LCN Fund Tier 1 Close out Report

Early learning of LV network impacts from estate PV cluster

Steven Gough

May 2013

LCN Fund Tier 1 Close out Report

1. Executive Summary

This project collected data from a small housing estate in Crickhowel, South Wales, where all the houses have photovoltaic (PV) panels. The key objective was to establish what effect this high density of PV had on low voltage (LV) network, in particular looking the voltages for different sizes of LV main. Monitoring was installed mid feeder and the feeder end for each phase which was complimented with extra data on PV output, tap change data and solar irradiance. The key learning from the project is the voltage is not significantly affected by the LV main impedance or by the PV panels, leading us to recommend revisiting the LV planning assumptions.

2. Project Overview

Early learning of LV network impacts from estate PV cluster project was registered with the LCN Fund in July 2011. The following table outlines the project objectives as laid out in the registration proforma.

Project Title	**Early learning of LV network impacts from estate PV cluster**
Project Background	A new low carbon housing development of some 20 houses has been developed by Melin Homes in Crickhowell, South Wales. The estate features high efficiency houses each equipped with PV. Traditional network studies indicate that voltage limits would be exceeded without an overlay of existing 95sq mm LV cable. The scheme provides a low cost opportunity for early learning of PV voltage impacts and validity of existing design assumptions. Installation of two different size LV cables in parallel to the existing cable, with linking facilities at each end, provides a real life, on load, capability to change the impedance of the feeding LV cable and measure resulting changes in voltage performance.
Scope and objectives	The project seeks to test the accuracy of present modelling through real life voltage and load measurements on one feeder of an LV system The objectives are to seek early data on behaviour of multiple densely populated PV units on a single estate and to test the validity of the traditional network modelling that indicated that no more than 12 units could be accommodated. Such data will benefit modelling with consequential impact on seeking to reduce reinforcement cost for future connection of multiple LV PV installations
Success criteria	• The estate having all PV units installed. • WPD installing the cabling, pillars and monitoring. • Data being captured and analysed. • WPD writing report and sharing with other DNOs

3. Details of the work carried out

Details of what Methods the DNO trialled. The DNO should also describe the trialling methodology that it used.

3.1. Project Background

Western Power Distribution (WPD) has seen a significant increase of domestic PV panels across its license areas which have led to concerns of the impact and potential future implications on LV networks. The design assumptions on the LV network tend to be cautious to ensure reliable network infrastructure. As there is less visibility of the LV network in general, the design assumptions need to take into account of the possibility of issues that may have not been originally envisaged at the time of design. In this project we wanted to understand the potential implications of a high concentration of domestic PV installations on the local feeder.

In particular we wanted to explore what effect the LV main impedance would have on the voltage rise caused by the PV. By gathering the data for various scenarios with different LV mains in service for this estate, we were able to challenge the assumptions currently in use for LV design.

3.2. Project Works

Melin homes had built a housing estate in Crickhowel where they wanted to install PV shortly after building the homes. The LV designer calculated, using his standard tools, that the voltage rise would be above statutory limits and therefore a 300mm^2 cable would need to be installed to replace the existing 95mm^2 cable. We decided to explore what effect replacing the cable would have, and compare this with a scenario where reinforcement was not applied.

To allow us to understand these effects we installed two pillars for the LV main which allows us to select either 95mm^2, 185mm^2 or 300mm^2 cable.

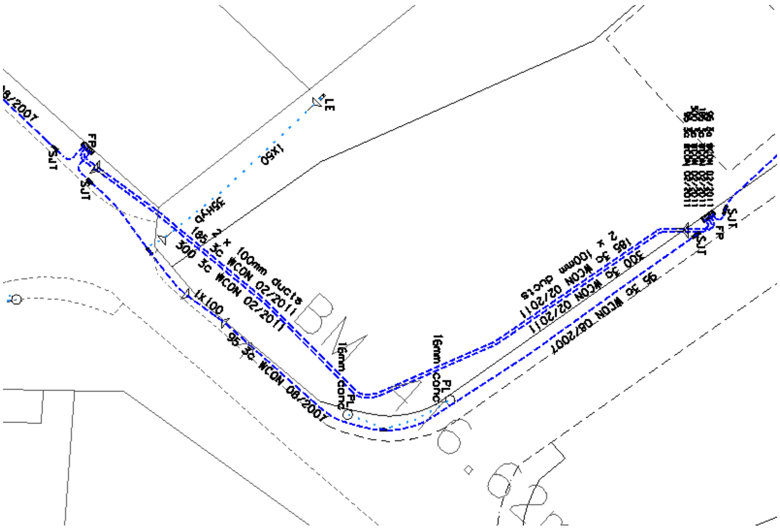

Figure 1 – Cable and cabinet install

The cabinets were standard pavement mounted 3 phase, three feeder cabinets. The cables were selected by inserting or removing links into the cabinets. To avoid any interruptions to the customers supply each cable was put in parallel briefly while changing over. The entire feeder length is 223m and we overlaid 60m of this with the other two cable types.

Initially we installed two PM3000 power quality meters at each of the cabinets, however the values were very similar. Subsequently we removed one unit just leaving one PM3000 at the cabinet closest the domestic homes.

The PM3000 was selected as it is widely used by the staff in the local office for data collection purposes. The PM3000 is a ruggedized 3 phase power quality meter which can measure voltage, current, real and reactive power, harmonics and flicker. The units were readily available from the local depots and local staff had the relevant software on their laptops. They are Class 1 devices and can record down to very fast intervals, adapting to the rate of change of the signal using an algorithm. The disadvantage is that they have no communications module so the data needed to be downloaded every two weeks by the local planner when the local memory became full.

Several months after the project had been running we decided to install single phase PM1000s at 3 customer's meter boxes which were at the end of the feeder on each of the three phases. This allowed us to see the feeder end voltage and compare this to the cabinet, but also a proxy for the PV export. The data which came back from the feeder ends was very informative so further PV meters were installed on three houses with varying PV panel orientations.

The data was collected from initially from February 2012 with the main body of data being collected from May 2012 onwards at the pillar and feeder ends. This meant we had data through the summer months at the four main locations. The PV meters were more difficult to install and set up so data only started being collected from November. To allow us to approximate the PV output of the site we used post code specific irradiance data for the summer months. Additional data was collected on the time of the tap changes on the local Primary Substation. The Distribution Substation at the site was the first on the 11kV feeder, so the voltage was highly affected by taps at the Primary Substation. This data allowed us attribute any large voltage step changes to the tap changer rather than local effects.

The data we collected was the three phase voltage and the real and reactive power from the PM1000s and PM3000. The PV data was kWh data of output from the PV. All of this data was used in the analysis however it was the voltage with relation to PV export where the key conclusions were drawn. The vast majority of this data was recorded from April 2012 through to February 2013. The only data which was used prior to this was background data measured at the pillars.

We were naturally very cautious when changing the cables from 300mm^2 down to the other sizes. We ensured that we had plenty of background 300mm^2 data before deciding to reduce the size of the cable. We analysed the absolute peak, the statutory 10 minute average peak and the time of day the peaks were occurring. The LV planner had designed network for the homes without the PV so we knew that the thermal capabilities and voltage drop of the load were well within limits. It was only the voltage rise from the PV which was the concerning factor. From the initial data (please see E.ON New Build & Technology's report Experiences with Building-Mounted Photovoltaics in Appendix A) it was easy to see that the voltages were not remotely close to the statuary limits. Although the occasional instantaneous peak was over the 253V limit, these were invariably late at night when load was low, rather than when the PV output was high. We did the same analysis between the change between 185mm^2 and 95mm^2 too. The new smaller cable was in service for a few days before changing back to the higher size again to analyse the voltages and only utilised if voltages were well below the statutory limits.

Cable	Impedance (ohm/km)	Impedance for 60m (ohm)	Summer cyclic rating (A)	Spring/autumn cyclic rating (A)	Winter cyclic rating (A)
95 SAC EPR	0.427011647	0.025621	273	242	308
185 SAC EPR	0.236080166	0.01416481	399	426	452
300 SAC EPR	0.162989488	0.009779369	526	561	598

4. The outcomes of the Project

Comprehensive details of the project's outcomes are to be reported. Where quantitative data is available to describe these outcomes it should be included in the report. Wherever possible, the performance improvement attributable to the Project should be described. If the TRL of the Method has changed as a result of the Trial this should be reported.

This trial has allowed us to explore what impact cable impedance has on voltage rise due to domestic PV. We have collected a large amount of high resolution data which has allowed us to conclude that in this case the impedance of the cable has negligible effect on the voltage. The other data collected has given us clearer understanding of how voltage at the feeder ends relates to the LV main during different times of day and scenarios included properties net exporting from PV. Also a view of how installed capacity can be affected by orientation of PV panel and its efficiency meaning that the tangible effect on the distribution network is less than initially expected.

All data from the project was collated in E.ON New Build & Technology's report Experiences with Building-Mounted Photovoltaics which explored and concluded the findings in a statically robust way.

5. Performance compared to the original Project aims, objectives and success criteria

Details of whether and how the Project helped solve the distribution issue described in the First Tier LCN Project Registration Pro-forma.

Details of how the Project performed relative to its aims, objectives and success criteria.

The registration proforma outlined the following core objectives for the project.

- The estate having all PV units installed.
- WPD installing the cabling, pillars and monitoring.
- Data being captured and analysed.
- WPD writing report and sharing with other DNOs

The first two criteria were completed very early on in the project. To allow the PV units to be installed the larger 300mm^2 cable needed to be laid under current design policy. This was carried out as connection works to allow Melin homes to install its PV panels. However rather than install the least cost scheme WPD installed the additional pillars with the selectable alternative cables: both 185mm^2 and 300mm^2 in addition to the existing 95mm^2 cable. The additional cost of these works were covered by the project.

Monitoring in the form of PM3000s, were added shortly after the PV panels were installed by the developer, eventually including the feeder end monitors. In addition to this PV meters were installed to compliment the data later on in the project. Tap change indication and solar irradiance data was also collected to help analysis.

The data was collected consistently through the key times although a few two week blocks were missed during the less critical times. This data was briefly analysed when it was initially uploaded to ensure that the voltages were within limits and to check if there were any unusual patterns. Then at the end of the project all of the data was collated and analysed in a statically robust way to produce the Experiences with Building-Mounted Photovoltaics in Appendix A.

This report, along with the findings from the data in the data analysis study, will be submitted to Ofgem and made available through both the Ofgem and WPD Innovation websites. In addition the learning from this project will feed into the LV Templates Tier 2 project and will be shared alongside its findings as part of its wider dissemination.

In Summary all the objectives have been achieved and in some cases expanded on from the original scoping for the project.

6. Required modifications to the planned approach during the course of the Project

The DNO should state any changes to its planned methodology and describe why the planned approach proved to be inappropriate.

The scope remained broadly unchanged with the exception of more data being collected from more locations than originally planned. With this data we were able to do more in depth analysis and therefore draw more useful conclusions in comparison from the fairly basic, original set up of the project. This allowed us to reap more benefits from the analysis without increasing the cost above what was budgeted for by using already available monitoring kit from the local depots.

7. Significant variance in expected costs and benefits

The DNO should describe if any parts of the Project ended up costing more or less than expected (+/- 10 per cent). In relevant cases, the DNO can link the cost changes to the section on required modifications to the planned approach.

If costs were different to what the DNO expected, the DNO should provide details of why this was the case.

The DNO should discuss whether the benefits of the Project matched the DNO's expectations. This should include any changes to incentive payments and any changes to expected savings in revenue allowed for in the DPCR5 settlement.

The project has been delivered on budget with more than the planned objectives met. The key benefits from the project are twofold. Firstly the high resolution data can be used help inform specific instances of high propagation of domestic solar and feed directly into the LV templates project. Secondly the learning from the analysis will be able to inform changes to the LV design assumption to reduce the installation of oversized cables for embedded domestic generation. Also the monitoring equipment, which is capable to high accuracy voltage, current, power and power quality measurements, is portable and can be used for other projects going forward.

Equipment: Monitoring kit, cables and cabinets	£7.7k
Labour: Installation of cabinets	£3.5k
Contractors: Laying the cables	£5k
Future Networks Team Project Management	£2k
Total	**£18k**
Total to be claimed through LCNF	£16.2k
DNO Contribution	£1.8k

8. Lessons learnt for future Projects

Recommendations on how the outcome of the Project could be exploited further. This may include recommendations of what form of trialling will be required to move the Method to the next TRL. The DNO should also state if the Project discovered significant problems with the trialled Methods. The DNO should comment on the likelihood that the Method will be deployed on a large scale in future. The DNO should discuss the effectiveness of any contractual Methods that formed part of the Project

The key lessons learnt, and how they were derived, are documented in E.ON New Build & Technology's report Experiences with Building-Mounted Photovoltaics included in Appendix A.

As concluded in Experiences with Building-Mounted Photovoltaics, the voltage seems to be unaffected from the choice of cable. The differences in impedance seem not to be large enough to cause concern. The fact that the original LV design prior to the PV was installed indicated that

95mm^2 cable would be sufficient and the peak highest voltages were seem while PV output was minimal suggests the approach for modelling embedded domestic generation ought to be reviewed. The current methodology predicted significantly higher voltages which have not materialised. This is probably influenced by the relatively small changes in impedance of the circuit, just over 25% of the cable was overlaid with the alternative cable choices while the overall feeder impedance is dominated by the transformer.

When the PV units were installed a maximum PV output of 37.8kW was calculated, with 10% of peak demand assumed, for the net export used in voltage rise calculations. This assumption seems sensible as the efficiency of the PV panels were not known and their maximum export was likely to coincide with days of minimum demand. However with the recorded data it is clear that PV outputs did not reach this level, the maximum export actually only reached 29.8kW suggesting that a PV efficiency or diversity factor could be implemented. If, for instance, a value of 30kW was used for the voltage rise calculation rather than 37.8kW then a similar cable size to the existing one would have been selected.

Also, as noted from the Experiences with Building-Mounted Photovoltaics, the PV has little direct influence to the voltage at the feeder level although there is some increase of the average voltage at the feeder ends. This being said, it is still a long way short of the statutory limits so it is not concerning. The voltage looks to be driven from the primary substation's voltage which at its extremes is dominated by low demand. This particular substation is the first distribution substation along the 11kV feeder from the primary substation so this effect is even more noticeable. This also explains the generally high voltages which were noted. In this area of Wales, the 11kV feeders are typically long, therefore the voltage at the primary substations are kept high to ensure that the customers at the feeder ends are within the statutory lower limit at peak demand.

The solar PV data gives a good picture on how variable the output from the PV panels is. This is particularly highlighted by the significant difference between House C and D which are adjacent but have large differences in output. It is worth investigating this further across a wider sample of houses, this could be implemented as a DNO applied PV efficiency factor and be applied to all domestic PV from its installed capacity. This would allow LV planners to take a more realistic view of the PV output similar to how diversity factors are applied to load. A factor like this would also take into account the morning or evening bias which is observable from the data caused by the panel's orientation.

Other than the learning directly from the data there were a few other parts of learning from the implementation of the project. From a customer engagement perspective, face to face discussion with customers proved successful when arranging the installation of PM1000 at customer's houses. Conversely when we tried to remotely arrange appointments to install the PV meters, it was a lot more difficult to arrange a time and it took several attempts to actually install the meter. The local contact and immediacy of getting the monitoring kit in was a far better approach.

Another noteworthy aspect is the advantages and disadvantages of manually downloaded data. The disadvantage is clear. It is easy to miss slots and requires being a lot more proactive and therefore more of a burden to the project. However the fact that it was a more proactive approach meant the data was analysed at high level as it was downloaded making it easier to keep abreast of the key learning in real time.

Finally once we got to the end of the data recording phase we needed to collate the data from several different sources which were not consistent due to differing recording systems and inconsistent time stamps. Bringing together all this data meant some of the data was disregarded if there were not corresponding parts but this was a time consuming process. It is therefore very important to have as much corresponding data being recorded at the monitoring stage to try avoiding this issue at the analysis stage.

9. Planned implementation

Details on whether and how the DNO plans to modify its Distribution System based on learning from the Project. If the Method is not ready to be implemented, the DNO should explain what needs to happen before the Method can be implemented. The DNO can break down the requirements into actions required by DNOs and actions required by non-DNO parties.

The learning will feed directly into the learning for LV Templates on the area specifically looking at the LV effects of high propagation of PV. Equally from the basis of these findings we can reassess the assumptions being used in LV design for embedded generators and how voltage rise calculations are being carried out. Currently we assume that the minimum day time demand on an LV circuit feeding a significant number of domestic customers is approximately 20% of the maximum load. We also assume the maximum output of a PV system is 100% of its rating and that there is no diversity between different PV systems connected to the same LV circuit. These assumptions will be reviewed and amended (if appropriate) in light of the findings of this project and the LV Templates project.

This data is being incorporated into LV templates to give a much sharper focus on domestic generation. The data will also allow the key settings in WinDebut, that influence the PV assumptions and the load factors, to be adjusted in light of the data collected in this project. The current version of WinDebut used by WPD does not specifically model generation however techniques have been developed to allow the impact of generation to be assessed. The assumptions that are currently when employing these techniques are described above.

WPD is currently working with EA Technology to develop a new version of WinDebut that models different generator types, including PV. It is expected that we will have a working version of this software by the end of July. This version of WinDebut will include a standard PV profile and also use a scaling factor that is used to amend the customer load profiles to take account of periods of minimum demand. This report and the output from the LV Templates project will be used to refine the PV profile and to determine an appropriate scaling factors.

Going forward it may also be possible to specify separate customer profiles for minimum demand and to apply some diversity between generators of the same type, however, the software development work that would allow this has not been initiated yet. We intend to do this once current developments listed above have been completed.

10. Facilitate Replication

Details on the knowledge and products/services required to replicate the outcomes of the project. The DNO should include details of ownership and how to access, the relevant IPR for each item listed.

The key learning and output from this project is contained in this close out report and its appendix. It is not intended that this project will need to be replicated however the learning from the project will be available through WinDebut from EA Technology.

11. Appendix A

Please see subsequent pages.

E.ON New Build & Technology

E.ON New Build & Technology Limited, Technology Centre, Ratcliffe on Soar, Nottinghamshire, NG11 0EE T+44 (0) 2476 192900 F+44 (0) 115 902 4012 entcommunications@eon.com www.eon.com/technology

COMMERCIAL IN CONFIDENCE

ENT/13/TEP/EN/624/R Revision 1
Job No: 2122.C30395.001
May 2013

EXPERIENCES WITH BUILDING-MOUNTED PHOTOVOLTAICS
prepared for
MR R HEY, INNOVATION MANAGER
WESTERN POWER DISTRIBUTION
by
P D Belben

SUMMARY

On a housing estate in Crickhowell, Powys, fitted with photovoltaic (PV) arrays on each house, WPD have collected readings of voltage, current and derived quantities for most of the period from 20th February 2012 to 4th April 2013. At times during this period the feeder supplying the estate has been variously configured as a 300 mm², a 185 mm² and a 95 mm² cable.

This study examines the data to explore the effect of the choice of cable on voltages, and the effect of the PV on demand curves, and hence on the requirements for serving the estate.

It concludes that the effect of the cable on voltage is much smaller than the effect of external conditions. The 95 mm² cable increases the range of voltage experienced, but the 185 mm² and 300 mm² cables are practically indistinguishable.

Measured output of PV arrays is available for selected houses, but not for the range of orientations desired. If the PV output is instead calculated by comparing net demand with a standard curve, the orientation of the PV is evident in some cases. In others, however, the load curve does not follow this pattern. For the estate as a whole, the load curve follows much more closely the standard curve for the appropriate number of dwellings; superimposed are a PV output curve broadened according to the diversity of orientation, and an approximately constant demand of about 100 W per dwelling. No explanation is found for the constant component.

Prepared by **Approved for publication**

Master copy signed by P D Belben & P A Newton (24/05/2013)

P D Belben
Electrical Networks Engineer

P A Newton
Technical Head
Electrical Analysis

COMMERCIAL IN CONFIDENCE

This report was prepared by E.ON New Build & Technology for Western Power Distribution.

Except as expressly provided for in a relevant contract to which E.ON New Build & Technology is a party; neither E.ON New Build & Technology, nor any person acting on its behalf, provides any express or implied warranty, with respect to the use of any information, method or process disclosed in this document or that such use may not infringe the rights of any third party or assumes any liabilities with respect to the use of, or for damage resulting in any way from the use of, any information, apparatus, method or process disclosed in the document.

Telephone	+44 (0) 2476 192900 (please ask for customer administration)
Fax	+44 (0) 115 902 4001
E-mail	entcustomeradmin@eon.com

© E.ON New Build & Technology Limited 2013

Except as expressly provided for in a relevant contract to which E.ON New Build & Technology is a party; no part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means electronic, mechanical, photocopying, recording or otherwise.

CLIENT DISTRIBUTION LIST

EF	Mr R Hey	Innovation Manager, WPD
EF	Mrs H Sawdon	Innovation Development Support, WPD
EF	Mr S Gough	Western Power Distribution

CONTENTS

1 INTRODUCTION

In order to study the impact of high penetrations of distributed generation (DG), WPD have installed monitoring equipment at a housing estate in Crickhowell, Powys, that has a photovoltaic installation on each house. Voltage, current and other quantities derived from these (including real and reactive power) are monitored at three houses (one connected to each phase) and at the roadside pillar where the feeder to the estate is terminated.

In addition, three cables have been laid in parallel for the feeder (although they are not operated in parallel); this allows the feeder to be studied as a cable of 95 mm², 185 mm² and 300 mm².

Since all the houses in the estate were fitted with photovoltaics soon after construction, no measurements have been taken of the installation without the generation. It is therefore not possible to compare the behaviour of the system with and without it.

1.1 Data

The data were provided by WPD in the form of large CSV files of measurements, and smaller files of other material (including transformer taps). When the measurements had been assembled into a single array, this had more than 400,000 lines, representing samples taken at one-minute intervals between 20th February 2012 and 4th April 2013. Nearly 70% of this period is included in the dataset, but no quantity measured has readings on every line. In general, there is no entry when no reading is available, but there were some spurious readings (mostly zeros) for the voltages at the phase A and B houses on 4th May 2012. All the analysis below has been carried out with these spurious voltage readings deleted.

In order to analyse the daily power curves for the three houses, these were compared with standard load curves from Elexon [1]. The published load profiles include separate curves for winter, spring, summer, high summer and autumn, and for weekdays, Saturdays and Sundays. This multitude of curves was combined into a single curve by taking a weighted average of the different curves, the weight being the number of days in each season/weekday combination for which solar irradiation data were available. The readings for the houses were restricted, in these studies, also to days with solar irradiation data; this is not a perfect match, since each house has some gaps in the record, but it provides a common framework for comparing houses with each other and with the solar data.

2 EXTREMES OF POWER AND VOLTAGE

2.1 Statutory Voltage Limits

The voltage must be within the range 230 V +10% -6%, i.e. 216.2 V to 253.0 V. This applies to the average voltage across ten minutes; since the dataset comprises readings for each minute, a rolling ten-minute average was calculated from the one-minute averages in the data. This was applied wherever there was good data for ten readings on consecutive minutes.

The lowest voltage observed was at the phase A house, where the ten-minute average fell to 228.18 volts during the period 16:45 to 16:55 on 26 January 2013. Nowhere else did the voltage fall below 230 V, so the lower limit is not an issue for this estate.

At the higher end, voltages are closer to the limit; the maxima seem to be associated with two high voltage events, one shortly after midnight on 15th September 2012, and one shortly before 8 am on 4th April 2013, as shown in the following table:

Measurement Point	Highest Voltage	When Occurred
Pillar phase A	249.40 V	2012-09-15 00:11-00:21
Pillar phase B	250.62 V	2013-04-04 07:49-07:59
Pillar phase C	250.55 V	2012-09-15 00:11-00:21
Phase A house	248.92 V	2012-09-15 00:12-00:22
Phase B house	251.22 V	2013-04-04 07:50-08:00
Phase C house	250.51 V	2012-09-15 00:10-00:20

Although the voltage was on no occasion unacceptably high, this housing estate could tolerate or even benefit from a lower voltage. This will, of course, depend on other consumers connected. It is understood that the generally high voltages occur because the distribution transformer is electrically close to the primary substation; if so, it is likely that voltage could be reduced by one tap step (typically 6 V) without ill effect.

2.2 The Effect of the Cable

Although there appears to be little danger of exceeding statutory limits with any cable, these results can be broken down according to which cable was in service at the time. This gives rise to Figure 1.

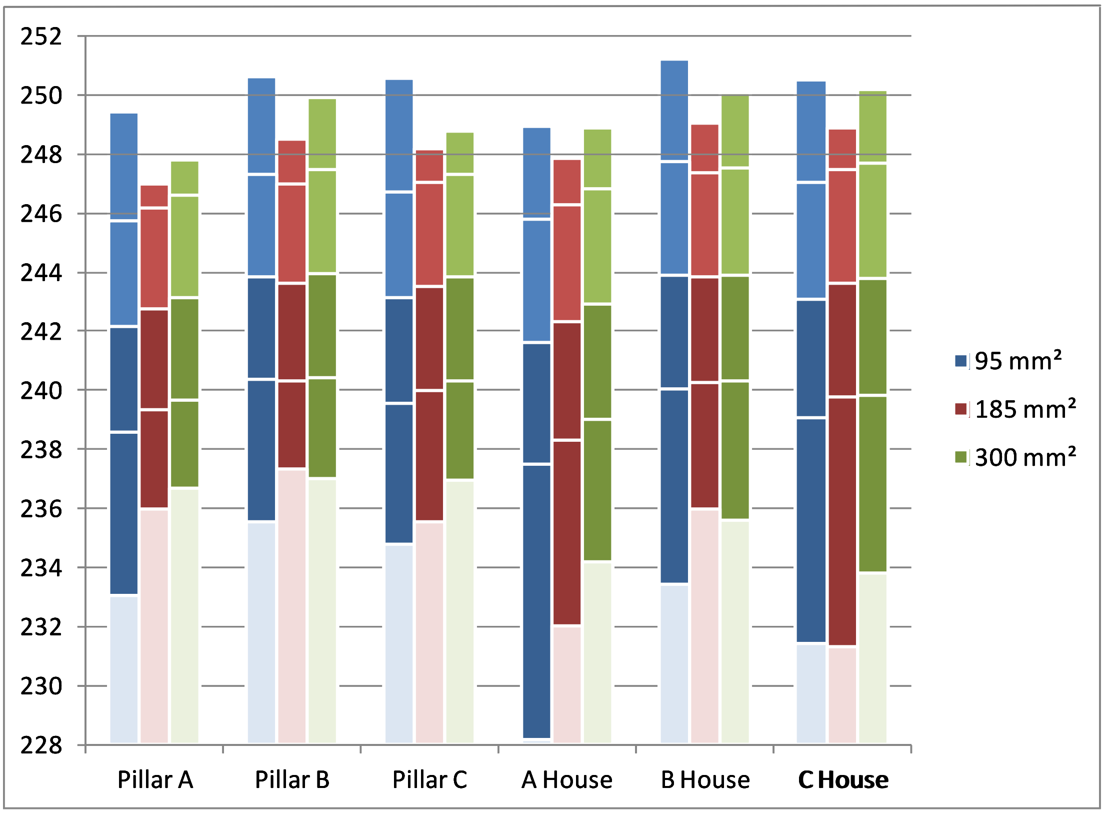

Figure 1: Range of Voltages (ten-minute average) according to Cable Size

Each group of columns on Figure 1 represents a measurement point, with each column a cable size. The columns are coloured dark between the minimum observed voltage and the mean, and paler between the mean and the maximum, so that the mean and both limits are easily visible. The white horizontal marks on each column are placed two standard deviations above and below the mean.

From Figure 1 we see that the 95 mm² cable consistently has a wider range of voltages than the other two, as one would expect; but the narrowest range is not always the 300 mm². This does indeed give a narrower range for the C phase at the pillar and for the phase A and C houses; but the pillar A phase sees little difference between 185 and 300 mm², while for phase B at both house and pillar the largest cable actually correlates with an increased range of voltage.

Looking at the extreme measurements is sensitive to the differing lengths of time for which the three cables were in service; the longer a cable is in service, the more extreme the events it will see. A measure that compensates for this is the standard deviation: this takes all the differences between measurements and the mean, and averages them using the “root mean square” average; as well as treating both positive and negative differences the same, this gives a measured bias in favour of greater deviation from the mean. Looking at the standard deviation, there is very little difference between the cables (the marks on Figure 1 are at twice the standard deviation, which for a normal distribution would mean that about 86% of readings came within the interval).

The mean voltage also varies little with cable size.

The important conclusion to draw from these results is that the voltage is affected more by external conditions than by the choice of cable in this installation.

2.3 Maximum Import and Export

The maximum import or export of any one dwelling has little importance, but that for the estate as a whole has some bearing on the choice of cable. The following table summarises the results. All are three-phase power readings, since power for the individual phases was not measured.

Condition	Reading	When Occurred	Voltage
Maximum Export (based on actual maxima)	29.8 kW	2012-07-30 12:45	243.6 V (Phase C)
Maximum Export (based on ten-minute averages)	23.8 kW	2012-06-18 13:05-13:15	243.1 V (Phase A)
Maximum Import (based on actual maxima)	58.2 kW	2012-03-04 19:05	240.2 V (Phase C)
Maximum Import (based on ten-minute averages)	47.6 kW	2012-03-04 19:01-19:11	240.2 V (Phase C)

The maximum export from the estate is around half its maximum demand. Not surprisingly, it occurs in the early afternoon in midsummer. As it happens, it occurred when the 185 mm² cable was in service, for both the criteria (absolute maximum and ten-minute average). The voltage was much lower than the maximum observed, and very close to the average voltage over the entire monitoring period. This reinforces the conclusion above that the voltage depends mainly on external causes.

Unlike export, the maximum import shows the same event whether one examines the absolute maximum or the maximum of the ten-minute average. This event occurred in the evening of

4th March, when the 300 mm² cable was in service. It can be seen from Figure 1 that the voltage is only slightly below half way between minimum and mean for the pillar phase C while this cable was in service.

Finally, on the subject of extreme power, it is worth noting the maximum current that flows in the feeder. There is no reading in amps, but 68.8 kVA flowed on 21 May 2012 at 19:57, corresponding to less than 100 A per phase (95.5 A if the load is perfectly balanced) at 240.2 V.

3 DAILY CURVES

In this section, the curves in figures 2–4 show averages taken over the whole dataset. In figures 6–9 the average covers that period for which irradiation data are available, while for figures 5 and 10 the average covers just the three months for which PV output was recorded.

3.1 Power and Voltage Curves

In a housing estate such as the one under study, there are daily load curves for the consumers and daily generation curves for the solar panels. While these are predictable in large populations, they are much more random as individuals. In addition, the data available give only the difference between demand and generation for each of the three installations; correlating generation with external factors such as solar irradiation involves reconstructing the generation curve from the composite data, and the results are very imprecise.

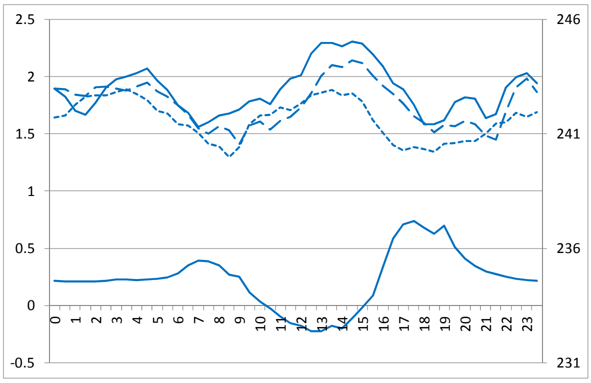

Figure 2: Daily Curves, Phase A House

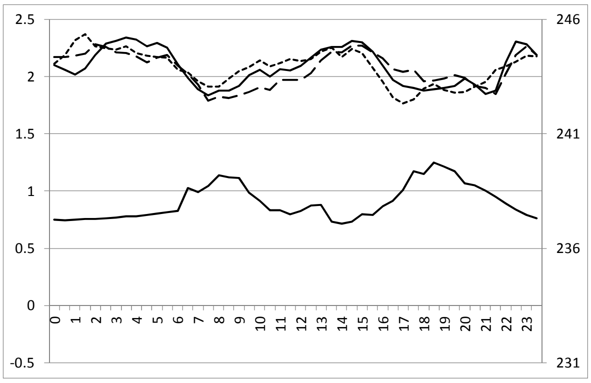

Figure 3: Daily Curves, Phase B House

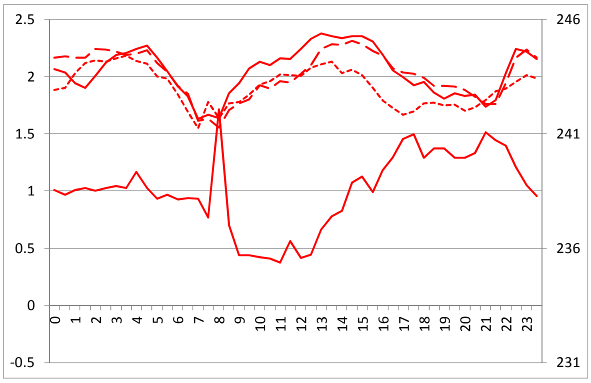

Figure 4: Daily Curves, Phase C House

The first analysis is a simple visual comparison of the net demand curve with voltage, each averaged across half-hour time slots; Figures 2, 3 and 4 show the curves for the phase A B and C houses respectively: the solid curve at the bottom of each graph shows the net demand (in kW), while the three curves at the top show the average voltage, again according to which cable is in service: the dotted line represents the 95 mm² cable, the dashed line 185 mm² and the solid line 300 mm².

In all cases there is a dip in load during the day, corresponding roughly to when photovoltaics are most likely to generate; but only on the phase A house, where the background demand is the smallest of the three at about 200 W, does net demand become negative. The phase B house, where the demand averages around 800 W overnight, barely sees the daytime demand fall below this; and the curve from the phase C house, where the overnight demand is even higher at 1 kW, shows the dip superimposed on an apparently highly predictable daily routine, with (for example) a large demand spike around 8 o'clock each morning. This spike is a kilowatt above the underlying trend, and may represent a few minutes use of an electrically heated shower averaged over the half-hour.

3.2 PV Profiles: Individual Houses

Three houses in the estate had monitoring installed on the PV systems to record actual generation. These provided readings from November 2012 to January 2013, perhaps not the best period for assessing the impact of photovoltaics on the distribution system. Two of the monitors were on the B and C houses, which also had their supplies monitored, but the third was not the A house above but a different house that can conveniently be called D. The B and D houses are semi-detached and in the same building; the PV arrays are next to each other on the same roof slope. This does not give the diversity of orientation that the original three houses would have had, but it allows two arrays that see essentially the same solar conditions to be compared directly. Figure 5 shows the recorded outputs from the three houses, compared with the measured solar irradiation.

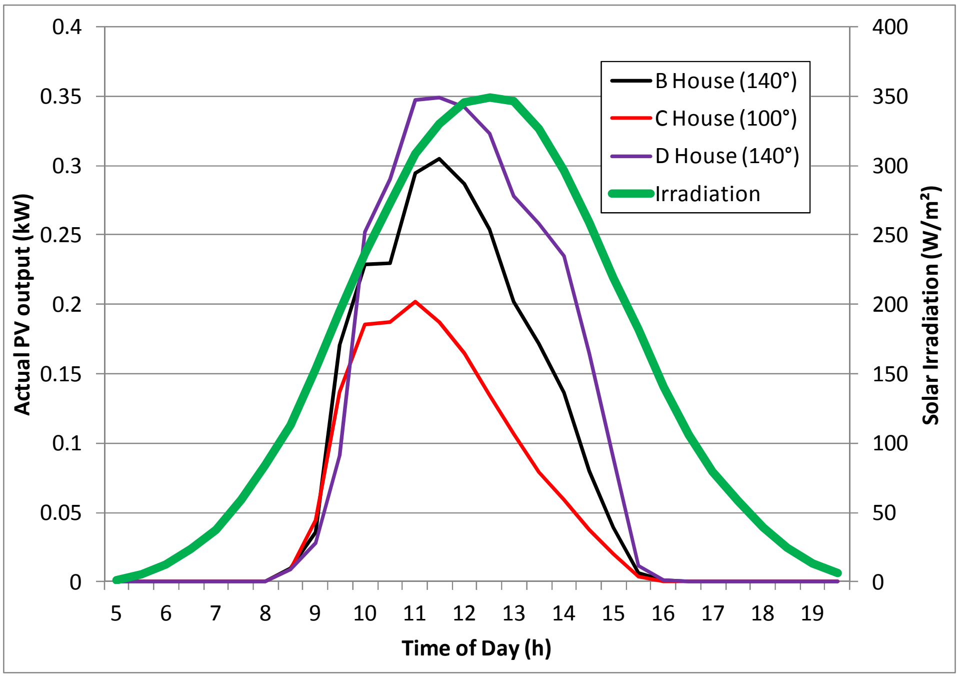

Figure 5: Demand Curves for the Monitored Sites with Standard Curves

All three of these arrays face to the east of due south, and all three curves consequently have their peak before the peak of the irradiation curve. The C house faces almost due east, but its peak is not much earlier than that of the two houses facing south-east; the biggest difference is in the size of the peak, not much more than half that of house D. An interesting feature of the C curve is the long tail, with the output reaching zero at about the same time in the evening of the two other houses. All three have essentially zero output after 4 pm and before 8 am; this reflects the winter sampling period as opposed to the irradiation measured over a whole year.

Also interesting is the difference in height between curves B and D. These are two essentially identical PV arrays, mounted next to each other on the same roof; but there is a difference of about 50 W between them for most of the day. This cannot be accounted for by the different period of measurement, since the D house was monitored for only one extra day, 29th January; possibilities include variations in manufacturing of the PV panels or in subsequent cleanliness; shade from nearby objects (trees, buildings, lamp posts, maybe even birds); parasitic loads within the control electronics.

3.3 PV Profiles Calculated from Demand

Another measure of PV output can be derived from looking at the demand of each house, and comparing it with that expected for a house without PV. In this case there is much more data available for this method than the three (winter) months of direct readings; and this is arguably more relevant to the DNO's business.

The demand profiles of the three houses each consist of the actual consumption – gross demand – from which the PV output has been subtracted, giving net demand. To derive the output profile, the demand is first compared with a standard demand curve. Figure 6 shows the three demand profiles together with two standard profiles – for single rate customers and "economy seven" customers – derived from Elexon data as described in Section 2.

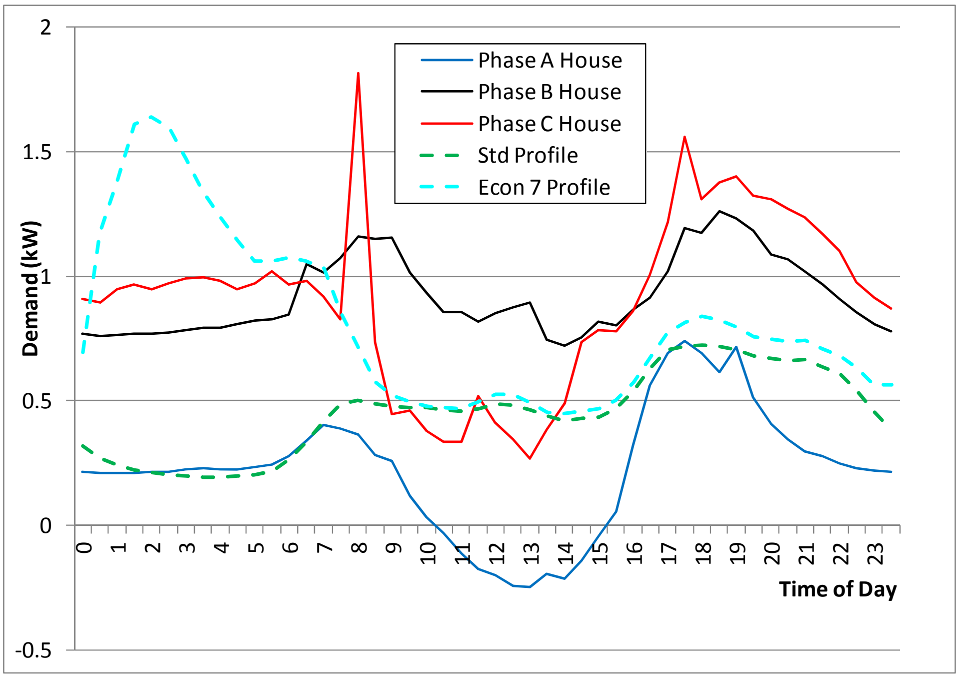

Figure 6: Demand Curves for the Monitored Sites with Standard Curves

The curve for phase A follows the single-rate curve quite closely, apart from the expected dip when the photovoltaics generate, and some reduced demand in the evening. The phase B and C houses, however, do not follow either standard curve at all. There is no peak in the early morning corresponding to economy 7; but they seem to be displaced from the single-rate curve (or the phase A curve) by a constant amount of around 600 W.

As an arbitrary estimate of the underlying demand (that which must be subtracted to show the PV output), the following was taken: phase A, the single-rate curve; phase B, the single-rate curve plus 550 W; phase C, the single-rate curve plus 700 W. The resulting curves are predominantly negative – representing the photovoltaic output – so they have been inverted for comparison with solar data. Figure 7 shows the three resulting curves, together with the solar irradiation curve, between 5 am and 8 pm.

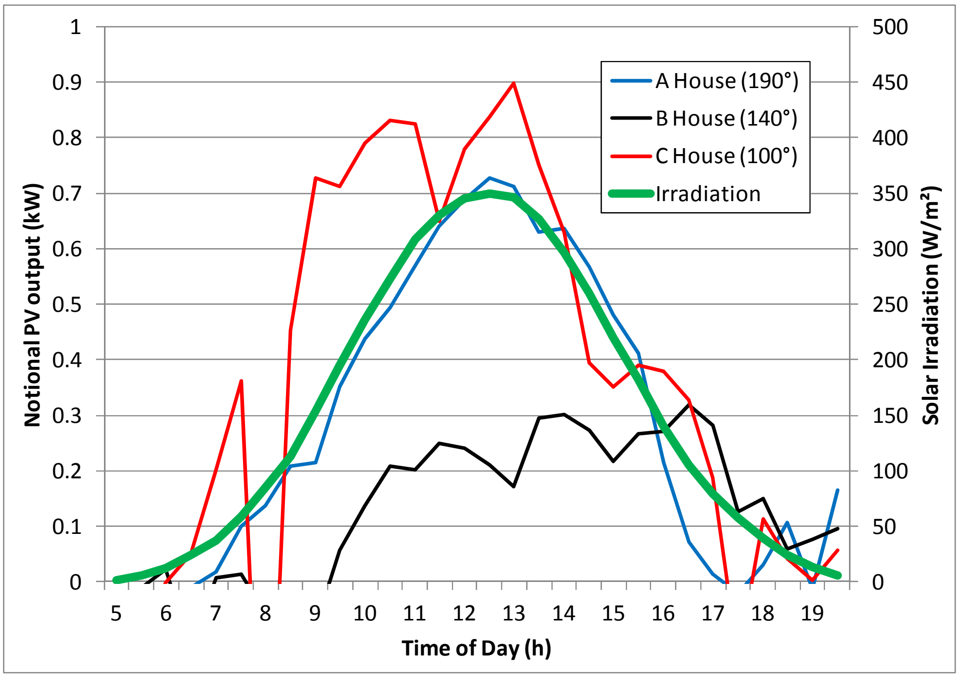

Figure 7: Curves Matched to Solar Irradiation

Phase A follows the PV curve very closely, with a slight lag. This is unsurprising, since the PV array faces slightly west of south. There is a noticeable dip in the late afternoon; this could either be an effect on the array (such as the shadow of another building) or an afternoon routine that consumes power (such as a favourite television programme).

Phase C, where the array faces slightly south of east, also follows the irradiation curve, but with considerably higher output in the morning, again as expected. The irregular nature of the curve is probably indicative more of the house's demand than of any peculiarities in the array's catching the sun (the deep dip at 8 am has already been mentioned).

Finally, at the phase B house the array faces south-east. Here one would expect to see another curve with a peak in the morning, but later than that on phase A. Instead, the peak occurs in the afternoon, and is much smaller than those on phases A and C. The data cannot explain this; the background demand – the single-rate curve plus 550 W – is arbitrary, and is probably not a good representation of the load here. This result shows that for a single dwelling the pattern of use has a much greater effect on the curve than the orientation of the array.

3.4 PV Profiles: The Whole Estate

Looking at the whole of the estate, one can derive a demand profile much less dependent on the behaviour of individual residents. Figure 8 shows the daily load curve for the power measured at the feeder pillar, with standard curves superimposed as before (the scales are different because the standard curves represent only one dwelling, while that at the feeder pillar represents twenty-four).

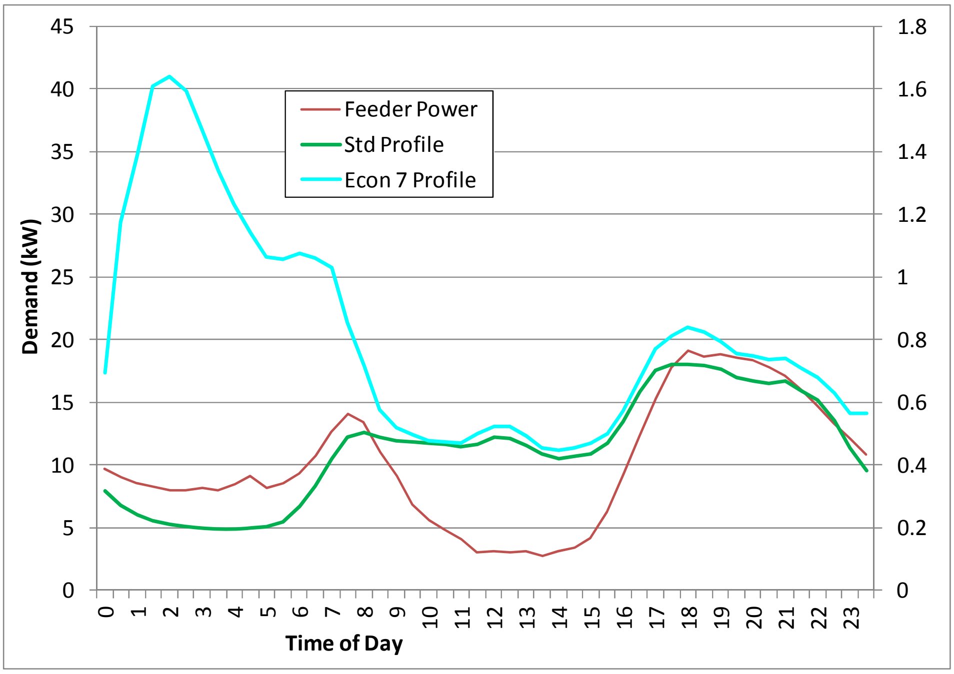

Figure 8: Demand Curve for the Feeder with Standard Curves

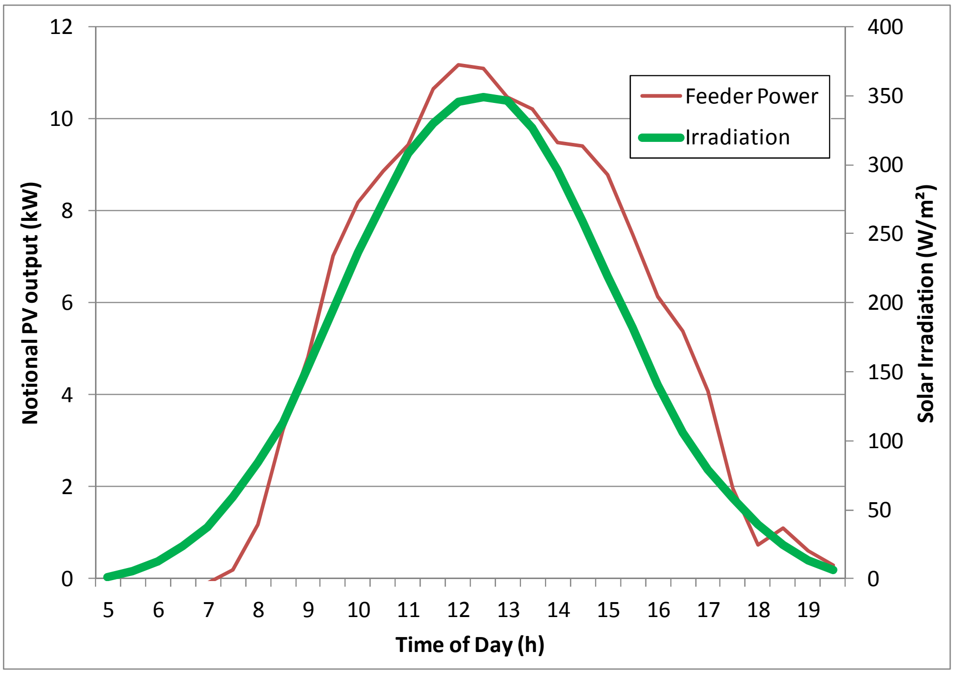

Figure 9: Curve Matched to Solar Irradiation

Again the curve resembles the standard curve with a dip for PV output during the day, and a small constant offset. Although the curve seems to exceed the standard curve mainly in the morning, including even a small amount of economy seven in the background demand was not a good fit, and the background demand was eventually taken as 24 x the standard demand plus 2.5 kW. When this is netted off to give notional PV output, the result is the curve in Figure 9.

The curve is a good match to the solar curve, but broader, possibly reflecting the diversity of orientation of PV panels in the estate. The deviations from a smooth curve may be partly due to there being just six orientations used in the estate; but this hypothesis would be hard to test. In a large population of houses, all facing the same way (such as a 19th Century housing estate), the orientation would probably show at this level.

The most puzzling feature of this graph is the constant term needed to fit the curves. This may benefit from further investigation, for example to determine whether it is a parasitic load within the PV electronics. If so, this has important implications for further PV projects.

3.5 Comparison of Measured and Calculated Profiles

Finally, although the measured and calculated profiles cover different periods, there is some value in comparing the two. For the two houses where both are available, B and C, the graph in Figure 10 shows the measured and calculated figures.

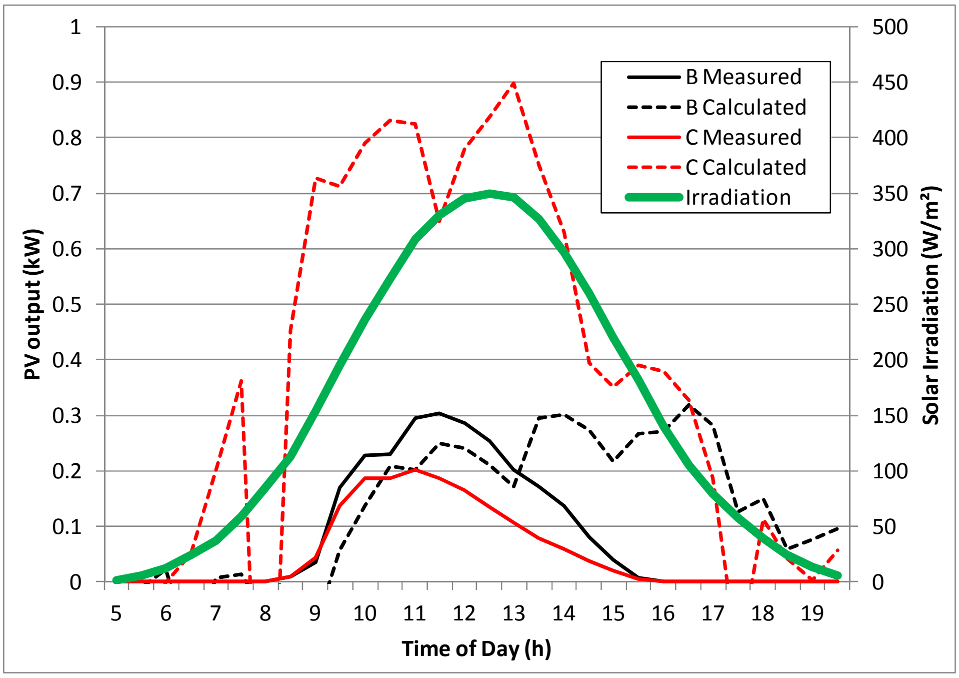

Figure 10: Curves for Measured and Calculated PV Output

For the C house, the curves agree in shape, apart from the irregular demand mentioned above; the difference in the height of the peak is probably due to their being measured data available only in the winter. For the B house, the peaks are about the same height, despite the seasonal difference, but the calculated curve covers a quite different time of day. This further emphasises how poor the standard curves are at predicting the demand of individual dwellings.

4 CONCLUSIONS

The choice of cable has very little effect on the voltages seen by the consumers. Use of a 95 mm² cable increases the range of voltage slightly, but the 185 mm² and 300 mm² cables are practically indistinguishable.

Extremes of measured power appear unrelated to extremes of voltage; this together with the results for the 185 mm² and 300 mm² cables suggests that external conditions have by far the greatest influence on voltage.

In this particular installation, voltages are generally high, although statutory limits are not exceeded. Depending on the requirements of other consumers supplied via the same transformer, the system might benefit from a reduction in voltage by one tap step.

In correlating demand with solar irradiation, a standard (single rate) demand curve plus a small constant power minus a component for photovoltaic output is a good match for the estate as a whole, but a poor match for individual dwellings. The effect of orientation was discernible on two of the dwellings monitored, but on the third, the model was a very poor fit, and the resultant curve showed no trace of the array's south-easterly orientation, although this is evident in the (more limited) measured data. This shows how electricity usage by a particular consumer has a far greater effect on the load pattern than orientation of the solar array, although this is not expected to hold for large groups of houses all facing one direction.

One feature of the model, that of adding a constant demand to the standard curve to fit the observed data better, is unexplained. This varied between zero and more than 500 W for individual consumers, and was about 2.5 kW (100 W per consumer) for the whole estate.

5 FURTHER WORK

The greatest benefit would come from monitoring a wider range of installations, including if possible similar installations with and without photovoltaic panels, in order to compare the results.

Some investigation seems desirable to find the reason for the constant term that was required to fit the demand at the phase B and C houses, and on the estate as a whole, to the standard load curves - in other words, why the overnight demand is so high. This may, however, be of limited benefit to a DNO.

With the existing data, some further improvements are possible. Since the standard load curves are published for weekdays, Saturdays and Sundays for five "seasons", and these seasons also have a strong effect on the solar irradiation climate, it may be worth breaking the data down on this basis. On the other hand, the dataset may be too small for such a breakdown to be useful.

When the power curves were compared with standard load curves, the fit was optimised by hand. A full numerical optimisation could be of benefit, although this will depend on finding an explanation for the constant term. Without it, such a fit is arbitrary, and careful numerical analysis adds little.

Tap change data was available, but not used in this study. Since the voltage is controlled at the primary substation in response to events over a comparatively wide area, tap changing may well cause step changes that could be analysed for flicker. For ten-minute averages and absolute maxima and minima, tap change data is of little importance.

Finally, a fuller investigation of the effect of swapping out the cable could be made with data from the source end of the cable. With monitoring already in place on the estate, this could be achieved by adding only one more data recorder. Measurements further upstream might also enable a more meaningful interpretation of tap changer data.

6 REFERENCES

[1] UK Energy Research Centre, *Energy Data Browse Archive*. The Elexon load curves were a spreadsheet “AllProfileClasses.xls” downloaded from http://data.ukedc.rl.ac.uk/browse/edc/Electricity/LoadProfile/data (accessed 7 May 2013).