Impacts and integration of PV in LV networks

Work Package 1: PV2025 Project Review Meeting,
University of Loughborough, October 2015

Dr Paul Westacott and Dr Chiara Candelise
Outline

• What can we learn from DNO field trials?
  Localised monitoring of PV
  DNOs have monitored PV in their networks – notably at LV
  Findings from the LCNF

• How is PV distributed across demand customers and network assets?
  Trends across an entire licence area / rural and urban areas
  How does this impact on local demand / power flows?

• How could PV + energy storage facilitate integration?
  How can we maximise the system benefits of PV?
  Can we firm the capacity of PV to meet winter peak?
LV Monitoring studies of PV  → Overview

- **6 LNCF projects**: Monitoring and analysis >1000 distribution substations, >3000 endpoints (e.g. at households with PV systems)
- **Rural/urban networks**
- **Domestic/non-domestic** PV market segments
- **Up to 100-200 kWp PV** installed, and up to 40% of households per feeder
- **Monitored**: Voltage, Current, Power (P and Q), Quality (harmonics)
LV Monitoring studies of PV → Results

- **Half-hourly average PV generation**
  - WPD measured aggregate domestic PV generation <81% nameplate
  - Measured at and above feeder level, 1 year observations
  - Multiple areas, in South Wales (we use this findings later...)

- **Adverse impacts on power quality generally low**
  - Reduction in power factor, due to locally met active power
  - Some increase in current harmonics

- **Voltage rise not as significant as anticipated**
  - Impacted by lower than expected generation?
  - Highly sensitive to feeder length and level of deployment
  - In many networks min demand was as impactful as max PV

- **Reverse power flow observed in a number of cases**
  - Characterising where this occurs important locally and upstream
  - Largest RPF observed from feeder with non-domestic PV

- **Rurality is important**
  - Phase imbalance observed to be generally greater in rural
  - Rural may be more susceptible to overvoltage
UKPVD framework extension: PV / consumers / network

New data acquired from WPD characterising **Network Assets** and **Consumers** across rural and urban networks

**PV deployment**
- Number of systems
- Installed capacity
- Market segments
- Voltage levels
- Date

**Consumers**
- Type & number
- Annual consumption
- Load profiles
  (DECC/WPD/Elexon)

**Network Assets**
- **Substations:** Capacity
  - pole/ground?
- **Feeders:**
  - underground/overhead?
  - Number/type customers

*PV deployment across Greater London*
Mapping of PV generation with demand

Domestic

Non-domestic

Ground-mount

Daily Power Flow

Load Demand
PV Generation
Net Power Flow

Monthly Totals

Energy Import
PV self-consumed
PV Export
South-West England distribution region – LV analysis

- **Highest % of annual load met by LV PV** *(Low demand/high PV)*
- **Network asset data**
  - Collaboration with WPD had yielded LV network information
- **Upstream implications…**
  - Large capacity of PV upstream (solar farms)
  - Transmission/distribution flows evolved rapidly *(Elexon)*
  - DNO constraints *(F-route, 132 kV)*
  - National Grid constraints *(high volts)*

Power flow data courtesy of Elexon
PV deployment in LV networks

- Large variation in LSOA level PV deployment, typically higher in rural
- Some high deployment LSOAs, in both rural and urban areas...
High Penetration rural LSOA example / comparison of all LSOAs

- Load demand calculated from UKPVD inputs
- Over half load met by PV installed in the LV network
- Overall, trends are diverse, generally more significant in rural areas
- Small number of areas have generation greater than 100%
- **Outcome:** Framework used to identify current impacts and future hotspots
Could energy storage help or hinder the system?

- Distributed energy storage could provide value to PV owners/DNOs/SO we investigate the wider-system value.
- How can the variability of PV generation across the winter impact on “Firm Capacity Credit”?

**Domestic**
- Increased self-consumption of PV? → Reduced import
- How related to time of use tariffs?

**DNO / SO**
- Reduce peak demand?
- Capacity margin implications?
- Load related reinforcement?
1) How does daily PV generation vary across winter?
   - example here uses a daily AC generation from a (>10 MWp) solar farm

2) Objective: Maximise energy that PV/Storage delivers everyday of winter
   - over a 3 hour period, e.g. winter peak

3) We model battery operation, as a “buffer” between sunny/dark days
   - enables some generated energy to be carried forwards between days
   - battery charges directly from all generation
   - discharge is for a fixed energy per day
   - maximises the energy the battery can dispatch without becoming empty
Assessing the potential of energy storage: Methodology

- Example of PV with 1 kWh storage per kWp of PV

- Here an optimised daily discharge is 0.32 kWh/kWp (purple)

- If this energy is dispatched over 3 h (w/storage round trip efficiency 80%) then 0.085 kW per kWp of PV can be dispatched every day.

- This yields a firm capacity credit of 8.5%

- PV is firmed and could displace most expensive/carbon intensive grid electricity
Conclusion

1. Meta-Analysis of measured impacts of PV in DNs has been carried out
   • Generally measured impacts of PV lower than anticipated

2. UKPVD has been extended and validated using newly obtained data from WPD
   • Improved picture of network assets and customer types from real networks and how PV is distributed across them

→ Outcome: LV PV deployment impacts on power flow relatively modest so far
→ Outcome: More detailed understanding of where network impacts may occur
→ Next Step: Incorporate higher voltage level PV? Future collaboration

2. PV/Storage could provide firm capacity to the system

→ Outcome: A methodology was developed using real solar farm data
→ Outcome: Inform debate on whole-system benefits of PV

→ Next Step: Costs? / Compare to longer run trends?
→ Next Step: Look at other system extreme (max generation / min demand) and input into GIS-framework to understand impacts on power flows
Assessing the potential of energy storage: Preliminary results

Example LSOA:
- 780 households + Non-domestic
- Domestic PV 370x (50% pen)

Storage added to each PV system:
- 5 kWh storage
- Operated in different modes

- Significant differences with storage / operational mode
- Minimum demand (maximum reverse power flow)
- Differences in ramping of net demand
PV deployment in LV networks: High deployment examples
**PV deployment in LV networks: High penetration examples**

<table>
<thead>
<tr>
<th>Consumers</th>
<th>Embedded Generation</th>
<th>Network Assets</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>PMT</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
</table>

- **Area of LSOA**
  - Rural: 100 km²
  - Urban: 0.31 km²

- **Electricity consumers and demand**

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of consumers: Domestic / Non-domestic (NHH) / HH</td>
<td>1058 / 298 / 7</td>
<td>739 / 41 / 1</td>
</tr>
<tr>
<td>Annual consumption: Domestic / Non-domestic (NHH)</td>
<td>5,880 / 4,090 / 221 MWh/yr</td>
<td>2,595 / 538 / 190 MWh/yr</td>
</tr>
<tr>
<td>Percentage of consumers (based on MWh/yr) (%)</td>
<td>58 / 40 / 2</td>
<td>78 / 16 / 6</td>
</tr>
</tbody>
</table>

- **Network Assets**

<table>
<thead>
<tr>
<th>Network Assets</th>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution substations (GMT/ PMT)</td>
<td>6 / 272</td>
<td>6 / 0</td>
</tr>
<tr>
<td>Total substation rating (kVA)</td>
<td>11,900</td>
<td>3,500</td>
</tr>
<tr>
<td>Distribution substation density (km⁻²)</td>
<td>2.8 km⁻²</td>
<td>19 km⁻²</td>
</tr>
<tr>
<td>Av. customers per substation GMT / PMT</td>
<td>15 / 1</td>
<td>124 / -</td>
</tr>
<tr>
<td>Av. feeders per substation GMT / PMT</td>
<td>1 / 1</td>
<td>3 / -</td>
</tr>
<tr>
<td>Substation density (km⁻²)</td>
<td>2.8 km⁻²</td>
<td>19 km⁻²</td>
</tr>
<tr>
<td>Total 11 kV line length</td>
<td>112 km (ohl)</td>
<td>2.8 km (ugc)</td>
</tr>
</tbody>
</table>

- **PV Deployment**

<table>
<thead>
<tr>
<th>PV Deployment</th>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of PV systems: Domestic / ND</td>
<td>111 / 7</td>
<td>122 / 0</td>
</tr>
<tr>
<td>Installed PV capacity: Domestic / ND</td>
<td>486 / 171 kWp</td>
<td>265 / 0</td>
</tr>
<tr>
<td>PV capacity per customer (kWp)</td>
<td>0.6 kWp/customer</td>
<td>0.35 kWp/customer</td>
</tr>
<tr>
<td>Average number of PV per substation</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Average number of PV per feeder</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Comparison of network assets/customers

WPD have provided two datasets
- Individual characteristics of substations in these LSOAs
- Statistics of substation/feeder/customers across a whole license area

Rural
Approaching 300 substations
Majority pole-mounted with single feeder
Typically rated ~15-30 kVA, serving 1-3 customers

Urban
6 substations
All 500 kVA rated or above
Each has 3 feeders
Around 120 customers per substation

Rural area has more smaller transformers, spread over larger area

How does this trend relate to our GIS Urban/Rural classifications?