Institution: University of Bath		
Unit of Assessment: B12 Engineering		
Title of case study: Improving the efficiency of electricity distribution networks		
Period when the underpinning research was undertaken: 2013 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Furong Li	Professor	May 1997 – present
Ran Li	Lecturer, previously Research Associate	December 2014 - August 2020
Chenghong Gu	Lecturer, previously Research Fellow, Research Associate	February 2011 - present
Period when the claimed impact occurred: 2017 – 31 July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Bath has researched methodologies that, by monitoring only about 0.01% of the total substations in an electricity distribution network, can predict energy peak demand and usage profiles for the critical low-voltage "last-mile" part of the whole network. These methodologies enable real-time monitoring and control of the network voltage and have been adopted by the distributed network operator Western Power Distribution (WPD), ***which represents 40% of the entire UK distribution industry***.

The impact is that i) ***the operations of WPD have been changed*** as a direct result of Bath's research, ii) through this the ***environment has been improved*** by a decrease of 575,000tCO_2/year, and iii) WPD's ***performance has been improved***, delivering customer savings totalling GBP116,000,000 per year for approximately 7,900,000 customers.

2. Underpinning research

Electrical energy distribution networks face critical challenges as they must deliver reduced CO_2 emissions and integrate low-carbon technologies such as electric vehicles, heat pumps, photovoltaics and energy-storage systems – while at the same time managing customer costs. The majority of these low-carbon technologies must be connected to the low-voltage (LV) distribution networks (415V) that form the "last mile" of the electrical-supply chain. The Distributed Network Operators (DNOs) monitor and control the last-mile LV networks in a real-time, dynamic, flexible and responsive manner to meet these challenges. A key parameter they must control is the *primary voltage* of the LV network since this must be kept within statutory limits, but can also impact energy demand and consumption (see Section 4).

However, the last mile is notoriously difficult and expensive to monitor because it contains a very large number of individual substations (about 1 million across the UK). This leads to a lack of real-time visibility and controllability for the LV networks. The cost of monitoring all substations in the large LV networks to enable their visibility is estimated to be approximately GBP2,000,000,000 for the whole UK - a prohibitive cost. In response to this, DNOs have largely used historical load profiles and fixed network information about customer numbers, types and electricity use to estimate real-time utilisation and network behaviours. Such approaches are consequently inflexible and inefficient. There is thus a research need to develop methodologies to allow DNOs to monitor and control their LV networks in real time, but without having to monitor each individual substation.
To address this research need, Bath's Centre for Sustainable Power Distribution undertook fundamental research working with WPD through two Ofgem funded projects ("LV Network

Templates for a Low Carbon Future - Smart grid demonstration project in South Wales", 2011-14 and "Project Bristol – Buildings, Renewables, Integrated Energy Storage with Tariffs to Overcome Network Limitations, 2012-15). This research developed new methodologies able to accurately determine the condition of large LV networks to accommodate and manage the integration of low-carbon resources [1].

Li and her researchers at Bath developed *network templates* for DNOs, by using big-data analytics able to use minimal information metered at selected LV network sites. The network templates allow visualisation of real-time energy usage patterns across LV networks of various locations, types and customer mixes. The templates were developed using a novel three-stage network load-profiling method of *clustering*, *classification* and *scaling*. Unlike traditional approaches that rely on simple state estimation to visualise LV networks, the templates developed employ a bespoke set of typical load profiles that analytically characterise generation, networks and consumption. This method was demonstrated on the WPD South Wales licence area using the metered data from 800 monitored LV substations [1].

A novel contribution factor (CF) approach was then developed to predict the diversified daily peak load of LV substations. The CF for each LV template developed in [1] was determined by a novel cluster-wise weighted constrained regression, considering the contribution from different customer classes to substation peaks. *This method improves the accuracy of peak load estimation by 80% compared with earlier methods* [2].

The result of this research has allowed DNOs to accommodate a greater volume of local renewable and low-carbon appliances [3, 4, 5], such as EVs and heat pumps, and help energy customers to reduce their reliance on traditional centralised fossil-based generation, thereby ultimately helping to reduce CO_2 emissions. This research also enabled the development of decentralised local energy markets, connecting local energy resources to deliver low cost, low-carbon energy with very substantial benefits estimated to amount to GBP87,000,000,000 to end consumers between 2030 and 2050 [6, page 34].

3. References to the research

[1] Li, R, Gu, C, Li, F, Shaddick, G & Dale, M 2015, 'Development of Low Voltage Network Templates-Part I: Substation Clustering and Classification', *IEEE Transactions on Power Systems*, vol. 30, no. 6, 6981990, pp. 3036-3044. https://doi.org/10.1109/TPWRS.2014.2371474

[2] Li, R, Gu, C, Li, F, Shaddick, G & Dale, M 2015, 'Development of low voltage network templates - Part II: peak load estimation by clusterwise regression', *IEEE Transactions on Power Systems*, vol. 30, no. 6, 6981996, pp. 3045-3052. [Available on request]

[3] Wang, Z, Gu, C, Li, F, Bale, P & Sun, H 2013, 'Active Demand Response Using Shared Energy Storage for Household Energy Management', *IEEE Transactions on Smart Grids*, vol. 4, no. 4, 6558515, pp. 1888 -1897. https://doi.org/10.1109/TSG.2013.2258046

[4] Li, R, Li, F & Smith, ND 2016, 'Multi-resolution load profile clustering for smart metering data', *IEEE Transactions on Power Systems*, vol. 31, no. 6, 7428953, pp. 4473-4482. https://doi.org/10.1109/TPWRS.2016.2536781

[5] Zhao, C, Dong, S, Gu, C, Li, F, Song, Y & Padhy, NP 2018, 'New Problem Formulation for Optimal Demand Side Response in Hybrid AC/DC Systems', *IEEE Transactions on Smart Grid*, vol. 9, no. 4, 7742362, pp. 3154-3165. https://doi.org/10.1109/TSG.2016.2628040

[6] Li, F, Gu, C, Tang, C, Qin, H & Zhang, Z 2019, *Value Creation by local energy markets and the implications for the transition to a distribution system operator*. Northern PowerGrid. https://www.northernpowergrid.com/asset/0/document/5414.pdf

4. Details of the impact

How the research led to impact

The research conducted by Li and her team at Bath into LV network templates was adopted and implemented by the local Distribution Network Operator (DNO), Western Power Distribution (WPD) in 2015 following their Ofgem-funded Low Carbon Network Fund 2 project, *LV Network Templates*.

The implementation was in 2 phases: In the first one, WPD used the LV network templates to monitor voltage across LV networks in their South Wales licence area. This then allowed WPD to control the primary voltage in this area. In the second phase, WPD rolled out this voltage modification across all 4 of their licence areas, East and West Midlands, South Wales and the South West.

Details of the beneficiaries

The beneficiaries are:

i. Western Power Distribution, which has ***changed its operations*** as a result of the research – in particular, how they monitor and control LV network voltage across all their license areas – *Midland East*, *Midland West*, *South West* and *South Wales*.

ii. WPD's approximately 7,900,000 customers, who have benefitted from the fact that WPD's performance has been improved, delivering ***customer savings*** totalling approximately ***GBP116,000,000 per year***.

iii. Wider society has benefitted from the ***decrease of approximately 575,000tCO_2/year***, enabled by WPD's change in operations to accommodate a greater volume of local renewables, energy storage and low-carbon energy appliances.

Nature of impact

LV-network voltages must be kept within the statutory limits of 230V + 10% or - 6% (i.e., 253V to 216V). LV voltages are generally set as high as possible to allow for voltage drop along the network and to ensure that voltages never drop below the limit. However, reducing network voltage can have significant benefits, particularly where there is a large concentration of resistive loads. For these types of loads, reducing the voltage in turn reduces the maximum demand requirements and so can also reduce the consumption. Controlling the LV-network voltage can thus deliver significant reductions in energy demand and consumption. Bath's research delivered solutions that allowed this desired network voltage reduction to be achieved [A].

Based on Bath's research on Low Voltage Network Templates, WPD were able to replace the generic voltage-control scheme which they had used for the previous 30 years. The new replacement is a substation-specific, dynamic voltage monitoring and control scheme. This was implemented across WPD's South Wales licence area in 2017. In their 2017 letter [B], WPD's Innovation and Low-Carbon Networks Engineer wrote:

> *"Using the Templates classification, we can now create these templates on all WPD substations using existing fixed data".*
>
> *"The greatest benefit from the project is how the voltage monitoring has informed us of the voltage profile across South Wales".*

This monitoring allowed WPD to trial a primary voltage-reduction scheme in South Wales that reduced customer demand. WPD noted in their 2019 letter [C] that:

> *"Statistical analysis by The University of Bath showed this had a statistically significant impact on customer demand and consequently on bills. The 1% reduction of operation voltage tested resulted (in) an approximately GBP14,000,000 per year saving for customers in South Wales".*

Following on from this successful implementation in 2017, a further 1% reduction in primary voltage has now been rolled out across all four of WPD's licence areas, *Midland East*, *Midland West*, *South West* and *South Wales*, in a 3-year programme that ended in February 2020. WPD wrote in their 2019 letter [C] that:

> *"This should result in significant further cost savings to WPD's energy customers in the region of GBP116,000,000 per year and carbon savings in the region of 575,000 tonnes per year".*

5. Sources to corroborate the impact

[A] Western Power Distribution website. 2016. Voltage reduction analysis. Available at: https://www.westernpower.co.uk/projects/voltage-reduction-analysis

[B] Testimonial letter from Innovation and Low Carbon Networks Engineer, Western Power Distribution, 5 May 2017.

[C] Testimonial letter from Innovation and Low Carbon Networks Engineer, Western Power Distribution, 11 December 2019.