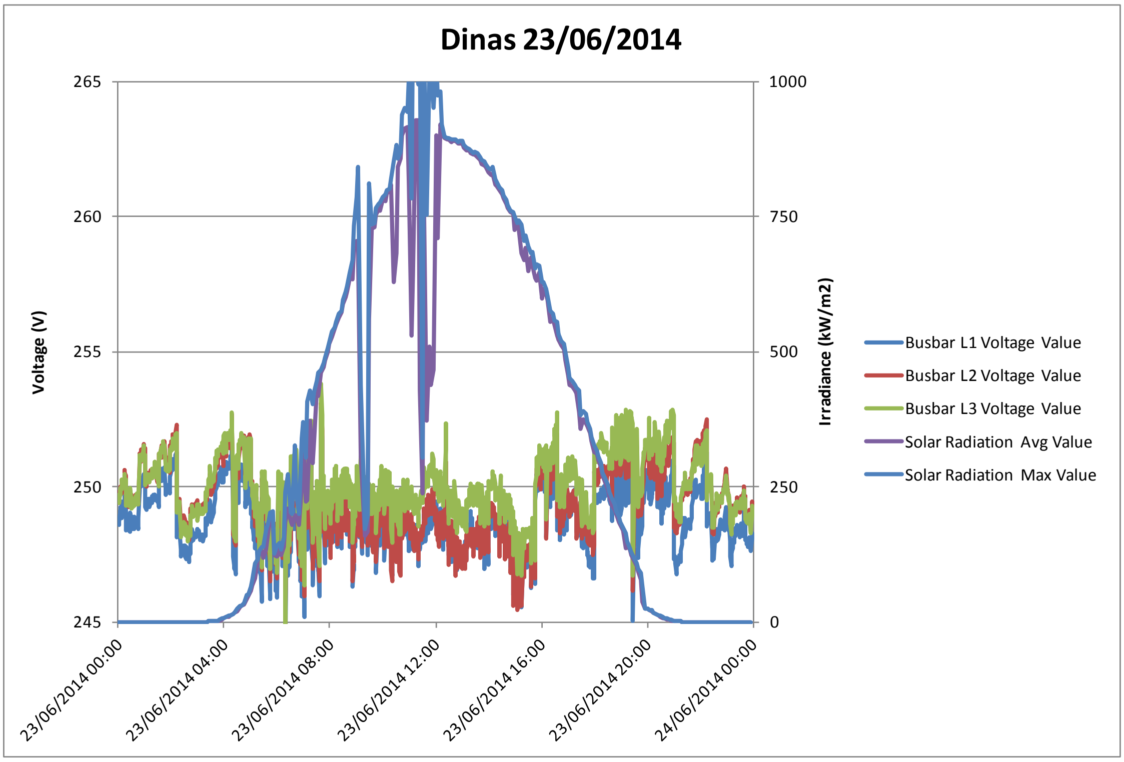


Figure 5-3 Dinas Measured Voltage and Solar Irradiance (23/06/2014)

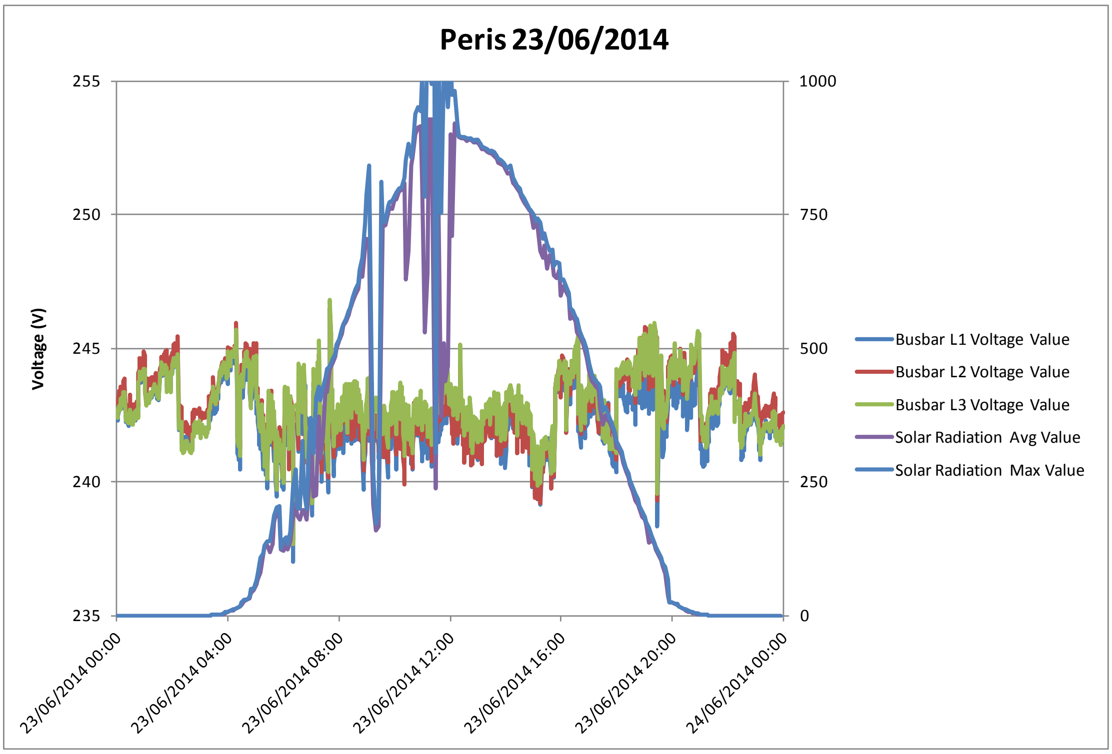


Figure 5-4 Peris Plas Madoc Measured Voltage and Solar Irradiance (23/06/2014)

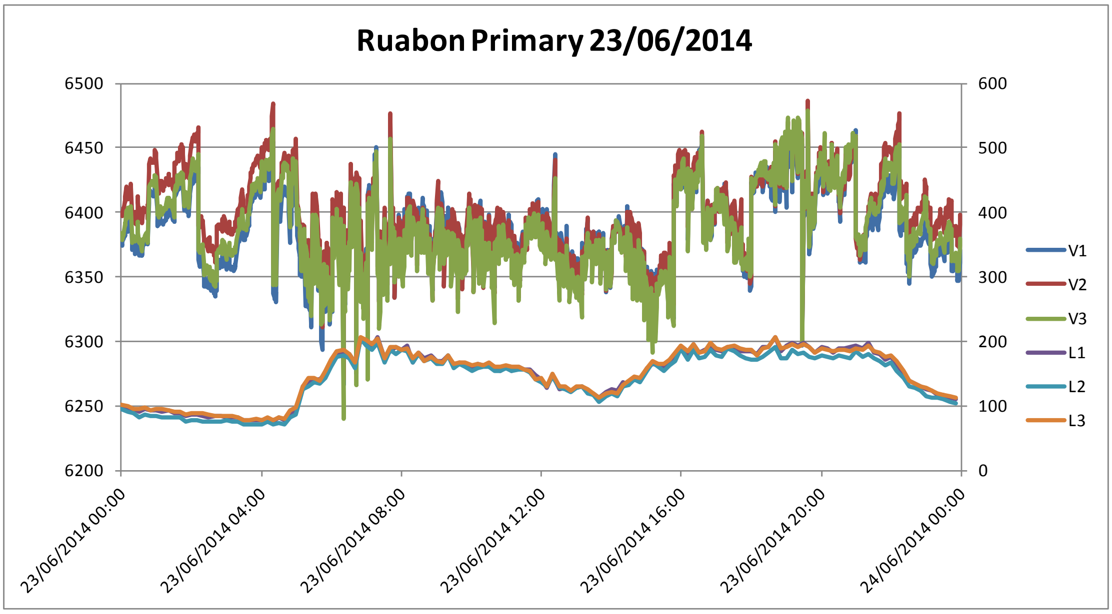


Figure 5-5 Ruabon Primary Measured Phase Voltage and Current (23/06/2014)

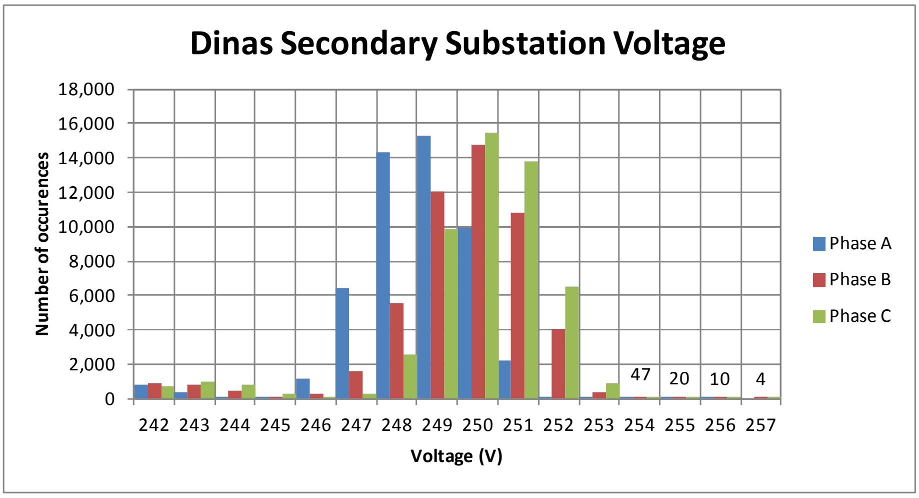


Figure 5-6 Voltage Distribution at Dinas Secondary substation

5.3 Solar Irradiance

In order to assess the distribution of solar irradiance in relation to the rated output of the PV generation, Figure 5-7 shows the distribution of 5 minute average measured solar irradiance from the 25th of September 2013 to the 24th of September 2014 with a data availability of about 71%. The solar irradiance values on the x axis represent the upper value of each band. It was found that the 5 minute average solar irradiance is above 1000 W/m^2 for 0.1% of the time. At and above this solar irradiance, the panels will saturate and (assuming they are correctly oriented) should provide the rated power output. However, this generally only occurs for brief periods of time.

Solar irradiance can also vary on smaller timescales during the measurement period (e.g. passing of clouds, reflecting objects, pollution) and these variations are not captured so well through the 5 minute average measurement. The 5 minute maximum solar irradiance is also monitored by the weather station as shown in Figure 5-7 during the same measurement period with a data availability of 71%. This indicates that 5 minute maximum solar irradiance at or above 1000 W/m^2 occurs for approximately 1% of the year, thus the probability of achieving sustained rated power output for PV generation in Ruabon is very small.

The WPD PV FiT metering analysis study found that for small-scale PV installations, the average (median) proportion of actual to potential output was 44% and the proportion of greater than 70% of potential output was extremely low (<0.01%), based on half-hourly kWh measurements. From our analysis, the proportion of 5 minute average solar irradiance greater than 70% of theoretical maximum output is 3%. It should be noted that there will be some smoothing of solar PV output with averaging over 30 minute periods compared to 5 minute averages.

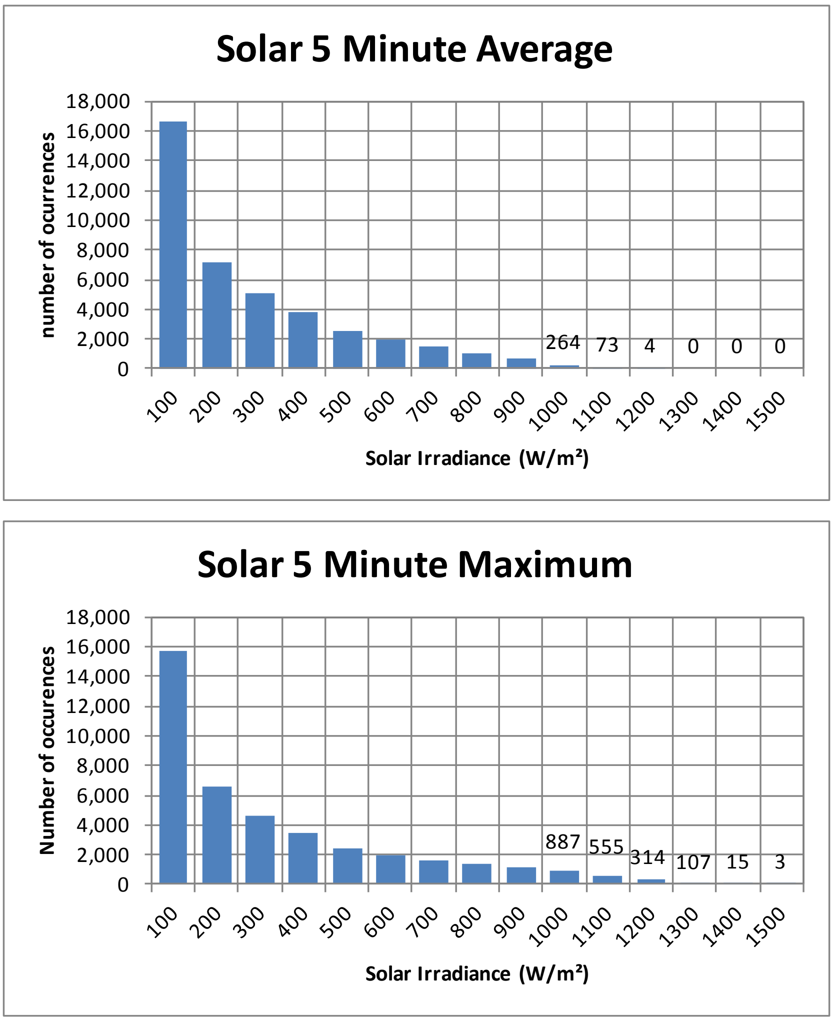


Figure 5-7. Distribution of Measured 5 Minute Average and Maximum Solar Irradiance at Ruabon

Our methodology for modelling of PV generation at Ruabon is based on a peak solar irradiance of 900 W/m^2, corresponding to a 90% PV generation load factor. Figure 5-8 shows the 5 minute average solar irradiance for the summer period (June and July 2014) which had a data availability of 81%. The 5 minute average solar irradiance exceeded 900 W/m^2 for 2% of the time and the average solar irradiance was 315 W/m^2. Even though PV generation rated output is likely to be achieved 0.5% of the time (i.e. at or above 1000 W/m^2), it was found that the instances when 5 minute average solar irradiance goes above 900 W/m^2 are generally short lived (less than 20 minutes duration); our more pragmatic approach reduces conservatism in assessing connections for PV installations.

Northern Power Grid (NPG) LCNF Tier 2 project "Customer Led Network Revolution" found that observed peak output over declared solar PV capacity output approaches 90% of nominal capacity with increasing number of customers in a group (>20)[6]. This is consistent with our approach.

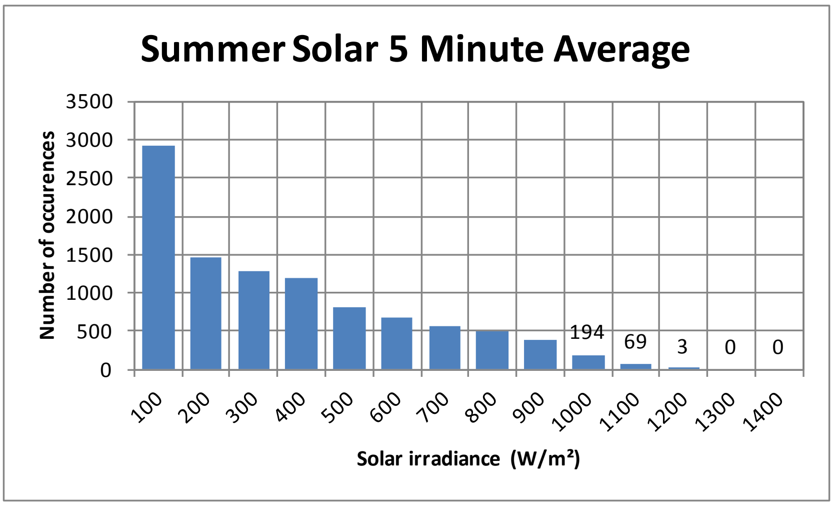


Figure 5-8. Distribution of Summer 5 Minute Average Solar Irradiance for Ruabon

[6] Northern Power Grid, Customer-Led Network Revolution – Technical Note: Solar Photovoltaic (PV) Installations, February 2015.

http://www.networkrevolution.co.uk/wp-content/uploads/2015/02/CLNR_L095-Solar-PV-Installations-Technical-Note.pdf

6 Validation with LV Customer Voltage Measurements

6.1 Introduction

In order to provide further validation of the modelling approach, to ensure that variations in voltage profile along LV feeders with feeder current and specifically due to high PV uptake was being adequately captured, modelled voltages were compared to LV customer voltage measurements.

6.2 Model Assumptions

A nominal no load three phase voltage at the secondary substation transformer of 433V (250V single phase) was assumed for all substations in the IPSA network model as per SPEN policy.

The impedance of the customer connection i.e. service cable, was not modelled explicitly in the IPSA model. There is typically a 0.4V drop for a power flow of 2kW and 10m service cable. For a PV generation installation of 1.6kW as modelled and a customer loading at peak PV generation of 0.6 x 0.555kW (0.333kW) as per the generic customer minimum demand profile, total load is (-1.6 + 0.333) = 1.267kW or just over 0.25V rise on a 10m service cable.

It is noted that a number of customers (2-4) are aggregated together in the network model.

6.3 LV Customer Measurement Details

Details of LV customer voltage monitoring where measurements are available are summarised in Table 6—1. The monitors were located in areas of the LV network with high PV uptake and/or where a number of PV installation requests have not been approved due to overvoltage concerns. The feeder number refers to the LV feeder denotation in the data acquisition system. Voltage snapshot measurements of 1s were recorded every 1 minute.

Table 6—1 LV Customer Monitor Details

Secondary Substation	**Dinas**	**Dinas**	**Idwal Plas Madoc**	**Hampden Way**	**Plas Madoc**	**Plas Madoc**
Monitor No.	5	4	2	8	7	6
LV Feeder No.	1	1	5	2	5	5
Phase	L2	L1	L3	3 phase	L2	L3

Measurements were not taken of current at customer premises due to customer confidentiality.

LV customer voltage measurements were selected for 30th December 2014 which experienced a peak solar irradiance (5 minute average) of about 250W/m^2. This was the highest level of solar irradiance within the measurement period currently available. The embedded PV generation in Ruabon at this level of solar irradiance does not produce reverse flow on the LV feeders analysed, as expected. However, the aim here is to validate the voltage-current relationship of the LV feeders in the model and this is still possible without reverse power flow. It would be desirable though to also validate during high PV generation and reverse flow conditions in future.

6.4 LV Feeder Voltage Drop

Measured phase voltage drop between the secondary substation and the LV customer is plotted against LV feeder phase current measured at the secondary substation for each LV customer monitor on 30th December 2014 in Appendix D. Table 6—2 shows the correlation of LV customer phase voltage with both the secondary substation LV feeder phase current and the secondary substation LV busbar phase voltage. These are all available as 1s snapshots at a 1 minute resolution.

Table 6—2 Correlation of LV Customer Phase Voltage with Secondary Substation Variables

Secondary Substation	Dinas	Dinas	Idwal Plas Madoc	Hampden Way	Plas Madoc	Plas Madoc
Monitor No.	5	4	2	8	7	6
LV Feeder No.	1	1	5	2	5	5
Phase	L2	L1	L3	3 phase	L2	L3
Correlation						
Customer Voltage to LV Feeder Phase Current	-0.20	-0.44	-0.77	-0.72	-0.89	-0.60
Customer Voltage to LV Busbar Phase Voltage	0.75	0.90	0.39	0.63	0.61	0.69

Voltage and current are negatively correlated as expected with only LV customer voltages on the Dinas LV network not showing a strong correlation. Two possible reasons for this are;

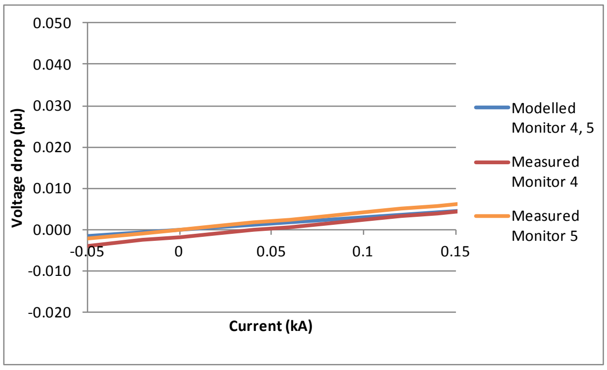
- The phase noted for monitor 5 may be incorrect, correlation is somewhat stronger for phase L3 (-0.38 for voltage to LV feeder phase current and 0.90 for voltage to LV busbar phase voltage at the secondary substation).
- The two monitors on Dinas LV feeder 1 are located very close to the secondary substation and thus, less sensitive to changes in feeder current due to limited voltage drop. This is corroborated by the LV customer

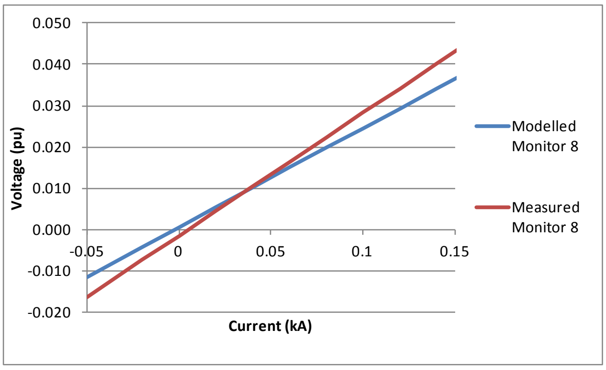
voltages being much more strongly correlated with the secondary substation phase voltage.

Trendlines are also plotted for measured phase voltage drop against LV feeder phase current measured at the secondary substation in Appendix D based on line of best fit. These show stochastic effects due to individual customer behaviour at the monitoring location and along the LV feeder phase. Generally, the trendline passes close to a voltage drop of 0V for no load.

6.5 Validation Results

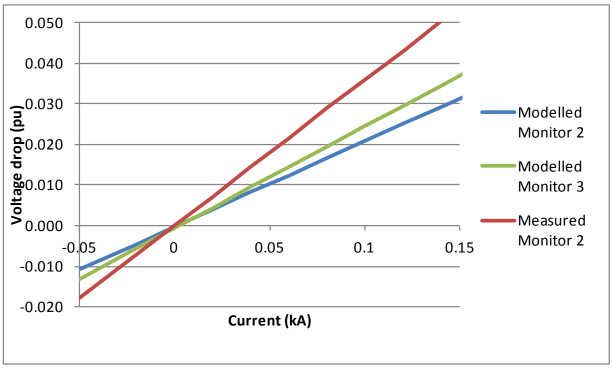
Trendlines for voltage drop/rise with feeder current based on voltage measurements at the customer LV monitors and current measurements at the secondary substation monitors were compared to the modelled voltage drop/rise, as shown below.

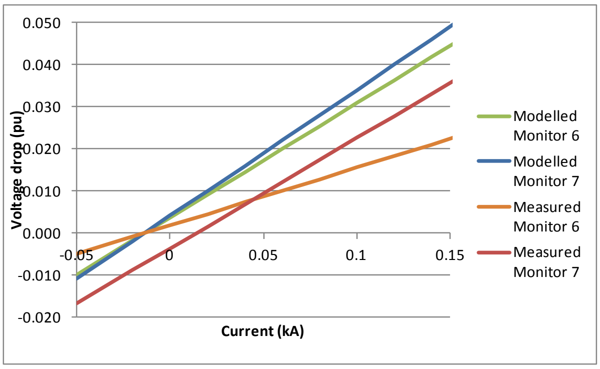




Dinas - Monitor 4 and 5

Hampden Way - Monitor 8





Idwal Plas Madoc - Monitor 2 and 3

Plas Madoc - Monitor 6 and 7

Figure 6-1 Comparison of Modelled and Measured Voltage-Current Trendlines

Results indicated that generally, the representation of voltage drop/rise at key locations along LV feeders in the network model is comparable to measurements. The network model appears to underpredict voltage drop/rise in some cases by up to 30% at 50A reverse current (or 36kW reverse power flow).

Divergence of the modelled voltage drop/rise behaviour to the trendlines derived from measurement is likely due to the following:

- LV customer voltage measurements for the monitors in the Dinas LV network are not well correlated with LV feeder phase currents so the relationship is difficult to accurately represent. However, the resultant voltage drop is comparatively low in any case.
- The derived voltage drop/rise shows significant variation around the trendline due to individual customer behaviour at the monitor and along the LV feeder phase. Ideally, LV feeder phase current measurements would be available adjacent to the customer location for a more rigorous validation.
- The IPSA model does not explicitly include voltage drop/rise of the service cable (about 0.4V or 0.002pu at customer ADMD) although it is included in the generation capacity headroom results in Chapter 5.
- Actual cable impedance may differ from the model.
- Individual customer loads are aggregated in the model and real distribution of loads down the LV feeder and across feeder phases may differ from the simplified model representation. The network model was not developed to provide an accurate voltage profile at the point of each LV customer but rather a generalised representation useful for network planning.

This suggests that it may be prudent to leave some margin of voltage near LV feeder ends to account for such phenomena as customer load variations, generation phase imbalance, and model simplification of demand/generation sources.

7 Recommendations and Future Work

7.1 Recommendations

The learning from the modelling approach developed and validated here e.g. generic minimum demand profile, PV generation and network voltage characteristics, is being used to refine the SPEN policy for evaluation of embedded PV connections on the LV network.

7.1.1 Recommendations for future monitoring in LV networks

One of the key data inputs is the local solar irradiance characteristics over the summer period. Solar irradiance based on publically available data[7] can give typical average monthly/daily solar irradiance profiles but provides no information on the frequency of high solar irradiance in particular.

It is recommended that solar irradiance measurements are taken in the vicinity of areas of the LV network experiencing increased and clustered PV uptake to more accurately characterise solar irradiance characteristics.

Monitoring of load on individual LV feeders and voltage along LV feeders with high PV uptake will contribute to verification of the modelling approach and understanding of the demand/generation characteristics including imbalance. It may be particularly useful in cases where voltage management, network meshing and/or demand side response schemes are applied and/or LV feeder characteristics are atypical.

7.2 Future Work

Further validation of this modelling approach and applicability to other networks and network types should be carried out in terms of defining a generic minimum demand profile and solar irradiance characteristics. It is envisaged that this would include further consideration of;

- various housing stock and related LV feeder topology
- commercial and industrial demand profiles and PV generation installations
- impact of demand side response and energy storage

This would enable the approach to be applied across the LV network with confidence via a simplified analysis on the LV network based on readily available information including type and number of customers, PV installations/rating and solar irradiance.

[7] European Commission: Joint Research Centre, "PVGIS: Solar Irradiation data," [Online] Available: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php

Appendix A - Existing SPEN PV Analysis Tool

The PV generation connection analysis tool estimates voltages in a three-phase LV distribution circuit divided into 3 sections as shown in Figure A-1. Calculation is performed for two different scenarios: summer midday (minimum load, maximum PV generation) and winter evening (maximum load, minimum or no PV output).

Customer loads and PV installations are either lumped at the end of each feeder section or evenly distributed along each section. In addition to customer loads and PV installations there is an option to connect lumped single phase loads at the end of each section, for example, to represent the load of spurs.

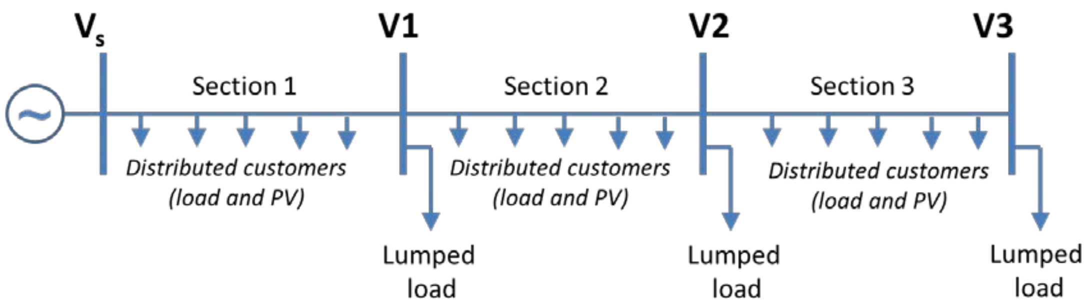


Figure A-1 Model of LV Feeder

The user can control:

- Cable type,
- Feeder length,
- Voltage at the substation,
- Number of customers,
- Number of PV installations,
- Load per customer in winter and summer,
- PV output in winter and summer,
- Distribution of the load and the PV between and within the three sections of the feeder,
- Distribution of the load and the PV between phases,
- Additional lumped loads,
- Impedance of the neutral line.

The tool outputs the predicted voltages at Vs, V1, V2 and V3 in summer and winter, and creates a graph showing the predicted voltage profile (Figure A-2).

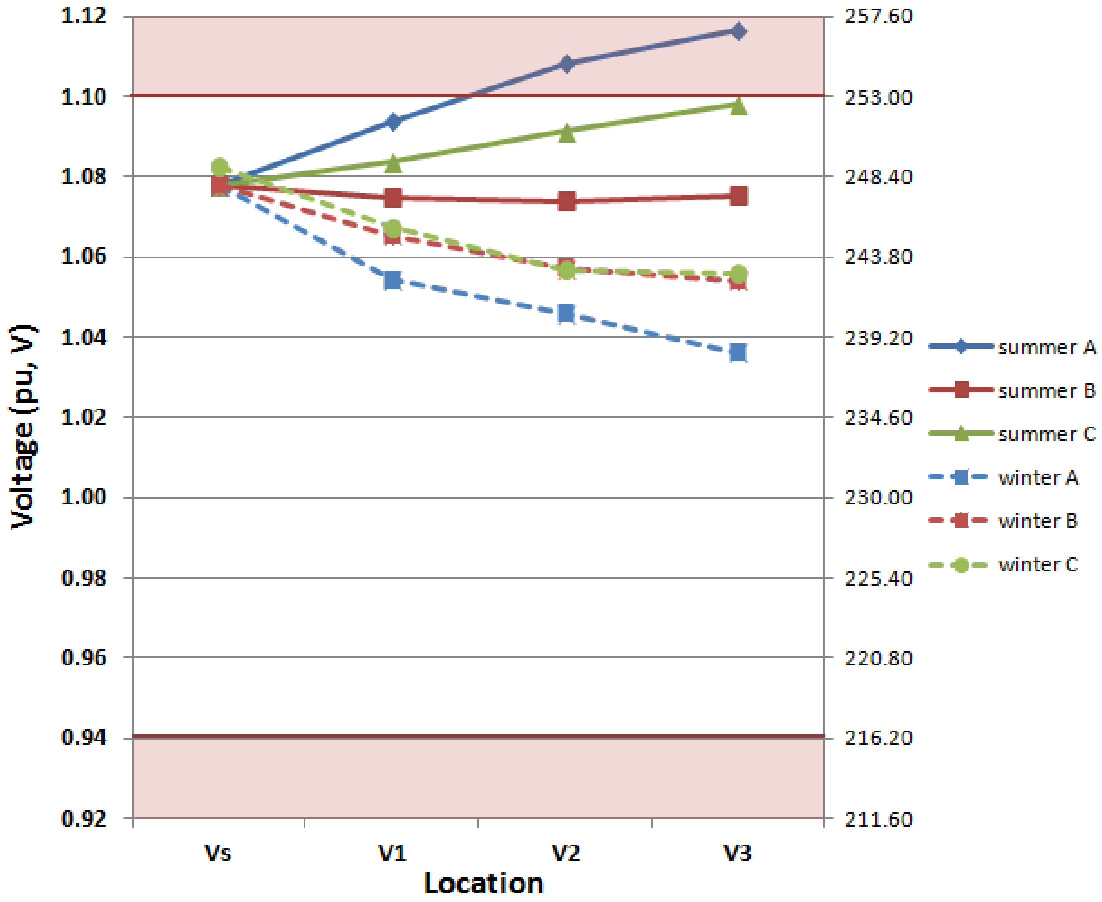
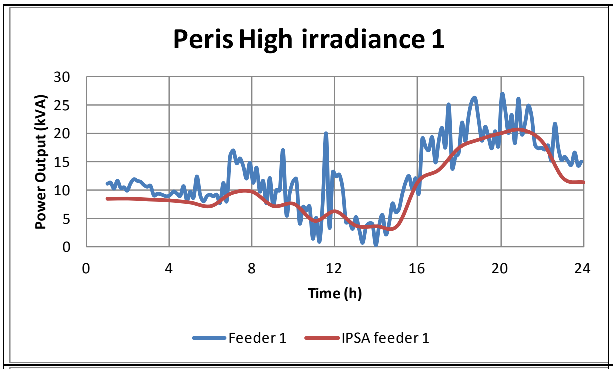


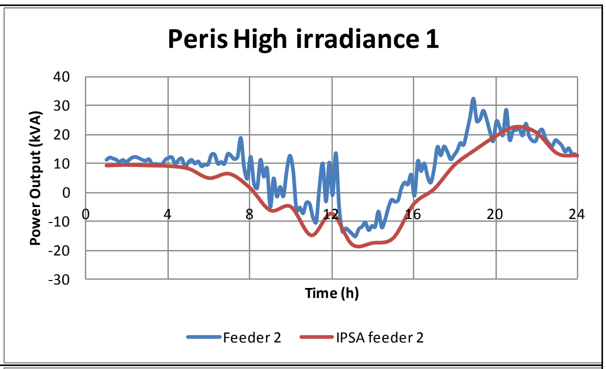
Figure A-2 Example of Summer and Winter Voltage Profiles along LV Feeder

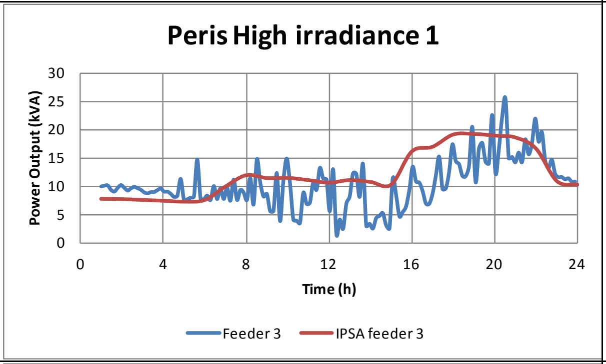
Appendix B - Validation of the Modelling Approach - Load Profile

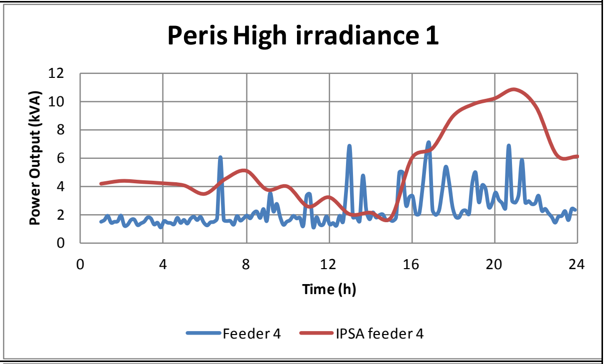
Comparison of measured and modelled load profiles are shown below for the Ruabon LV feeders analysed on selected 2014 summer days.

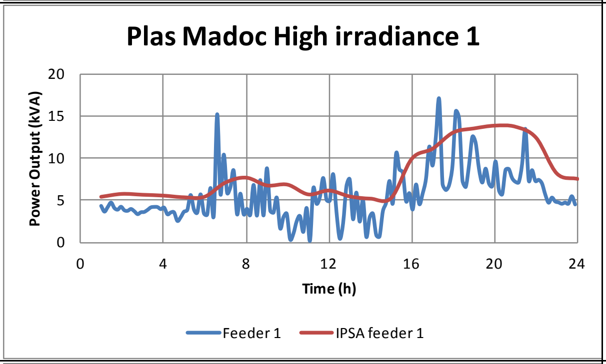
High Irradiance day 1

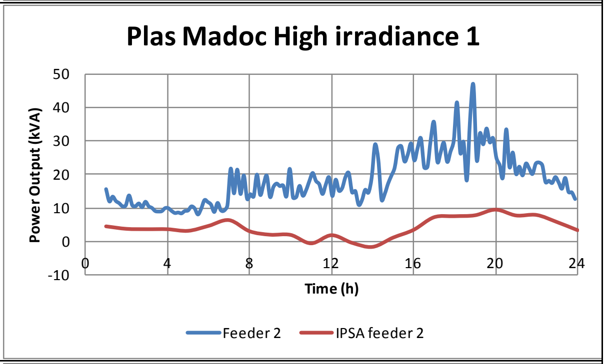


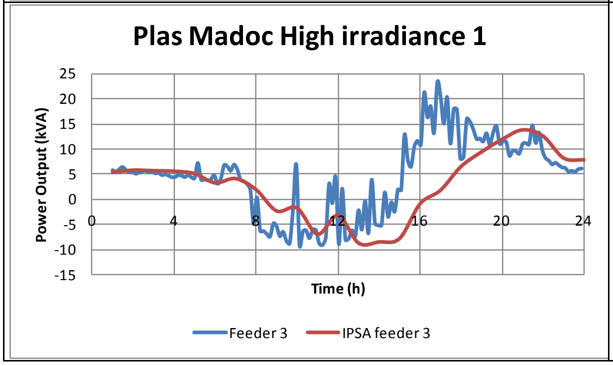


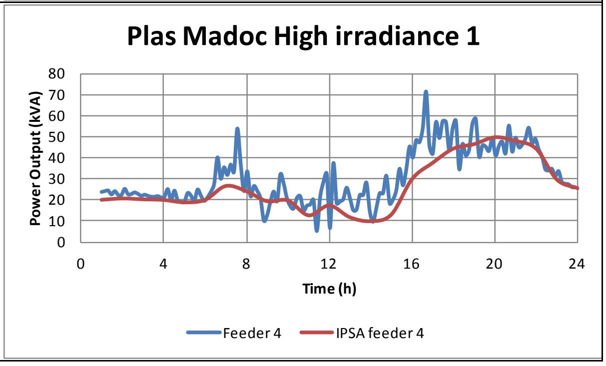


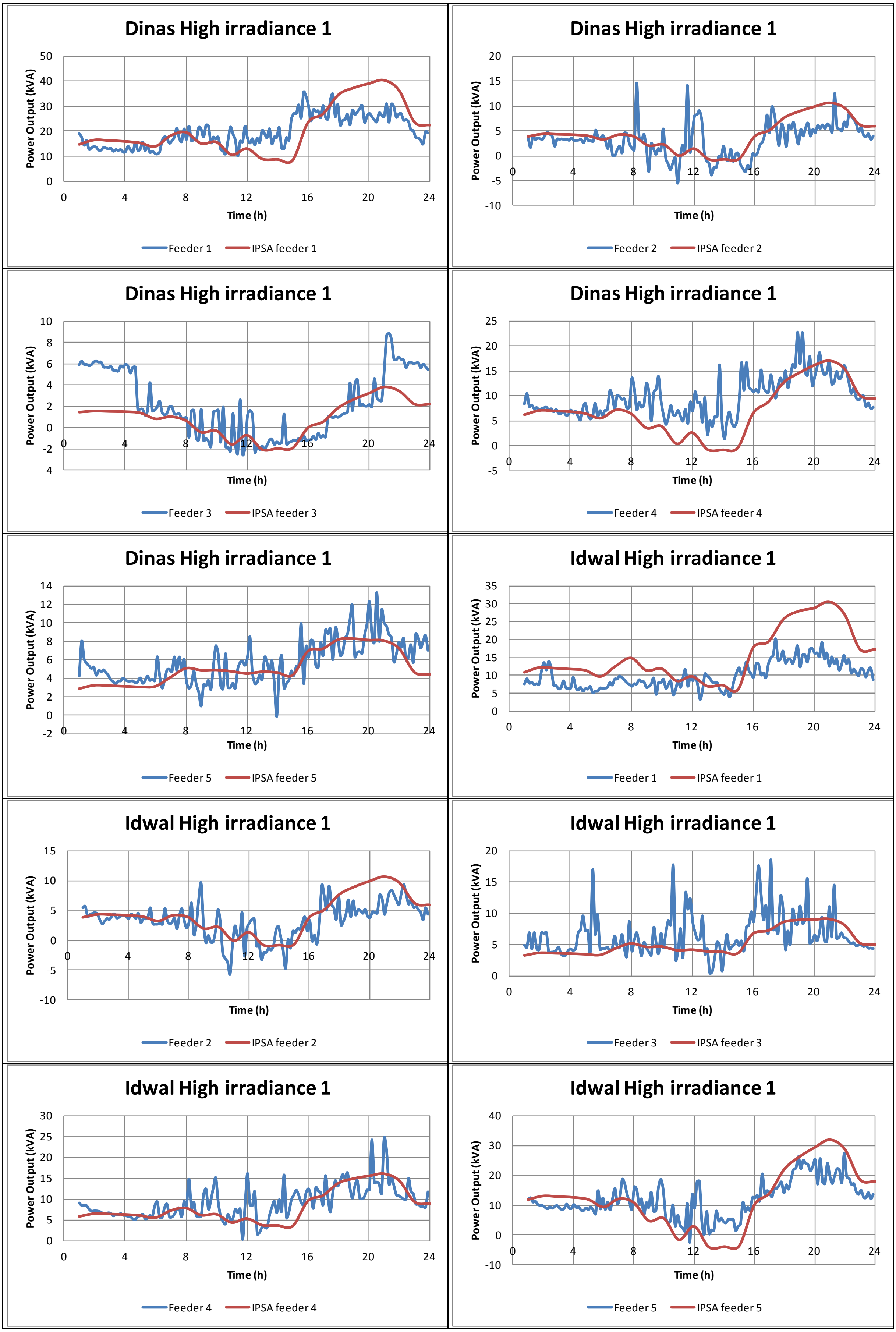


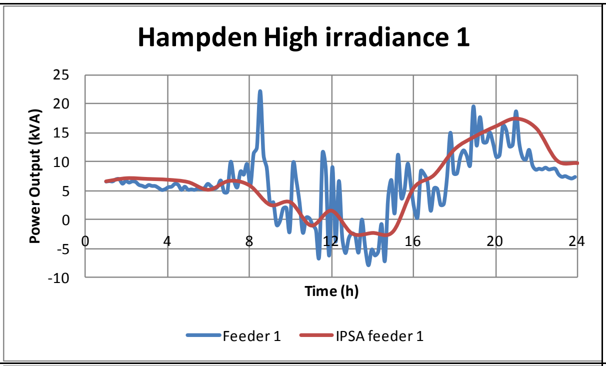


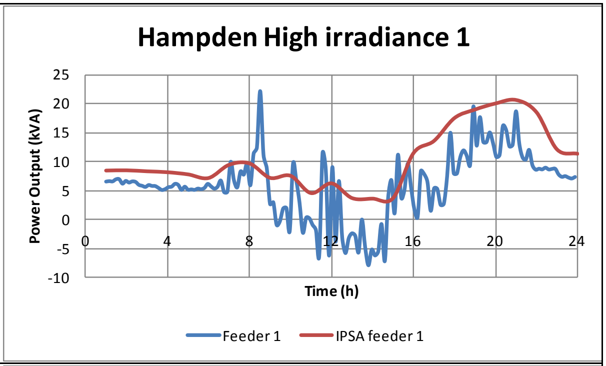


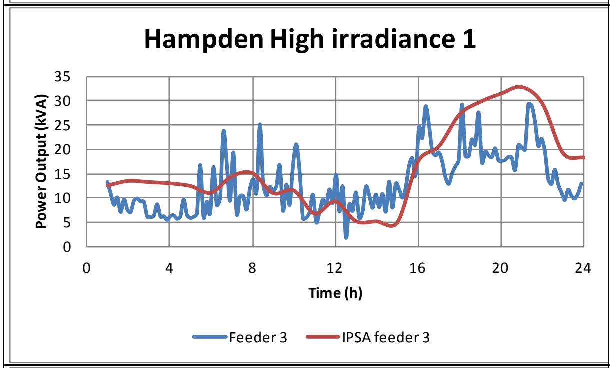


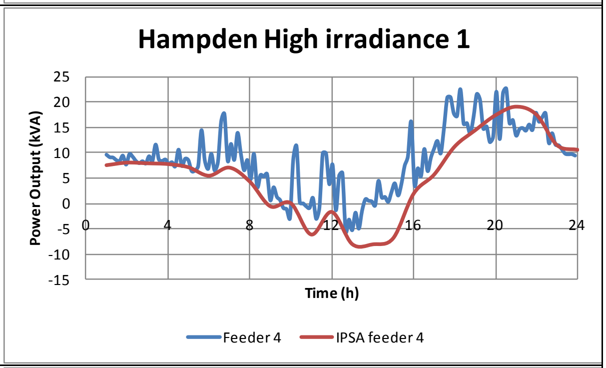


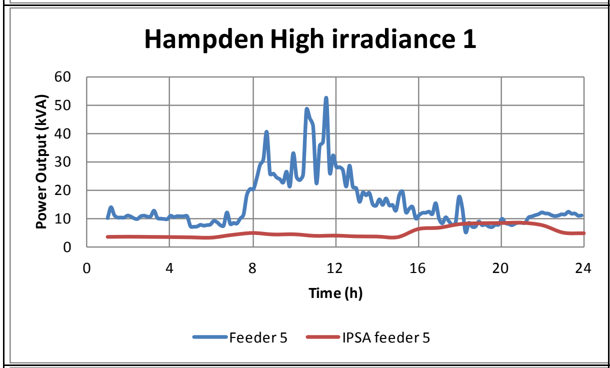

Dinas High irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1
Dinas High irradiance 1
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2
Dinas High irradiance 1
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3
Dinas High irradiance 1
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4
Dinas High irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5
Idwal High irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1
Idwal High irradiance 1
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2
Idwal High irradiance 1
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3
Idwal High irradiance 1
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4
Idwal High irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5

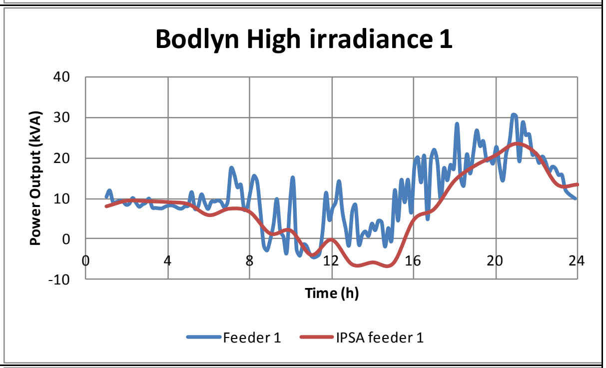

Hampden High irradiance 1
Power Output (kVA)
25
20
15
10
5
0
-5
-10
0
4
8
12
16
20
24
Time (h)
Feeder 1
IPSA feeder 1

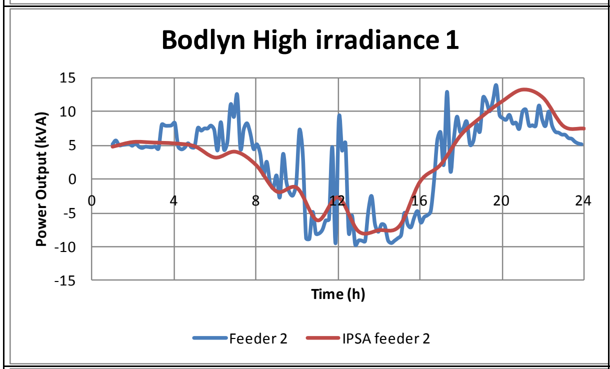

Hampden High irradiance 1
Power Output (kVA)
25
20
15
10
5
0
-5
-10
0
4
8
12
16
20
24
Time (h)
Feeder 1
IPSA feeder 1

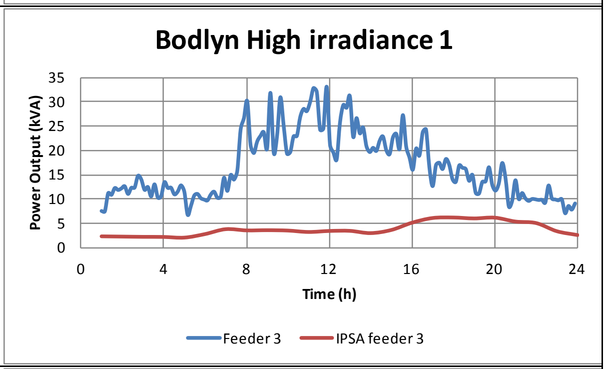

Hampden High irradiance 1
Power Output (kVA)
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
Time (h)
Feeder 3
IPSA feeder 3

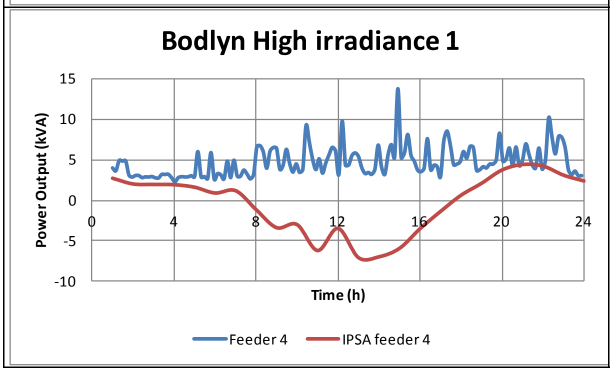

Hampden High irradiance 1
Power Output (kVA)
25
20
15
10
5
0
-5
-10
-15
0
4
8
12
16
20
24
Time (h)
Feeder 4
IPSA feeder 4

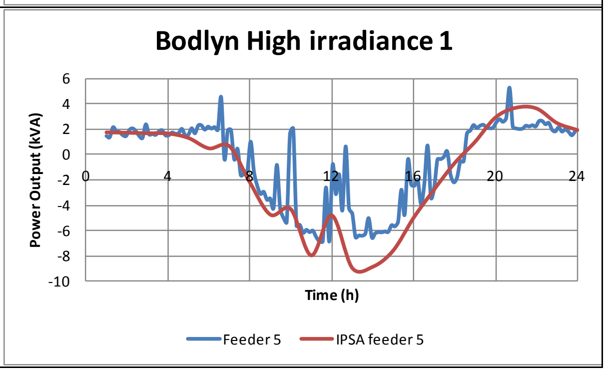

Hampden High irradiance 1
Power Output (kVA)
60
50
40
30
20
10
0
0
4
8
12
16
20
24
Time (h)
Feeder 5
IPSA feeder 5


Bodlyn High irradiance 1
Power Output (kVA)
40
30
20
10
0
-10
0
4
8
12
16
20
24
Time (h)
Feeder 1
IPSA feeder 1

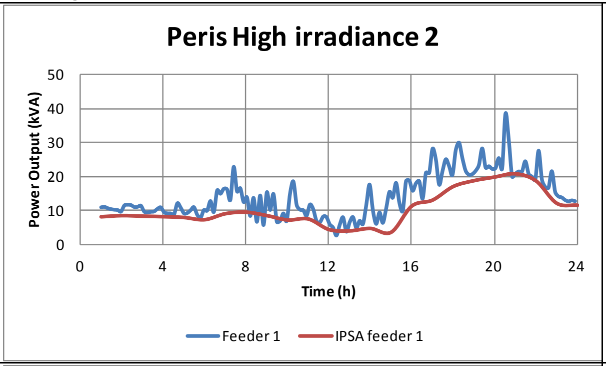

Bodlyn High irradiance 1
Power Output (kVA)
15
10
5
0
-5
-10
-15
0
4
8
12
16
20
24
Time (h)
Feeder 2
IPSA feeder 2

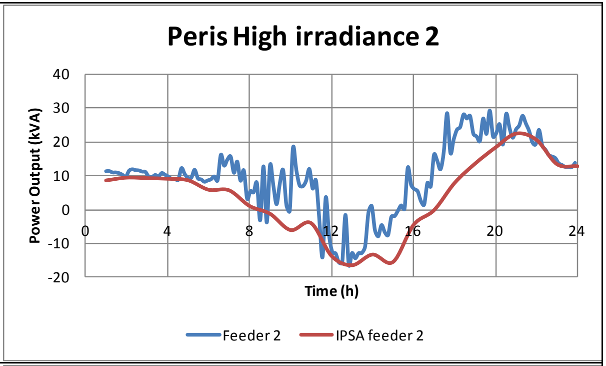

Bodlyn High irradiance 1
Power Output (kVA)
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
Time (h)
Feeder 3
IPSA feeder 3

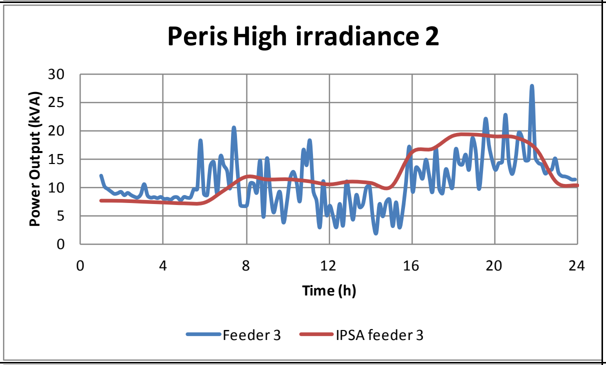

Bodlyn High irradiance 1
Power Output (kVA)
15
10
5
0
-5
-10
0
4
8
12
16
20
24
Time (h)
Feeder 4
IPSA feeder 4

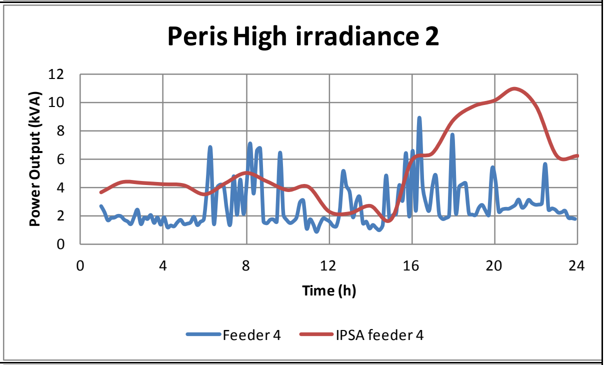

Bodlyn High irradiance 1
Power Output (kVA)
6
4
2
0
-2
-4
-6
-8
-10
0
4
8
12
16
20
24
Time (h)
Feeder 5
IPSA feeder 5

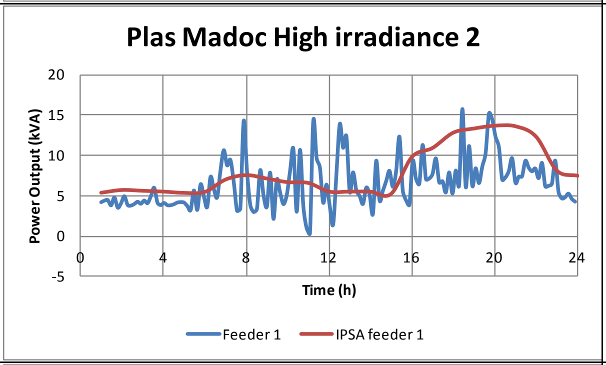
High Irradiance 2

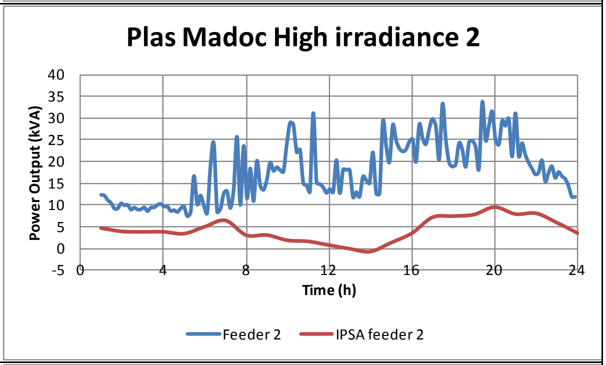


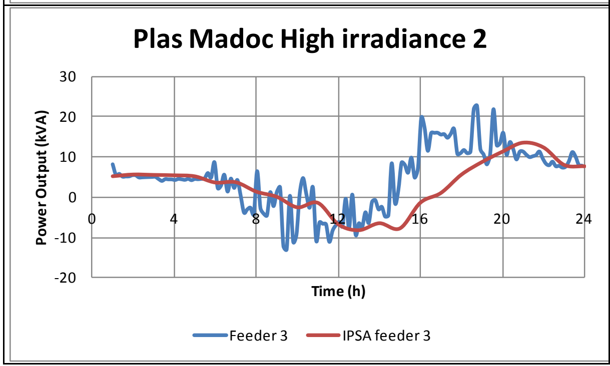


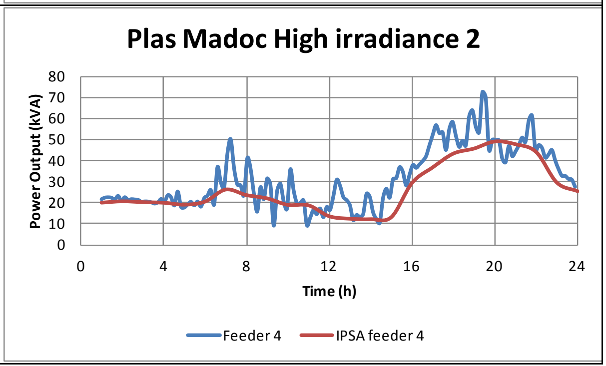


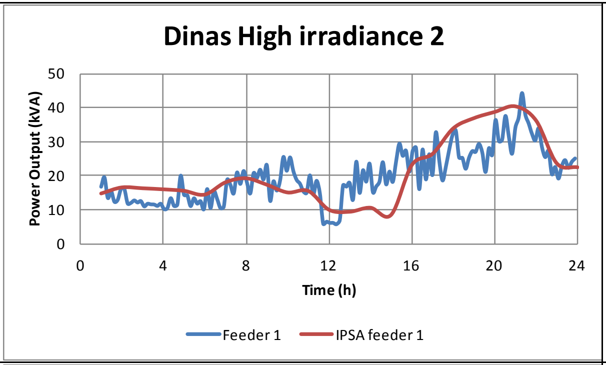


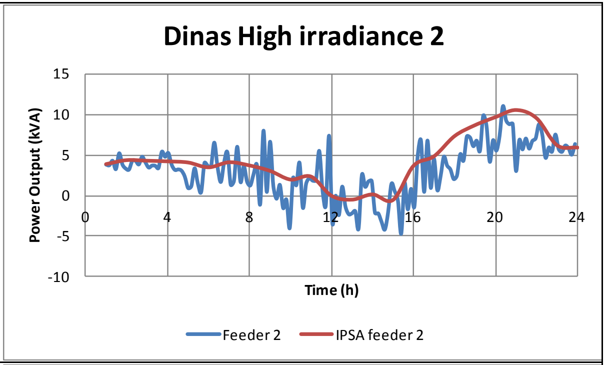


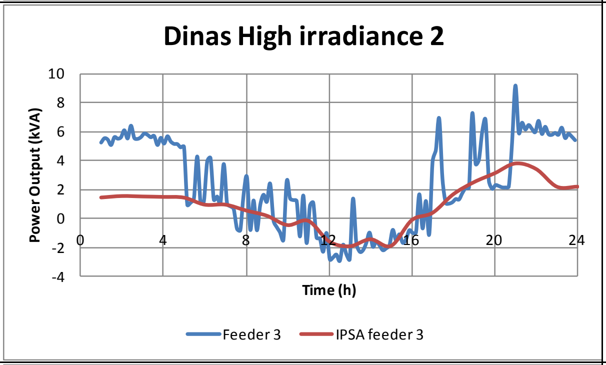


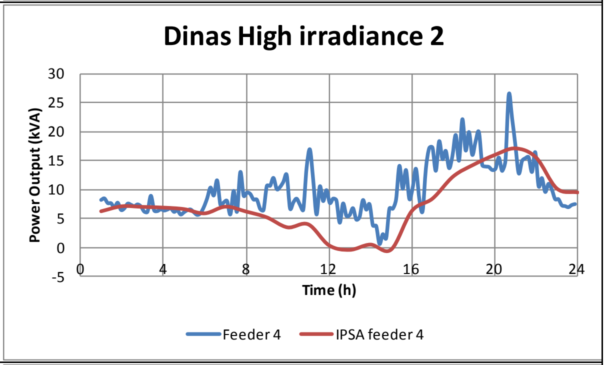


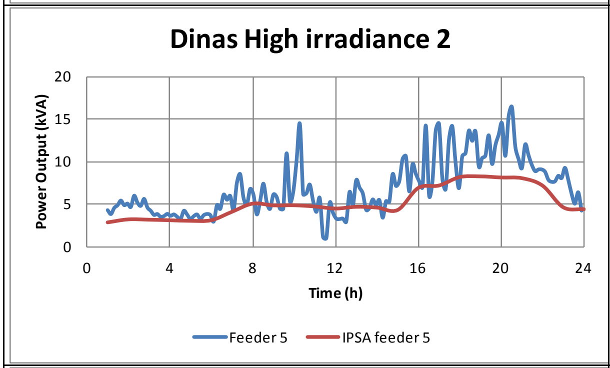


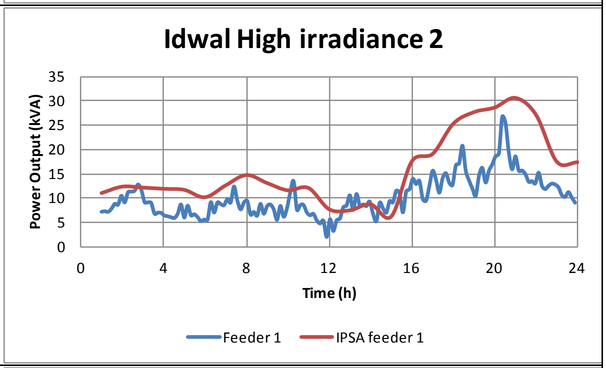

Dinas High irradiance 2
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1

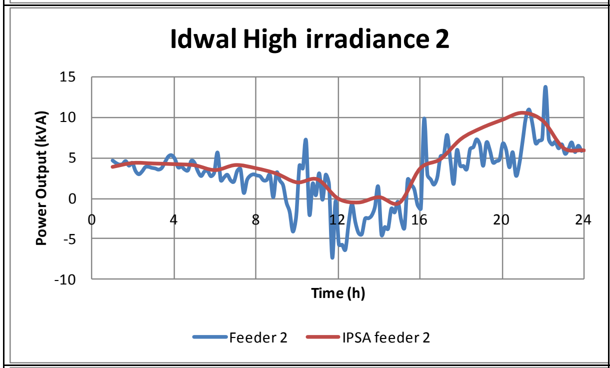

Dinas High irradiance 2
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2

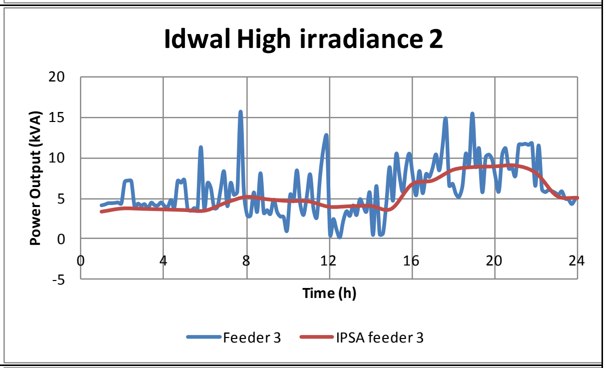

Dinas High irradiance 2
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3

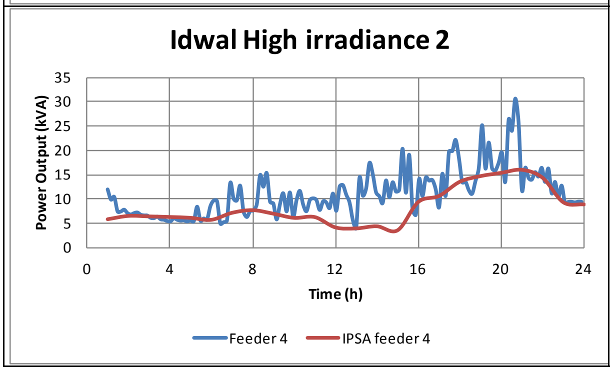

Dinas High irradiance 2
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4

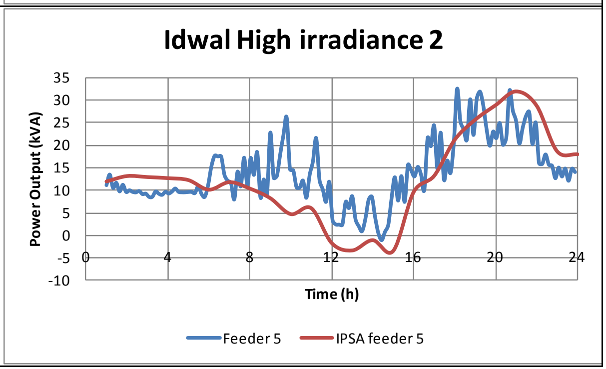

Dinas High irradiance 2
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5

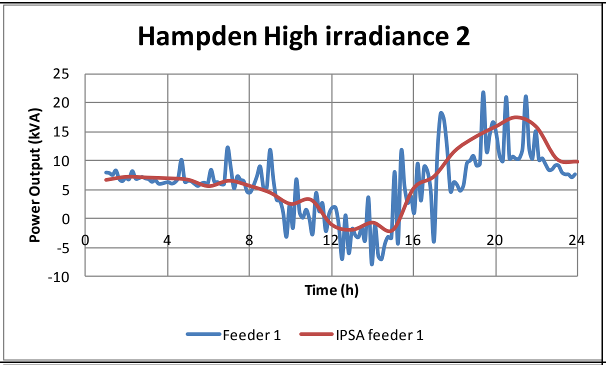

Idwal High irradiance 2
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1

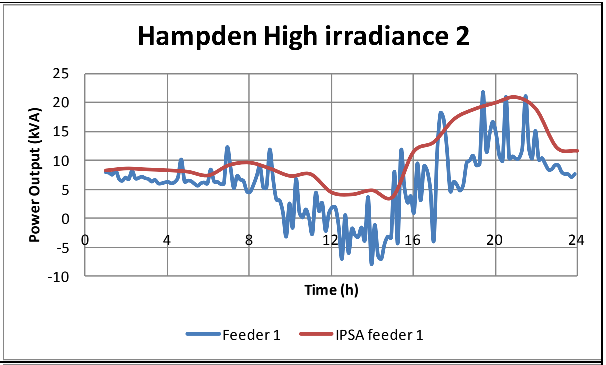

Idwal High irradiance 2
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2

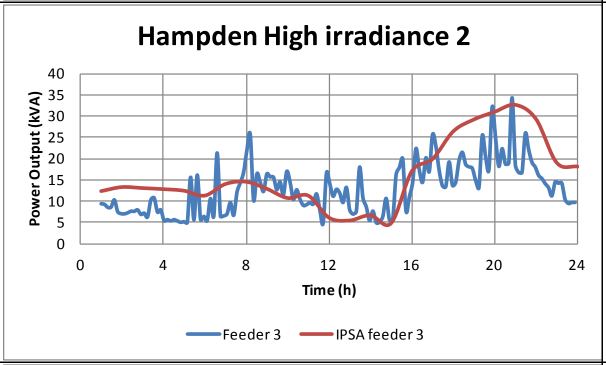

Idwal High irradiance 2
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3

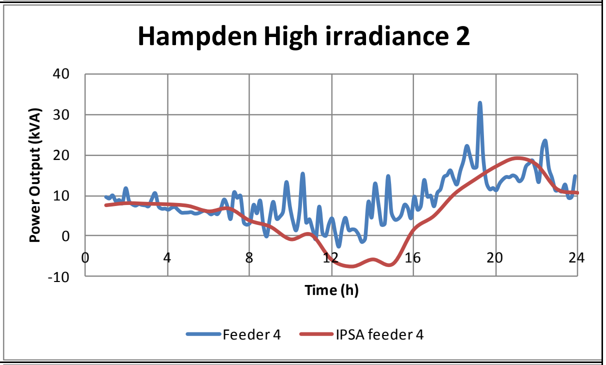

Idwal High irradiance 2
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4


Idwal High irradiance 2
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5


Hampden High irradiance 2
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1


Hampden High irradiance 2
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1


Hampden High irradiance 2
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3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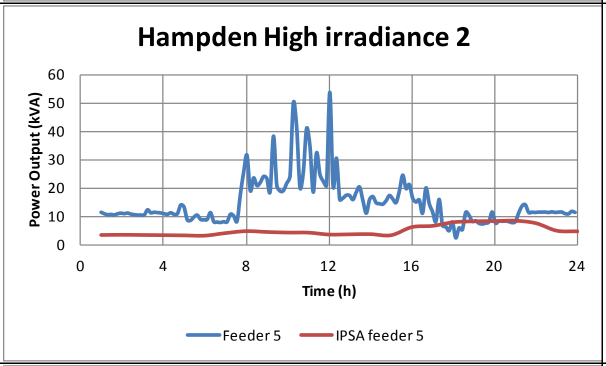
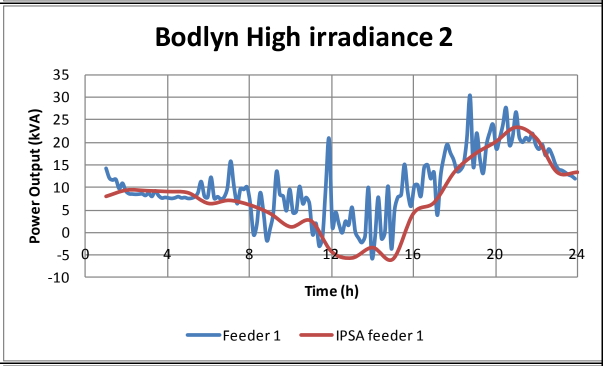
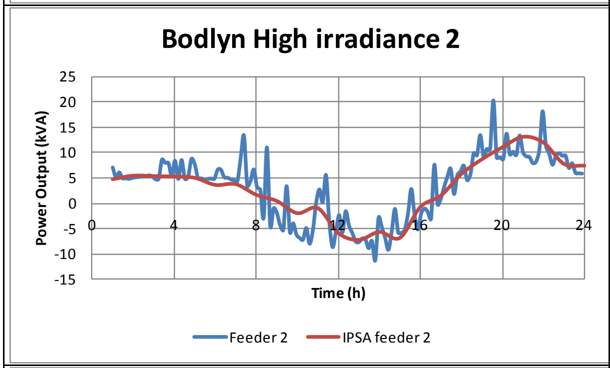
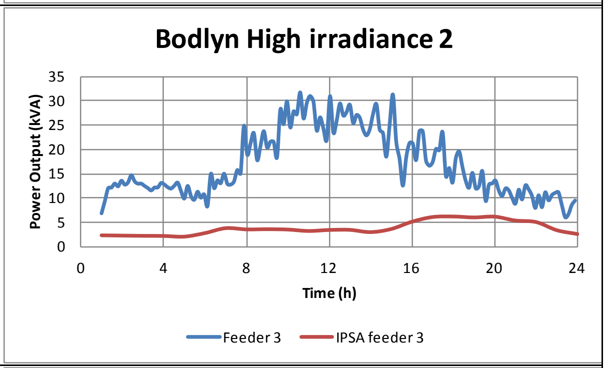
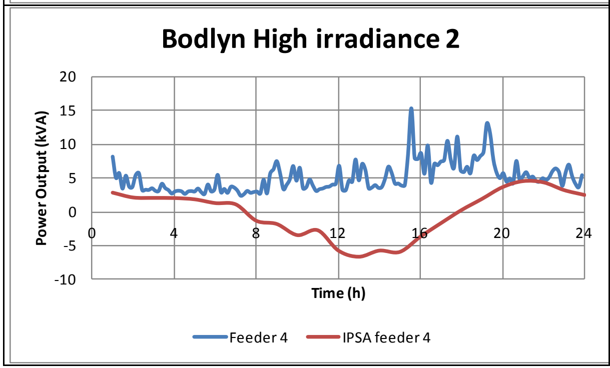
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4

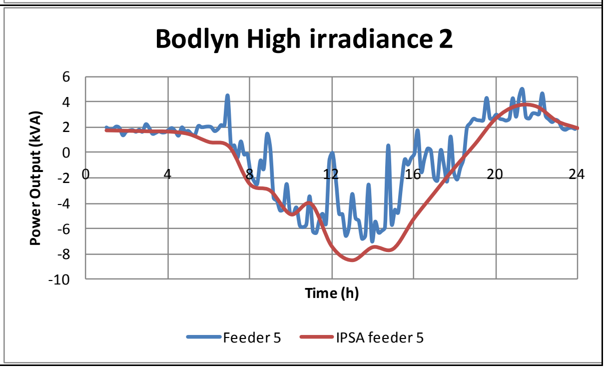

Hampden High irradiance 2
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5


Bodlyn High irradiance 2
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1

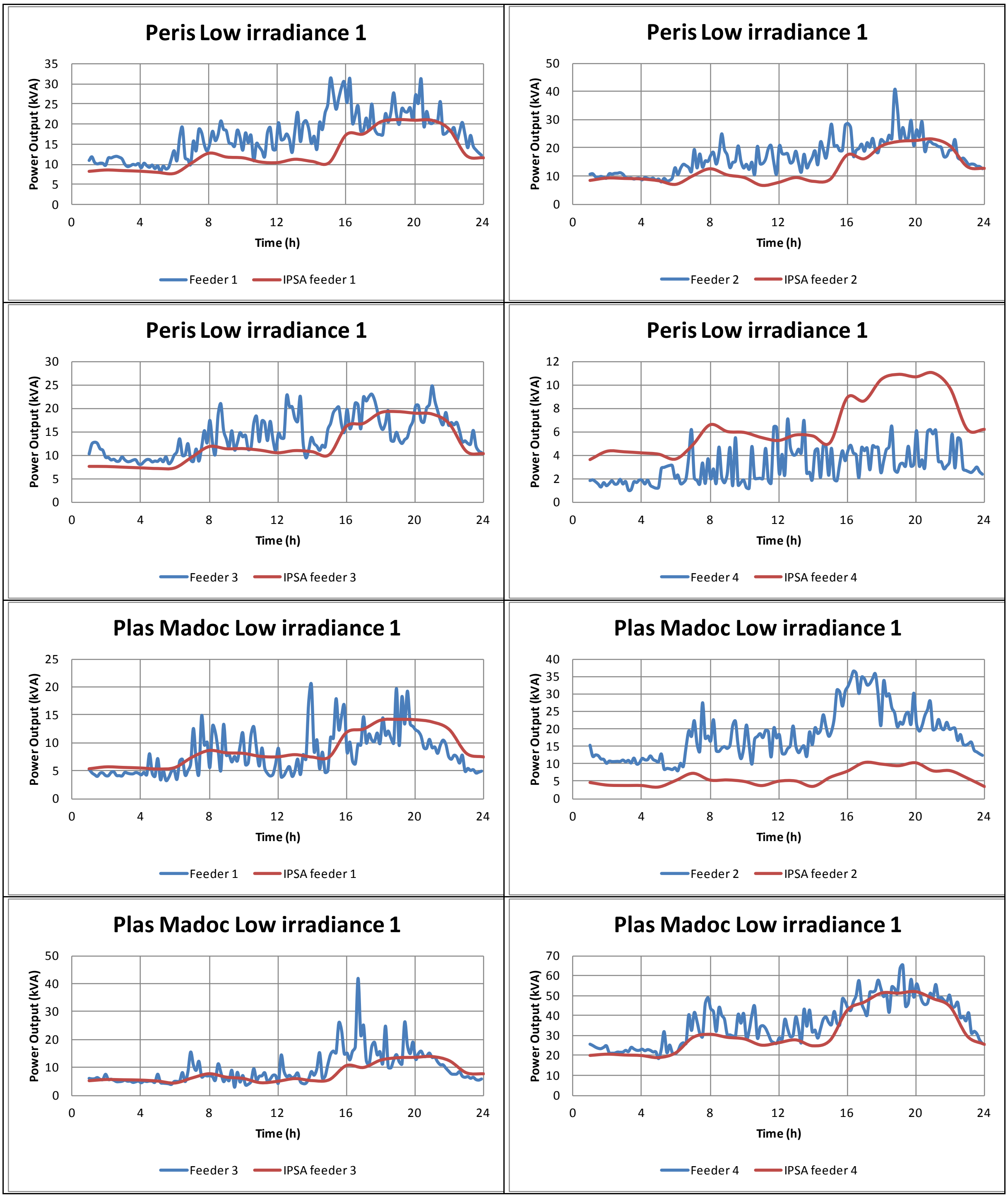

Bodlyn High irradiance 2
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2

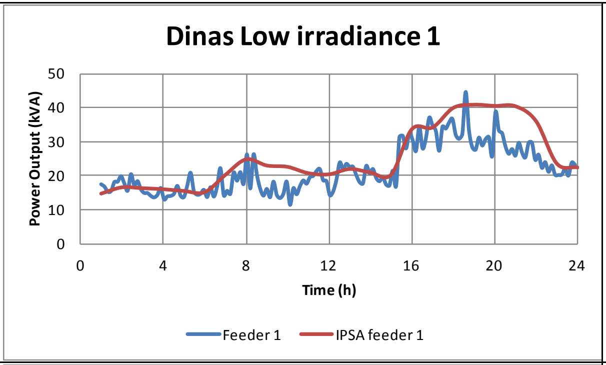

Bodlyn High irradiance 2
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3

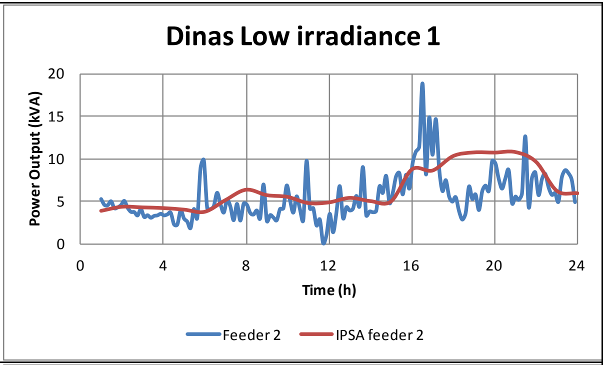

Bodlyn High irradiance 2
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4


Bodlyn High irradiance 2
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5

Low Irradiance 1




Dinas Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1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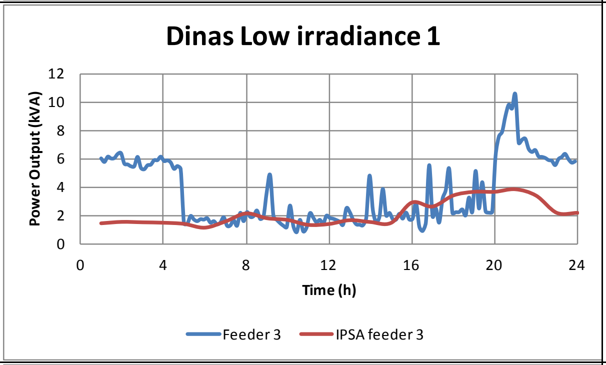
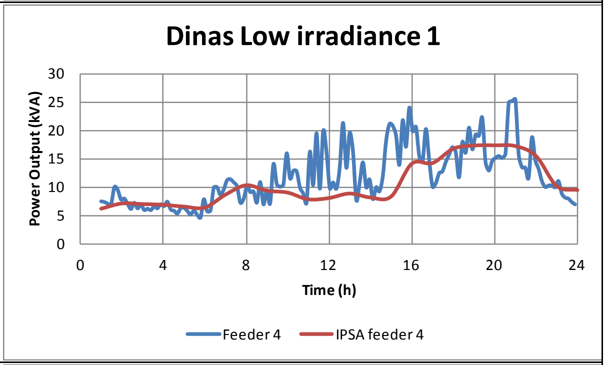
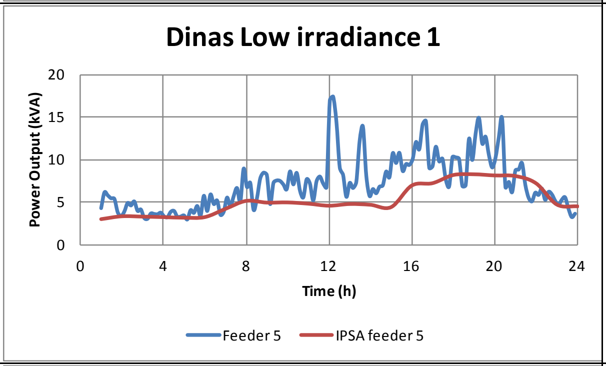
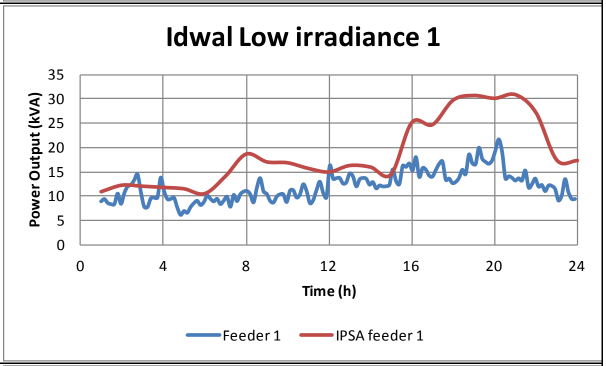
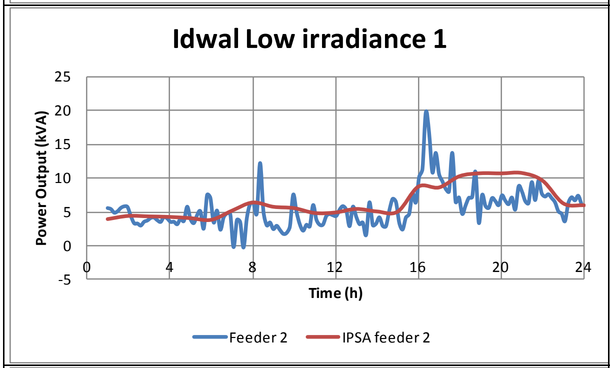
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2

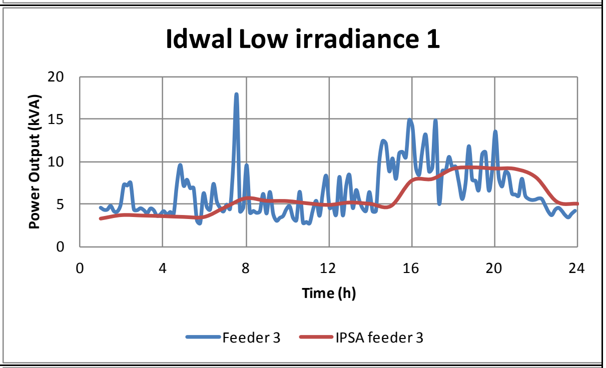

Dinas Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3

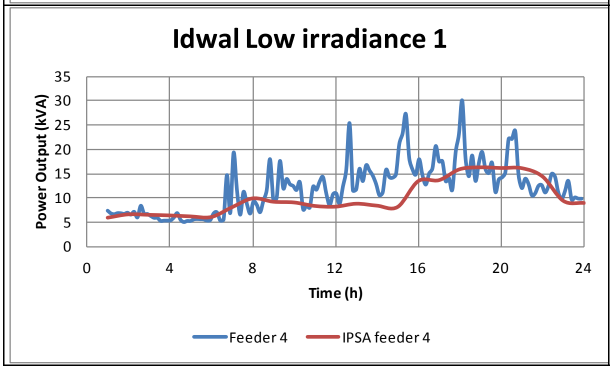

Dinas Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4

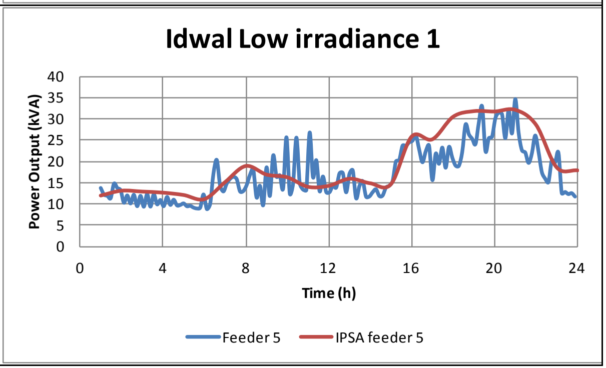

Dinas Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5

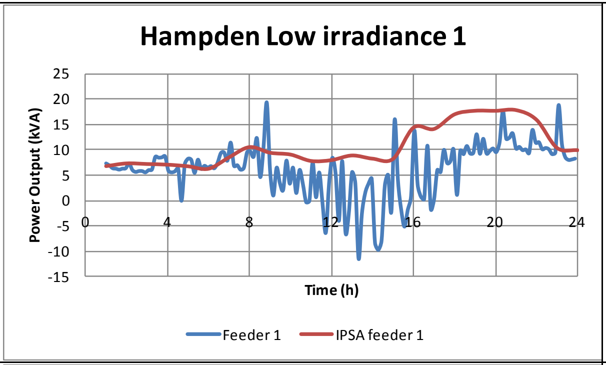

Idwal Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1

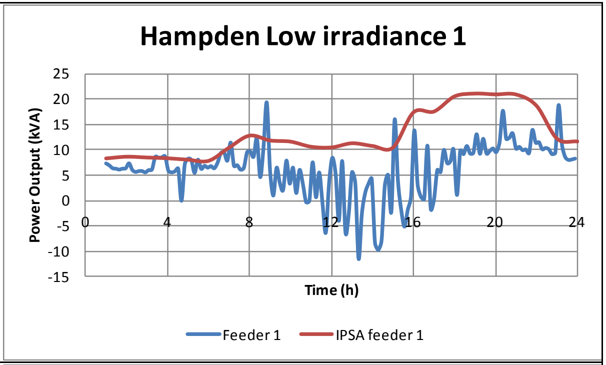

Idwal Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2


Idwal Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3


Idwal Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4


Idwal Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5


Hampden Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1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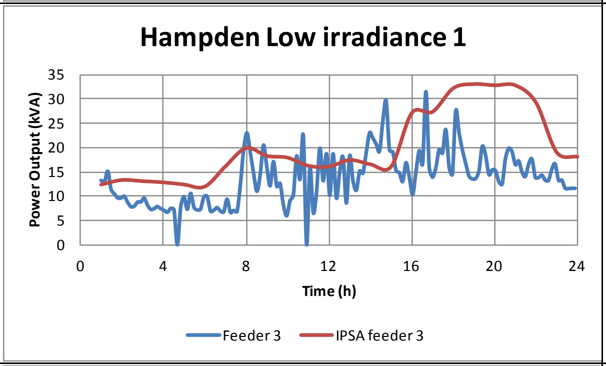
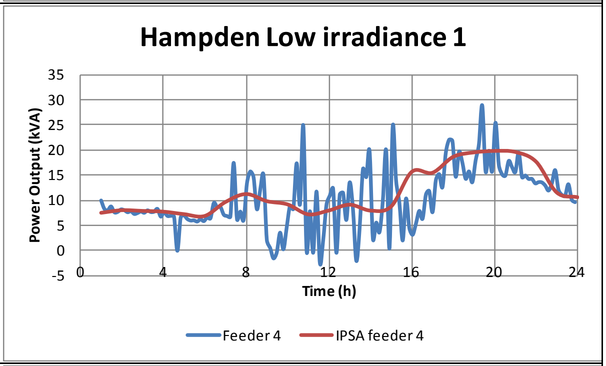
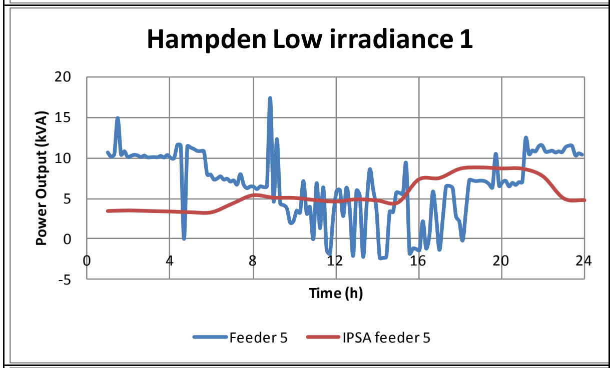
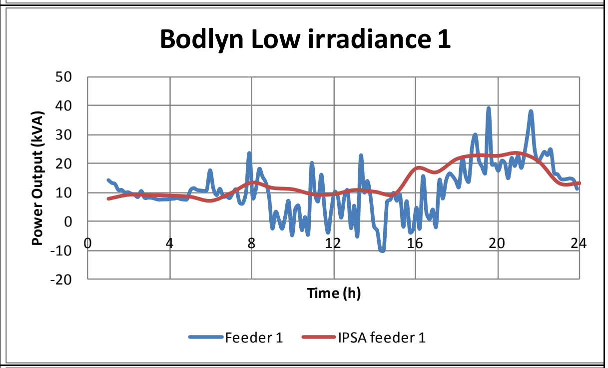
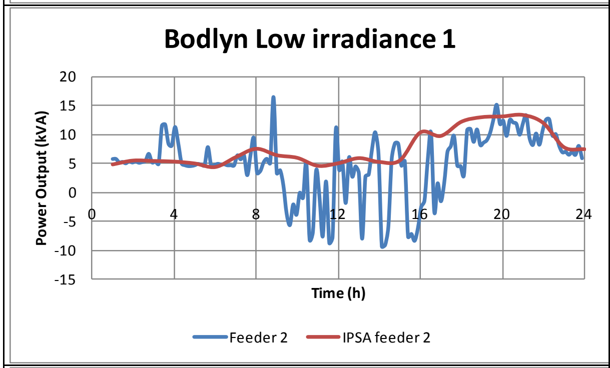
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1

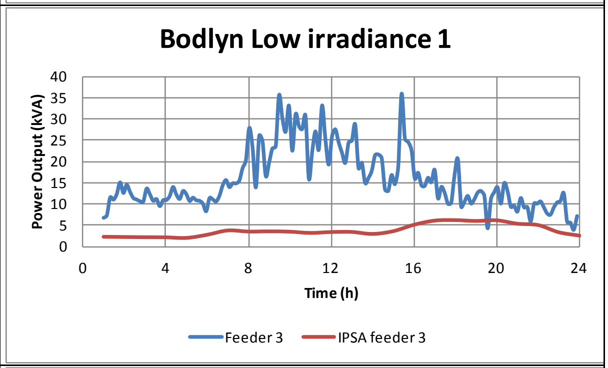

Hampden Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3


Hampden Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4


Hampden Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5


Bodlyn Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 1
IPSA feeder 1


Bodlyn Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 2
IPSA feeder 2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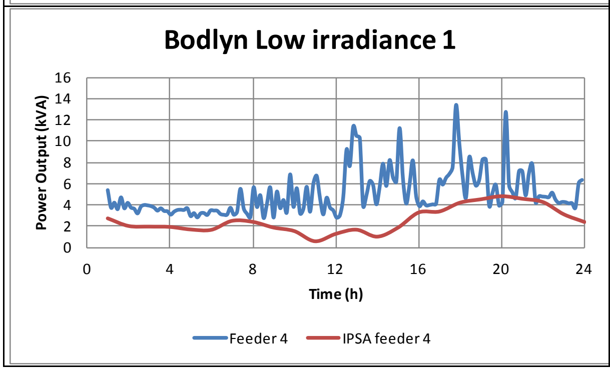
Power Output (kVA)
Time (h)
Feeder 3
IPSA feeder 3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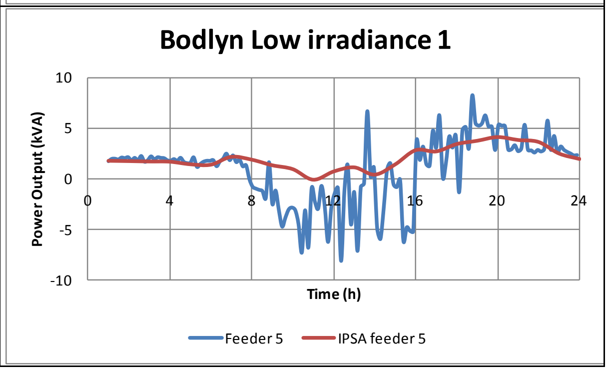
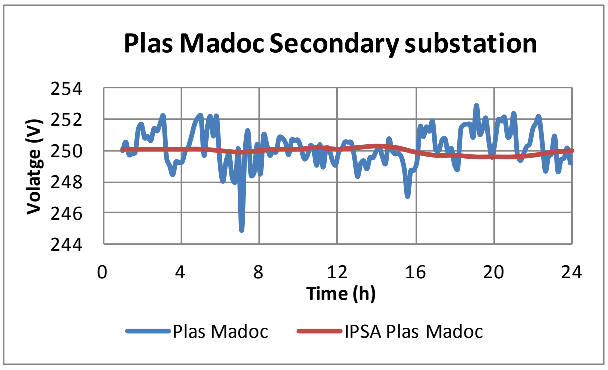
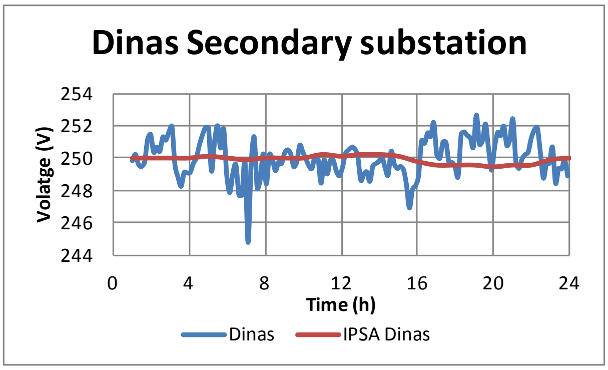
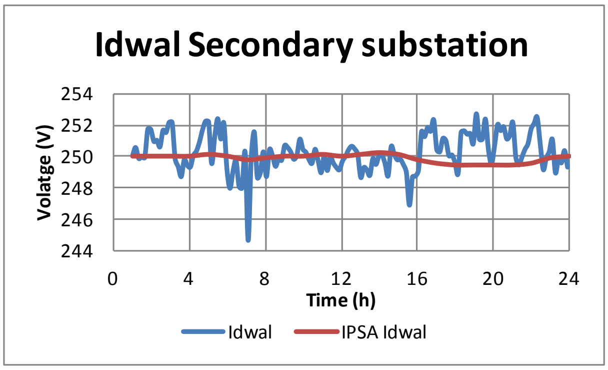
Power Output (kVA)
Time (h)
Feeder 4
IPSA feeder 4


Bodlyn Low irradiance 1
Power Output (kVA)
Time (h)
Feeder 5
IPSA feeder 5

Appendix C - Validation of the Modelling Approach - Voltage Profile

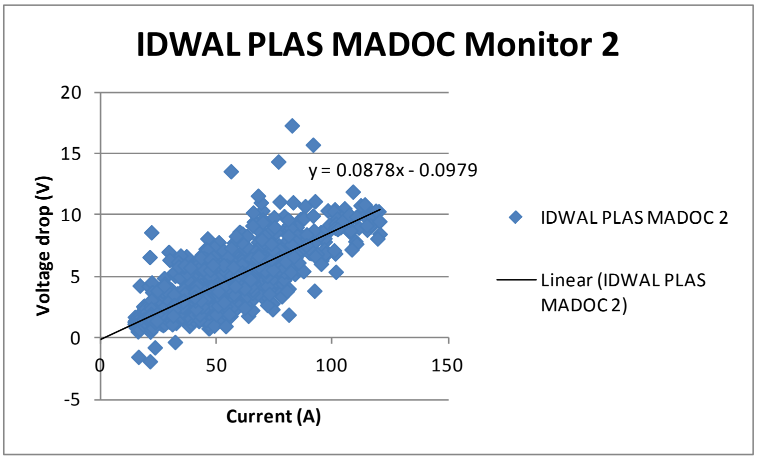


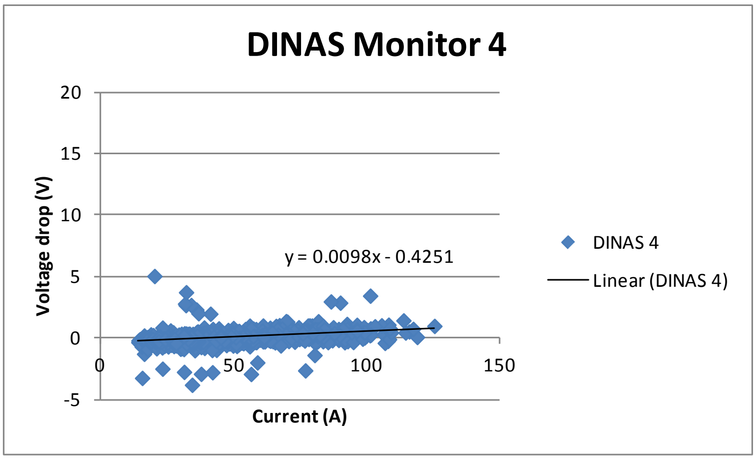


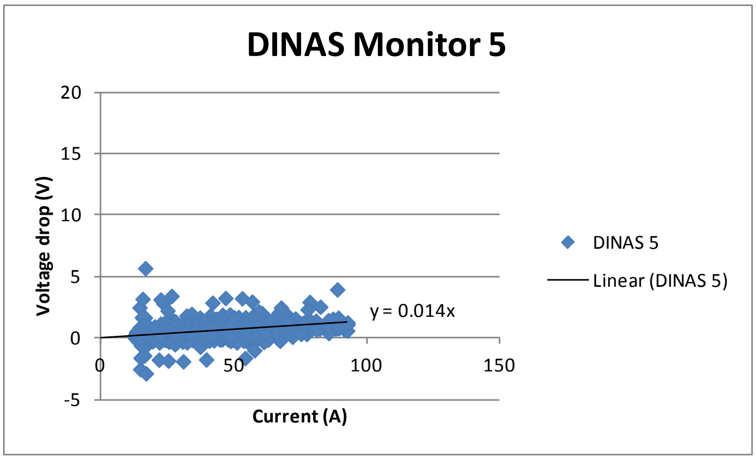


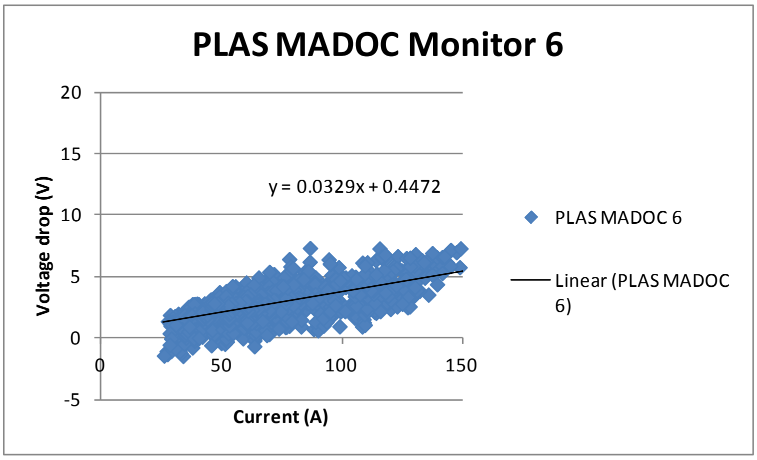
Appendix D - LV Customer Voltage Measurements

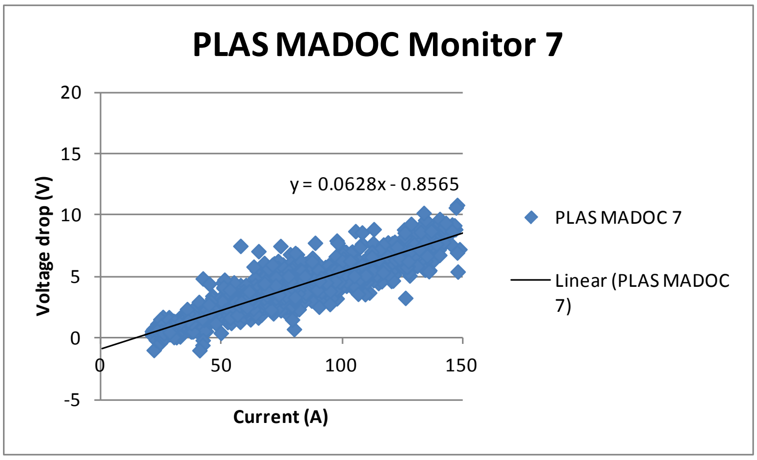
The plots below show single phase LV voltage drop (V) at the customer monitoring location (referencing corresponding single phase LV voltage measured at the secondary substation), plotted against corresponding single phase LV feeder current (A) measured at the secondary substation, unless noted otherwise.

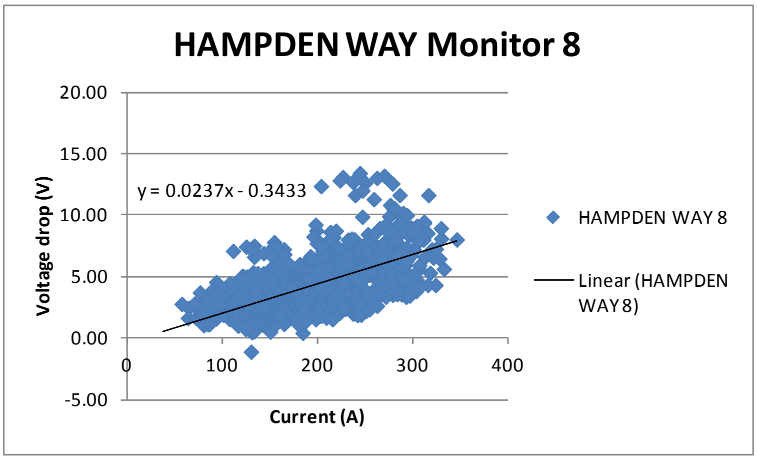




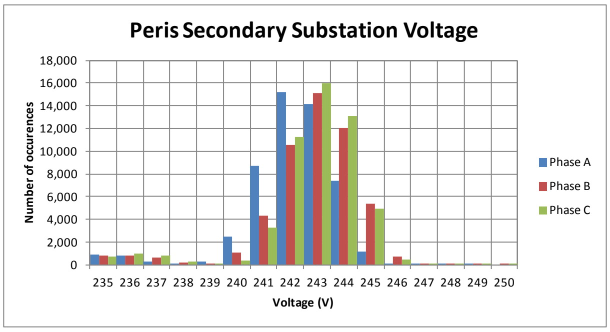


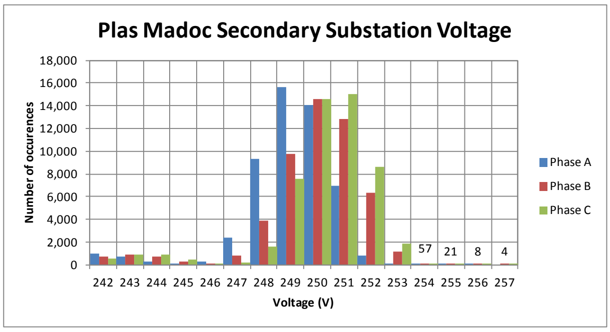

PLAS MADOC Monitor 6
y = 0.0329x + 0.4472
Voltage drop (V)
Current (A)
PLAS MADOC 6
Linear (PLAS MADOC 6)

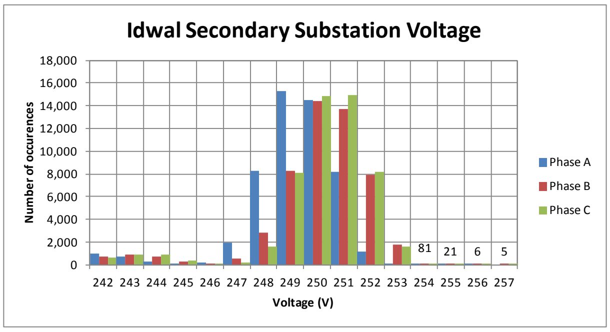

PLAS MADOC Monitor 7
y = 0.0628x - 0.8565
Voltage drop (V)
Current (A)
PLAS MADOC 7
Linear (PLAS MADOC 7)

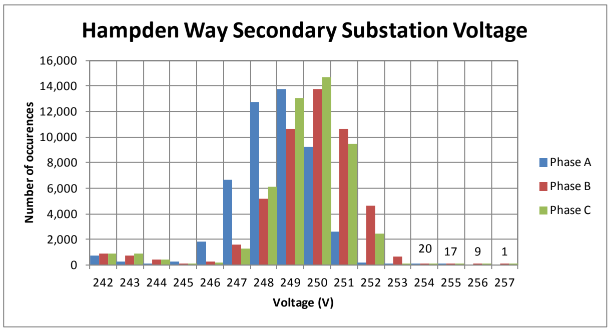

HAMPDEN WAY Monitor 8
y = 0.0237x - 0.3433
Voltage drop (V)
Current (A)
HAMPDEN WAY 8
Linear (HAMPDEN WAY 8)

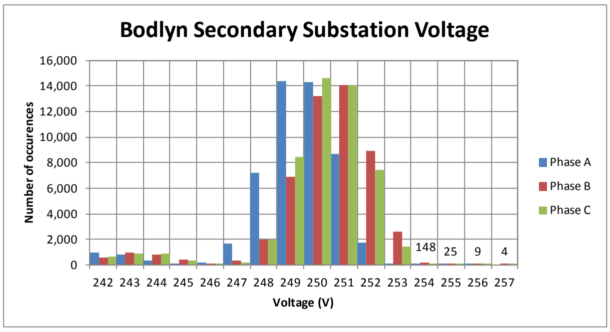
Appendix E – Voltage Probability Distributions











Appendix F. Background

Flexible Networks for a Low Carbon Future

'Flexible Networks for a Low Carbon Future' is a Scottish Power Energy Networks (SPEN) Tier 2 Low Carbon Network Fund (LCNF) trial project. LCNF Tier 2 projects are awarded annually on a competitive basis to UK Distribution Network Operators (DNO) and are administered through Ofgem.

Flexible Networks will provide the DNOs with economic, DNO-led solutions to enhance the capability of the networks as heat and transport are increasingly de-carbonised resulting in an increase in electricity use. Crucially, these solutions will be capable of being quickly implemented and will help to ensure that the networks do not impede the transition to a low carbon future.

Solutions are needed that can:

- Determine more accurately the capacity headroom while maintaining licence obligations,
- Allow that headroom to be exploited in a safe, reliable and cost-effective manner, and,
- Provide incremental increases in headroom in a timely and cost-effective manner.

Flexible Networks will aim to provide a 20% increase in network capacity through a number of innovative measures. This will enable more customers to make the transition to new low carbon generation and demand technologies. The project involves enhanced monitoring and analysis to better understand and improve existing performance, and the deployment of novel technology for improved network operation and capacity - including dynamic asset rating, network automation, voltage regulation and energy efficiency measures.

To ensure representative and replicable outputs, the project involves three carefully selected trial areas across SP Distribution and SP Manweb licence areas, covering various network topology and customer demographics: St Andrews in Scotland, Wrexham in Wales and Whitchurch in England, see Figure F-1.

The three trial areas have known capacity issues and consequently offer a real opportunity to analyse and implement alternative flexible solutions to network reinforcement. All three sites have different but representative characteristics and customer demographics, and are similar in that they have near-term constraints due to increasing demand and an uptake of low carbon technology. The rapid nature of these changes both imposes a requirement, but also provides the opportunity to trial solutions that are faster and more cost-effective to implement than traditional reinforcement.

Figure F-1 Trial Area Location Map

The specific issues facing these three locations are mirrored across the UK electricity distribution network, and this project will be able to provide generic solutions and recommendations to address these.

Improved characterisation of PV

As the uptake of embedded PV generation increases across the UK, particularly with clustering for certain socio-economic groups, DNOs must consider the impact of high numbers of PV connections on network security and quality. Flexible Networks is exploring the value of focussed secondary substation monitoring, in parallel with primary substation monitoring, to increase capacity headroom and better understand network characteristics and behaviour for high-density PV connections.

The impact of high-density PV generation is assessed through monitoring of areas with differing levels of PV generation. A focussed "cascade" approach is used, where the measurements are synchronised in time and monitoring equipment is installed from the primary substation down the chain to the customer across several adjacent LV networks. This is intended to maximise learning and provide insights for improved system modelling and long-term monitoring requirements.

As the networks become more dynamic in nature due to both LCT demand and embedded generation behaviour, network planners will need more sophisticated Decision Support tools to cope. These need to be able to provide appropriate guidance based on a representation of PV generation characteristics, where limited or detailed monitoring data available.

Ruabon network trial site

Ruabon is a small village located in the borough of Wrexham, Wales, with a population of approximately 2500. The Ruabon 33/11 kV system consists of one 10 MVA 33/11 kV primary transformer which supplies the 11 kV distribution network. The 11kV circuits from this primary substation are operated radially but with the facility to be interconnected to neighbouring networks supplied from Llangollen, Johnstown, Monsanto and Maelor Creamery following a system outage. The Ruabon LV network is operated radially but with the facility to be interconnected in some areas.

Wrexham Borough Council applied for 3000 embedded PV connections for its social housing programme. A reported total of 325 kW of PV generation is now connected in the Ruabon LV network with a further 100 kW on hold due to concerns about voltage rise. Ruabon is hence an ideal location to study the behaviour of clustered PV generation on the LV network with the aim of enabling the connection of all social housing PV by Wrexham Borough Council.