SP ENERGY NETWORKS

Flexible Networks
for a Low Carbon Future

Case Study

Multiple Domestic PV Connections

Ruabon Trial Area

September 2015

Contents

1 Background

This case study looks at applying the "Flexible Networks" Smart Grid network interventions to the Ruabon distribution network in order to increase the amount of PV generation that can be connected to the network. The part of the Ruabon distribution network assessed in this case study is primarily residential, and many of the domestic properties are council-owned. The combination of managing a large housing stock and having social responsibilities in terms of fuel poverty and environmental sustainability has led the local council to take a proactive approach in the management of their tenants energy use. As part of their strategy, the council has installed solar PV on the roofs of many of their properties. This has led to the connection of large "clusters" of PV installations to the local distribution network, sufficient to cause significant voltage rise and therefore potentially affecting the power quality of other, non-PV connected, customers.

The local council is one of the most progressive in Wales and it is clear that as other councils become aware of the possibilities for solar PV generation, they will likely follow their example. This Case Study therefore aims to set out some guidance in terms of applying the SPEN "Flexible Networks" Smart Grid network interventions to multiple PV connections within typical residential housing estates.

2 Our Initial Proposal

This project investigated methods for managing the impact of retro-fitting large clusters of domestic PV installations to existing LV networks on a typical residential housing estate, with the aim of enabling 20% more PV to be connected than would otherwise have been possible using our current, more conventional network design philosophy.

Our approach was to use network monitoring as an enabler to facilitate a more active approach to the design and operation of the network. This included improved network analysis techniques and voltage optimisation. These are discussed briefly below.

2.1 Enhanced Network Monitoring

Traditionally, secondary substations in the UK distribution networks have very basic maximum demand meters that do not provide any information on the timing, duration, or frequency of the peak demand. As these require manual reading, the data is gathered infrequently and because of this has limited use for network planning. As network planning and reinforcement decisions require a good characterisation of the network and the connected generation and demand profiles, a lack of good quality data means that conservative assumptions must be made to safeguard the network and customers.

Part of the innovation in this project, has been to develop a monitoring programme led by the network planning and operational needs, taking due consideration of the relatively low cost margins required by secondary distribution network applications. To this end, secondary substation monitors have been installed throughout the Ruabon area.

The monitoring specification used for Flexible Networks was as shown in Table 1.

Table 1 Primary and Secondary Substations

Variable	Resolution
RMS phase voltage	1 min snapshot
RMS phase current	10 min snapshot
Supply Frequency	10 min snapshot
Power factor (each phase), per measured current	10 min snapshot
Real, reactive and apparent power (per measured current)	10 min average values
THD (per measured phase voltage)	Last 10 min period value

Measurements are logged in a remote iHost server. The data is available to view over a web interface and for download by SPEN and our project partners for more detailed analysis.

2.2 Improved Network Analysis Techniques

It is critical to develop improved network planning and operations tools and processes to facilitate a future flexible network and make best use of existing assets. These tools will provide a greater understanding of network behaviour and enable a more appropriate response to load growth. In particular, the timing and rate of growth of new demand associated with increasing amounts of low carbon technology including PV, electric vehicles and heat pumps are uncertain and risks must be adequately managed, not least those of

- temporary overloading of the network (leading to accelerated plant aging),
- voltage excursions (affecting customers' power quality), or,
- severe overloading leading to load disconnection (affecting customers' quality of supply).

Whilst network reinforcement can alleviate these risks, such an action introduces the risk of stranded assets in the event that forecasts of demand growth do not materialise.

Detailed network monitoring is a key enabler for the future Smart Grid. Whilst detailed network monitoring does not create any additional network capacity directly, the analysis of the data can assist in making better use of existing assets. It is the first step towards better risk management, being more "risk aware", rather than simply "risk averse".

2.3 Voltage Optimisation

Voltage optimisation is considered to be one of the new tools available in the "Flexible Networks" toolbox to release network capacity in place of conventional network reinforcement.

Voltage optimisation has the potential to both facilitate the greater uptake of embedded generation as well as reduce customer energy consumption. The business & economic case for better management of network voltages has been assessed through a network voltage reduction trial undertaken at Ruabon.

3 Applying the Smart Grid Solutions to Ruabon

The voltage can approach and potentially exceed statutory limits when high PV uptake is present, especially when the uptake is "clustered", i.e. concentrated in a particular area, as tends to happen in practice, especially when the installations are related to social housing or council housing type projects.

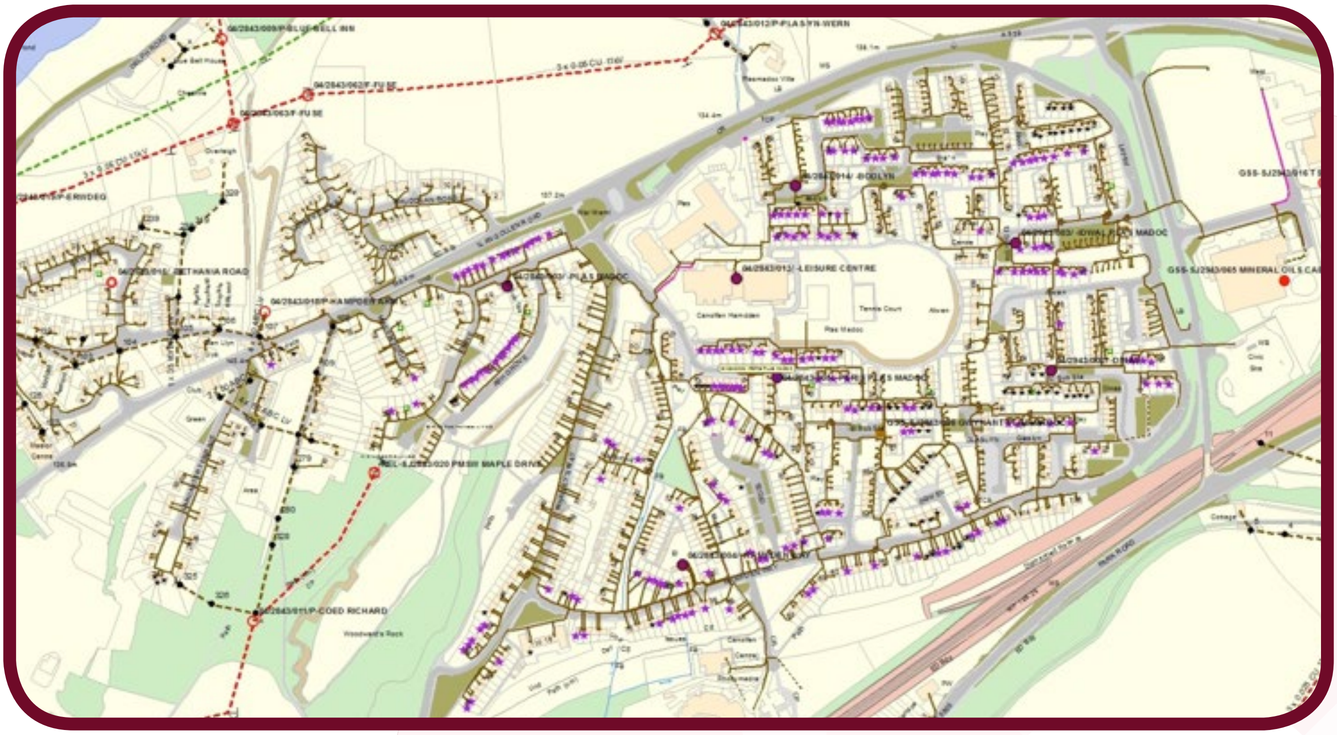

Figure 1: PV Installations at Ruabon

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. This was obtained through analysis and interpretation of the detailed LV network monitoring available from the Flexible Networks trial sites and development of analysis tools and more general learning such as generic "rules-of-thumb" to support this process. This work has led to an improved approach to characterising the behaviour of

i) embedded PV generation and
ii) residential load

which has led to a more effective assessment of network capacity headroom.

3 Applying the Smart Grid Solutions to Ruabon

[continued]

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.

- A generic summer profile for a residential housing estate was defined, as shown in Figure 2. A peak figure of 555W per customer was derived for Ruabon and this has been generalised to **500W per customer** as a more general rule of thumb.
- A generic mid-day (11am) minimum demand was defined for residential domestic housing estates of **60%** of the peak. 333W per customer was derived for the specific Ruabon trial site and this has been generalised to **300W per customer** as a more general rule of thumb.
- 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.

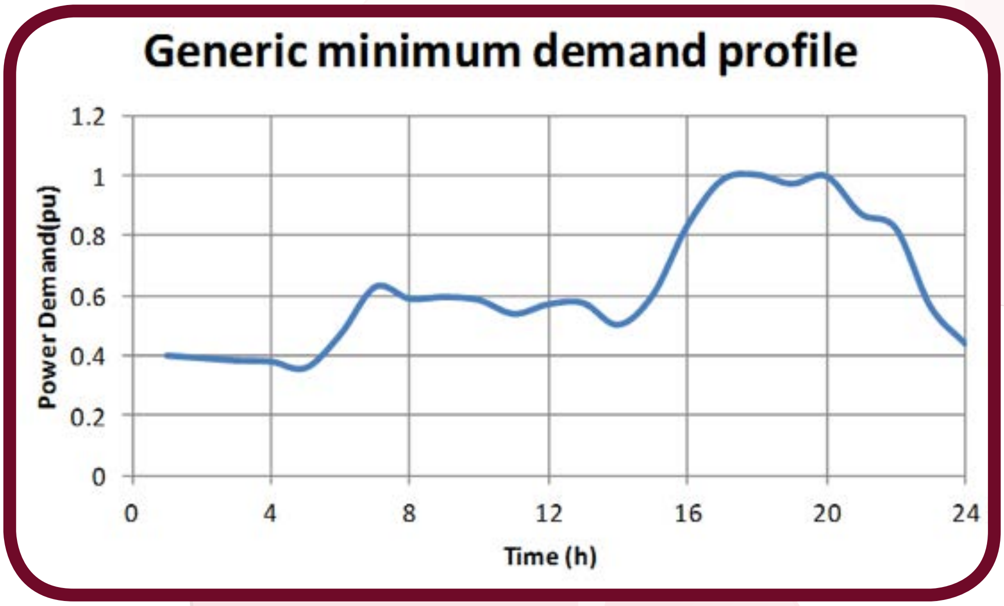

Figure 2: Generic Summer Load Profile

3.1 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 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 diversity. Furthermore, as PV generation uptake approaches **50% of LV customers**, on typical residential LV feeders, generation phase imbalance is likely to lead to only marginal overvoltages, if present at all.

Greater consideration of phase imbalance will be required for rural networks with PV generation uptake. Note that rural LV networks were not analysed as part of this case study.

3.2 Improved Characterisation of Generation Headroom at Ruabon

Application of this approach enabled us to identify further generation capacity headroom at the Flexible Networks trial site of Ruabon.

Approved and currently non-approved PV generation (an additional 33%) was modelled for the Ruabon LV network to give a total of 425kW of PV generation at rated capacity. A further 20% of PV generation volumes by customer can be connected (giving 510kW total), assuming it is distributed across the LV network consistent with existing clustering patterns. This equates to an average uptake of 35% of customers compared to 21% of customers approved initially, for an average installed capacity of a domestic solar photovoltaic of 1.6kW. Maximum PV generation uptake in this case is 60% of customers at one of the secondary substations.

This may be a conservative assumption as it does not consider that future PV uptake can occur on LV feeders with no existing PV generation connected (although this may be due to unfavourable street/house orientation). Whilst it also does not consider the possibility of additional PV clustering on LV feeders with high uptake already where network overvoltages will be experienced first, these are already starting to approach customer saturation at 30% additional PV.

Statutory voltage limits were not exceeded until approximately 30% additional PV generation (average uptake of 38% of customers) was connected in the model at which point some short feeders in the LV network were becoming close to saturated with PV generation due to existing clustering.

Voltage management through control of the primary transformer voltage relay to reduce HV busbar voltage by 3% and 6% or -2.5% at LV busbars with secondary transformer off line tap changer can provide significant additional low-cost incremental generation capacity headroom for the LV network. This was analysed partially for the Ruabon case study. However, further consideration of the following should be made before general rollout could be considered;

- Typical network winter loading and corresponding voltage drop (suitability for a permanent or seasonal voltage set point change or use of line drop compensation algorithms that are available in some voltage relays)
- HV and LV network meshing and backfeeding arrangements to avoid any current circulation due to voltage mismatch.
- Potential impact on HV connected customers and HV connected generation.

3.3 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/m2 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/m2 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/m2 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. This has implications for the connection of generation at HV particularly if on the same feeder that is 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 over the same period, so we would expect the voltage at customer terminals to be within statutory limits all of the time. Voltage excursions may be due to sudden loss of load with a network fault or voltage change further up the network (HV network).

In terms of wider LV network voltage management partly to enable further PV uptake and more generally reduce existing voltages, there several options to consider:

i) tapping down the voltage for all secondary transformers by 2.5%

ii) (seasonal) voltage reduction by 3% at the primary.

iii) 2% reduction in standard target voltage at the primary substation

There is generally about 8% voltage legroom during typical high demand conditions based on LV customer voltage measurements towards the ends of LV feeders in Ruabon.

3.4 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 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 approximately 0.5 – 1.0V of generation capacity headroom available near LV feeder ends to account for such phenomena as customer load variations, generation phase imbalance, and model simplification of demand/generation sources.

A connect-and-manage approach, where voltage management is applied at primary or secondary substation level when voltage excursions due to high PV generation uptake occur, is an alternative solution that can maximise utilisation of available network generation headroom. Also, in future, smart meters should enable voltage measurements to be extracted at key network locations to more actively evaluate and respond to the impact of high embedded PV generation uptake.

4 Lessons Learnt

- Use of detailed irradiance data measured over the summer period to provide an accurate representation of actual PV output. For the LV network studied, 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/m2.
- A generic summer profile was defined. A figure of 555W per customer was derived for the specific Ruabon trial site and this has been generalised to 500W per customer as a more general rule of thumb.
- A generic mid-day (11am) minimum demand was defined for residential domestic housing estates of 60% of the peak. A figure of 333W per customer was derived for the specific Ruabon trial site and this has been generalised to 300W per customer as a more general rule of thumb.

5 Comparison with Original Objectives

The table below shows a comparison of the capacity released by each method

	LV Feeder Level (W/customer)	% increase over base case	Secondary Substation Level (W/customer)	
Base Case	580	—	336	—
Improved Network Analysis	800	+38%	430	+28%
Voltage optimisa-tion	1100	+90%	662	+97%
Improved Network Analysis + Voltage Optimisation	1300	+124%	850	+153%

It can be seen that the initial overall target of 20% has been greatly exceeded.

We have learnt through the implementation in the Ruabon trial area: -

- Improved network analysis techniques have enabled up to 28% more generation headroom capacity to be released, compared with the conventional "fit and forget" approach
- Voltage optimisation has enabled up to 90% more generation headroom capacity to be released (based on a 2% voltage reduction)
- Voltage Optimisation has enabled up to 2% of customer energy efficiency improvements, based on a permanent 2% reduction in nominal network voltage

6 Business Case Update

A financial evaluation has been carried out to determine the benefits that can be obtained for the two methods employed in this case study:

i) Improved network analysis techniques (based on detailed monitoring), and,

ii) Voltage optimisation.

For this evaluation, the unit costs were obtained from indicative quotations from SPEN's approved suppliers and provided from SPEN's Unit Cost Manual document.

6.1 Trial Project Costs and Rollout (Method) Costs

The following costs are taken from the cost benefit analysis (CBA) included in the close down documentation and illustrate the share of the project cost for the Wrexham trial site as well as the generic method rollout cost for future implementation.

Technique	Trial Project Cost (£k)	Rollout (Method) Cost (£k)
Monitoring	583	306
Voltage Optimisation	57	31
Transformer dynamic rating	54	—
33kV OHL dynamic rating	39	—
Voltage regulator	82	—
Energy Efficiency	84	—
Other project activities	429	—
Total	1,328	337

6.2 Net Benefits

In comparison to the original submission business case; at Wrexham, traditional methods would require a number of additional 11kV/LV substations to be installed across the network. It can be particularly difficult to establish these substations in mature housing developments where spare land is generally unavailable. Extensive cable works would also be required to integrate these new substations onto the network. This would take approximately 1-2 years to complete and is budgeted at a minimum of **£1.2m**.

Our figures indicate a future roll-out cost for a similar site using these interventions would be approximately **£337k**. Compared to the Base Case costs of **£1.2M**, this represents a net benefit of **£991K**.

Details of the full CBA for both methods is given in reports "Flexible Networks Project Cost Benefit Analysis – Enhanced Network Monitoring" and "Flexible Networks Project Cost Benefit Analysis – Voltage Optimisation".

6.3 Applying the Smart Grid Solution to Other Areas

The key output from the project has been the revision and validation of the previous draft company policy for the connection of clusters of domestic PV generation. The previous draft policy was based on desk-top studies and network models created before the connection of PV. As such, many assumptions had to be made about the existing demand on the network and the PV characteristics. The additional monitoring installed as part of this project allowed the true demand on the network to be ascertained.

Finally, it is recommended that a simple low-cost solar irradiance measurement device is installed in network areas with high PV uptake to enable an accurate characterisation of maximum solar irradiance and solar irradiance distribution.

6.4 Summary of Key Rules of Thumb

- Diversified generation is **90% of total nameplate rating**
- Summer daytime maximum demand (at approximately 6pm) is **500W per customer**
- Summer daytime minimum demand (at approximately 11am) is **300W per customer**