Institution: Edinburgh Research Partnership in Engineering (ERPE: Edinburgh and Heriot-Watt Universities joint submission)		
Unit of Assessment: UoA12 Engineering		
Title of case study: Machine learning enables active asset management of power networks		
Period when the underpinning research was undertaken: February 2017 – October 2019		
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:**
Dr. Valentin Robu Prof. David Flynn Dr. Maizura Mokhtar	Associate Professor Professor Knowledge Transfer Research Associate	2014 – present 2010 – present 2017 – 2019
Period when the claimed impact occurred: 2019-2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Staff at Heriot-Watt University within the Edinburgh Research Partnership in Engineering (ERPE) led a collaborative project with Scottish Power Energy Networks (SPEN) to develop the *Network Constraints Early Warning System (NCEWS)*, with on-board machine learning for active asset management and maintenance/reinforcement planning of the electricity distribution system. This supports the critical pathway to enable decentralised energy networks for future low carbon renewable integration. The impacts included:

(A) Integration of NCEWS within SPEN's network management platform enabling more confident prediction of system response, penetration of renewable generation, supporting demand management and electric vehicle (EV) charging. Network design, analysis and contingency planning modelling time was reduced by 67%.

(B) Increased knowledge and closer management of the increasingly active network enabled consideration and deferral of network asset renewal and delivered operational cost savings (GBP1 billion in the SPEN distribution area alone).

(C) NCEWS was adopted in SPEN's Digitisation Strategy, enabling the Networks to help drive carbon reduction, increase security of supply and extend asset maintenance intervals and lifetimes.

(D) SPEN were able to leverage consequent funding to upgrade an area of their network in anticipation of electric vehicle rollout. The collaboration also won several significant national awards, including the E&T 2019 Innovation of the Year Award.

2. Underpinning research

The UK government has committed to an ambitious decarbonisation agenda, and electricity distribution network operators (DNOs) are mandated to prepare the electricity distribution and supply network for the integration of low-carbon technologies from the rapid rollout of electric vehicles to embedded renewable generation (PV panels, wind turbines and combined heat & power systems). UK DNOs are required to operate and maintain their networks with statutory responsibility to ensure quality of supply to end-use demand customers. They are also required to connect and accept production from new renewable energy generation schemes and to interact with third-party demand management systems, to the satisfaction of the regulatory bodies and their investors. Active asset management is a key component to support the decentralisation of energy into local renewable energy supply and enable future growth. The UK spent GBP34 Billion between 2014-2020 to replace aging infrastructure and to modernise, automate and reinforce the network. The complex and highly distributed network of assets previously operated in a largely passive manner, but is now active, both in supply and demand. Both old and newer distribution network assets now need to be managed in real time and maintained with increased foresight, in order to minimise constraint on new supply and to ensure quality of supply to prescribed, enforceable standards. Compliance can be costly for developers and DNOs alike. Failure to maintain continuity of supply within defined limits will result in the regulator, OFGEM, issuing fines for consumer redress. OFGEM fined energy service providers GBP60M between 2019 and 2020.

SPEN is one of the UK's 'Big 6' electricity network and distribution operators, with responsibility for keeping the lights on for over 3 million domestic and industrial customers in Scotland, Wales and England, incorporating 128,000km of electricity network overhead lines and underground cables. Their asset base (cables, transformers, switchgear, protection and metering) is ageing, with large parts having been installed many decades ago, often suffering from poor observability. For example, the exact disposition and capacity of cables installed at many locations is no longer known, and physical verification is very costly and disruptive. ERPE researchers found that new embedded loads and generation, if improperly connected and managed, could cause voltage and power quality violations [3.1]. The rollout of smart meters (SM) in nearly every home presents an opportunity, but also requires conversion of massive new data-streams into reliable, actionable information. Moreover, due to constraints from the UK's energy regulator, OFGEM, this must be done in a privacy-preserving way for individual domestic/industrial customers.

The NCEWS [P1] Knowledge Transfer Partnership project, involving SPEN and ERPE researchers, designed a network operation and planning decision support system. There were three fundamental challenges that the research addressed.

1. The network asset base is never fully described and always contains static unknowns, such as missing network cable data, and dynamic error. The current state of the art in machine learning cannot perform to the required levels of accuracy when using data acquired from the working electricity network. ERPE researchers developed new machine learning (ML) techniques, specifically, deep learning and ML algorithms that could perform matching on asset paths [3.2]. For the first time, they were then able to accommodate the highly variable and imperfect data scenarios of real electricity networks. This allowed SPEN to backfill their asset database, with a high degree of confidence, by extracting information from data on other similar assets in the area, as well as smart meter data.

2. The determination of how much SM coverage was required to represent and monitor the system, to be able to make confident prediction and create accurate forecasts. ERPE researchers developed an operational decision support (ODS) system for network modelling that utilised metadata, including that derived from Geographical Information Systems, Asset Management Databases and Real-time Monitoring Equipment, to support forecasting of voltage violations. The ODS also created a standardised data management platform that was scaled into parallel and future projects. This brought quality assurance and scalability to data analysis in the electrical network.

3. Understanding the impact of network topology, EV energy demand, current energy demand and Distributed Generation (type and Level) on network performance. ERPE researchers combined the latest advances in ML and AI, with state-of-the-art tools for simulation of electricity networks (PSSE techniques) [3.3]. For example, in order to address data privacy concerns, the underpinning research showed that it is sufficient to collect data from several 'key identified locations' to predict with very high accuracy voltage deviation estimates for the whole network, and that this analysis can be performed without individual power consumption data [3.4]. Thus, the system operator does not need to have full observability of the power consumption of individual users, protecting their privacy. This enabled SPEN to identify which areas/subnetworks of their low-voltage (LV) distribution network are potentially most at risk from dangerous voltage excursions, due to developments such as EV uptake or solar panel installations.

3. References to the research

[3.1] **Journal:** Mokhtar, M., Robu, V., Flynn, D., Higgins, C., Whyte, J., Loughran, C., & Fulton, F. “Automating the Verification of the Low Voltage Network Cables and Topologies”, IEEE Transactions on Smart Grid, vol. 11(2), pp. 1657-1666, IEEE. DOI: 10.1109/TSG.2019.2941722 (2020)

[3.2] **Conference:** Mokhtar, M., Robu, V., Flynn, D., Higgins, C., Whyte, J., Loughran, C., & Fulton, F. (Nov. 2019). “Predicting the Voltage Distribution for Low Voltage Networks using Deep Learning”. In Proceedings of 9th IEEE International Conference on Innovative Smart Grid Technologies (ISGT-Europe), IEEE, pp 1-5, Nov. (2019). https://doi.org/10.1109/ISGTEurope.2019.8905434

[3.3] **Conference:** Mokhtar, M., Robu, V., Flynn, D., Higgins, C., Whyte, J., & Fulton, F. (Oct. 2018). “Automated Verification of LV Network Topologies”. In Proceedings of the 8th IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT), 1-5, (October 2018) https://doi.org/10.1109/ISGTEurope.2018.8571892

[3.4] **Conference**: Mokhtar, M., Robu, V., Flynn, D., Higgins, C., Whyte, J., Loughran, C., & Fulton, F. "Enabling Autonomous Reconfiguration of Low Voltage Networks", Proceedings of 25th International Conference on Electricity Distribution, Madrid, 3-6 June 2019, Paper ID: 1510, (July 2019) https://tinyurl.com/CIRED2019Mokhta

Some of the outputs cited above were deliberately published at prestige, peer reviewed conferences organised by the IEEE/CIRED, as the key means of engaging the research and user community quickly and efficiently.

Related Research Project Funding

P1 – Flynn (PI): Network Constraints Early Warning System (NCEWS), InnovateUK - Knowledge Transfer Partnership (KTP), grant no. KTP010658 (GBP73,595) 2017-2019.

4. Details of the impact

The multi-award winning NCEWS project [P1], supported by Innovate UK through a Knowledge Transfer Partnership (KTP) designed an operational and planning decision support system (DSS) that embodied the functional, operational and compliance requirements of the SPEN distribution system. The ERPE team were able, through their underpinning research [3.1-3.4], to create advances in machine learning techniques that were integrated into SPEN’s information platform and used to support strategic network planning decisions. This has supported the critical pathway to enable decentralised energy networks for future dynamic low carbon renewable integration. The impacts include:

(A) Deployment and Integration of NCEWS within Utility Network Management Platform

The NCEWS project integrated metadata, network expertise and novel machine learning-based analysis that achieved [5.1] three primary aims:

(i) It backfilled missing asset data (especially cables) in the SPEN system, by applying machine learning (ML) to detect patterns from both existing assets and smart meter (SM) data. This provided critical new network information without the disruption and expense of physical inspection [5.1].

(ii) It leveraged large-scale real-time data available from the rollout of smart meters, while preserving the privacy of individual consumers. This allowed SPEN to detect areas of the network which are prone to voltage violations and potentially poor supply quality, and to simulate the benefits of new investments, for example new electric vehicle (EV) charging stations, under large numbers of scenarios [5.1].

(iii) ERPE research was able to identify the optimal strategic SM sparse deployment locations, providing the equivalent accuracy in voltage prediction of a 100% SM installation. It accelerated network monitoring and reduced the associated costs [5.1].

The impact was increased and assured through the integration of NCEWS with the SPEN Network Analysis and View (NAVI*)* platform. It was rolled out and integrated as business-as-usual (BAU) across the company, to support real business and planning decisions. For example, when a network planner is unsure of the type of cable present in a particular location, he/she can inquire of the ML tool to provide a prediction that includes the degree of statistical confidence. This has allowed decisions to be taken that, hitherto, would have required physical verification (which is often expensive/unfeasible, as cables are buried underground, in complex locations) [5.1].

(B) Deferral of Network Renewal and Associated Cost Savings

The use of the ML systems has also led to significant economic impact [5.1]. A key benefit of predictions made by users of NCEWS is the potential to safely defer expensive network reinforcements [5.1]. Recent internal figures from SPEN show that in order to accommodate the rollout of EV charging, network reinforcements could be deferred, with savings of around GBP1,000,000,000 in the SPEN distribution area alone [5.1].

NCEWS uses real smart meter data across the network and helps to pinpoint critical sub-networks, where deferrals will result in cost savings. Examples of such cost-saving decisions include smarter selection of the placement of EV charging stations, distributed storage and demand-side response, and avoiding placement in areas of likely voltage/power violations. The NCEWS predictive tool, that uses real smart meter data across the company's network and helps pinpoint critical sub-networks, is now central to achieving these deferral savings [5.1].

(C) Enabling Digitalisation Strategy and Supporting Decarbonisation

NCEWS is now being integrated into a larger national roll-out and rebranded as NAVI as part of SP Energy Networks' 'RIIO-RD2' plans with OFGEM [5.1]. In the SPEN Digitalisation Strategy 2019, the NCEWS project and outcomes was cited as a key project, '*by reducing modelling design time by two thirds (67%)*', '*automatic tracing of the network also means much larger geographical areas can be analysed…. leading to improved understanding supporting informed decision making regarding network reinforcement*' [5.2]

More significant impact for NCEWS was in the standardisation of data collection across other innovation projects relating to energy networks [5.2]. At the launch and introduction of the 2019 SPEN Digitisation Strategy, the CEO of SPEN stated that "*Improvements in control, automation, flexibility and demand side management are helping us create a more dynamic and active network*," [5.3]

NCEWS is assisting SPEN to support the UK's decarbonisation agenda [5.1]. In some cases, where there is uncertainty whether a new investment project (e.g. building a new EV charging station) could lead to voltage/power violations, SPEN has had to err on the side of caution in the past, until the local network can be physically assessed and/or reinforced. With the aid of NCEWS, however, acting on real smart meter data, SPEN can make faster approval decisions, and faster approval/rollout of the decarbonisation investments [5.1].

(D) Consequent Funding and National Awards

The results of the NCEWS project enabled SPEN to leverage consequent funding for the PACE project, in collaboration with Transport Scotland and Scottish Government. PACE sought to accelerate and widen the installation of EV charging points across a weak area of the low voltage distribution network in Lanarkshire [5.1].

The ERPE and SPEN partnership, and the resulting development of the NCEWS, won national awards including the prestigious E&T 2019 Innovation of the Year Award [5.4].

Fiona Fulton, SPEN, Smart Grid Manager stated the significance of the project and relationship to their low-voltage (LV) network: *"The NCEWS project with Heriot-Watt University was a real success, that met and exceeded our expectations. The information platform developed allows SPEN to automatically backfill missing asset data, as well as using advanced analytics to identify 'at risk areas' and potential voltage excursions in our LV distribution network. The project leverages the massive amounts of data made available by the smart meter rollout, and allows SPEN to be at the forefront of European innovation efforts in this key area. The ongoing Business-As-Usual rollout across SPEN will enable all parts of the business to benefit from its results, which is an outstanding result for a knowledge transfer project"* [5.5]. The project resulted in several further awards, including

- 2019 IET's Information Technology Award [5.6].
- Top "outstanding" rating for a KTP project from InnovateUK [5.7],
- Knowledge Transfer Partnership (KTP) "Rising Star" award for KTP Associate Maizura Mokhtar, [5.8]

Overall, the project positioned SPEN at the cutting edge of electrical network modernisation and importantly serves as a keystone in their acceleration of decarbonisation and incorporation of low carbon technologies. [5.1]

5. Sources to corroborate the impact

[5.1] Scottish Power Energy Networks, Smart Systems Manager (contact person who will confirm implementation of solution and economic impact)

[5.2] SPEN's Digitalisation Strategy 2019, (page 58) Citing the NCEWS project – 'What is it and what it means for us (SPEN)'. https://www.spenergynetworks.co.uk/userfiles/file/RIIO-T2_SP_Energy_Networks_Digitalisation_Strategy.pdf?v=1.3

[5.3] Current+, Online News Article, Statement by CEO SPEN at the launch of the 2019 SPEN Digitisation Strategy – stating the improvements being made as result of automation and digitalisation. https://www.current-news.co.uk/news/spen-unveils-digitalisation-strategy-targeting-open-data-smart-systems-and-improved-monitoring

[5.4] IET press release announcing the E&T (Engineering & Technology) 2019 'Innovation of the Year' (Nov, 2019). https://eandt.theiet.org/content/articles/2019/11/ai-platform-for-power-networks-wins-top-prize-at-iet-innovation-awards/

[5.5] IET E&T magazine article - Evidencing the award, statement of impacts from SPE Networks Smart Grid Manager, and further developments (May, 2020). https://eandt.theiet.org/content/articles/2020/05/et-innovation-awards-ai-future-proofs-power-network/

[5.6] IET press release announcing IET 'Information Technology' Award 2019 for Heriot-Watt University and SP Energy Networks for their Network Constraints Early Warning System (NCEWS). (Nov, 2019)

[5.7] InnovateUK – Outstanding rating for the NCEWS KTP project between SPEN and Heriot-Watt University.

[5.8] SFC Interface Knowledge Exchange Awards - "Rising Star" award for KTP Associate Maizura Mokhtar (NCEWS project with SPEN). https://www.insider.co.uk/news/scottish-knowledge-exchange-awards-winners-14036240