Institution: University of Strathclyde		
Unit of Assessment: B12 - Engineering		
Title of case study: Improved standards and codes regulating GB and EU power networks ensure safe, stable and economic supply of electricity		
Period when the underpinning research was undertaken: 2007-2018		
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:**
Keith Bell Adam Dyśko	Professor Senior Lecturer	10/08/2005 – present 15/03/1999 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

A team of researchers, led by Bell and Dyśko, have made critical contributions to reliability, stability and cost of the electricity supply in Great Britain and Europe, through expert advice and changes to industry-wide technical codes and engineering standards. This has enabled renewable energy to increasingly form part of the energy mix available to consumers, while ensuring safety and security of supply. Research has informed capital expenditure and long term investment in the GB transmission system. Technical innovations and changes to standards have lowered cost barriers to renewable generation and demonstrated that renewables can provide a flexible source of energy, replacing thermal generation to achieve low carbon targets.

2. Underpinning research

UK Government policy in recent years has driven a dramatic expansion in electricity generation from renewable sources in Great Britain. Wind and solar power have different technical characteristics from thermal generation from coal, gas or nuclear power stations, and are connected to the system in different places. Engineering solutions were therefore needed to ensure that the nation's power system could accommodate a massive growth in use of renewables, and maintain a safe and stable system, while avoiding excessive costs that would be passed on to consumers. Since 2006, Prof Keith Bell and Dr Adam Dyśko have led a team of researchers in the Engineering Faculty at University of Strathclyde to carry out this critical work in projects in collaboration with National Grid, Ofgem and the renewables industry. Key issues addressed by this body of research include:

The effect of wind generation on transmission system flows and associated costs; development of new planning methods: In 2006-2008 the team led by Bell undertook research into the complexities of spatial and temporal variability of wind, the development of a statistical model to analyse the variable wind energy outputs across Britain and how they may affect the need for network capacity. The concept of separating transmission capacity which is motivated by facilitation of the wholesale electricity market ('economy-driven') from transmission capacity motivated by security of supply ('reliability-driven') was developed and demonstrated [R1, R2]. New methods and tools were then developed in 2016-18 to cluster operational scenarios in which patterns of demand and the availability of power from renewables are similar, thus reducing need for detailed analysis by a network planner [R3]. This research also demonstrated automated assessment of power flow and voltage impacts through the use of optimisation to model operation of a wholesale electricity market and the actions of a system operator to re-dispatch generation in order to avoid breach of network limits [R3].

Safe operation of 'Distributed Generation' and 'Loss of Mains' protection: The Strathclyde team investigated the risks associated with different 'Loss of Mains' (LoM) protection settings to verify whether risk levels were acceptable by Health and Safety Executive standards [R4]. Small power generation – 'distributed generation' (DG) – is most cost-effectively connected within the distribution network, closer to the electricity consumers. However, when a connection between DG and the main interconnected transmission system is lost, this needs to be reliably detected by LoM relay, and the generator must be promptly disconnected to prevent unsafe islanded operation. If loss of connection is not detected it can cause safety issues for staff and plant; if settings are over-sensitive it can potentially lead to a blackout of the whole electricity system. As such the LoM relay settings are vital. The research studied the stability and sensitivity of two prevailing LoM protection methods, 'rate of change of frequency' and 'vector shift', and developed an innovative monitoring data-based assessment methodology, which provided the means and supporting evidence for achieving best compromise settings in LoM protection [**R4**].

Stability of electricity supply with increased penetration of converter connected sources of power: Through a 3-year collaborative project with National Grid, the research team demonstrated that the GB power system would be unable to accommodate levels of renewable generation expected by 2030 without risking instability or reduction of renewable generators' output, with subsequent curtailment payments to generators of potentially hundreds of millions of pounds per year [**R5**, **R6**]. The research showed that this is a fundamental issue with unstable interactions of converter-connected sources of power across a wide band of electrical frequencies. Factors were identified that would significantly reduce unnecessary curtailment of renewable generation and associated costs, including a requirement for a proportion of converter connected sources of power to have 'grid-forming' control, such as a virtual synchronous machine, rather than the 'grid-following' control typically used.

3. References to the research (Strathclyde affiliated authors in **bold**)

R1 **Ault, G.W.**, **Bell, K.R.W.** & **Galloway, SJ.** (2007). Calculation of economic transmission connection capacity for wind power generation. *IET Renewable Power Generation, 1(1)*, 61-69. https://doi.org/10.1049/iet-rpg:20060020

R2 **Bell, K.R.W.,** Nedic, D.P., & **Martin, L.A.S.S** (2012). The Need for Interconnection Reserve in a System With Wind Generation. *IEEE Transactions on Sustainable Energy, 3(4),* 703-712. https://doi.org/10.1109/TSTE.2012.2208989 [REF2 in 2014]

R3 **Bukhsh, W.**, **Bell, K.R.W.**, Vergnol, A., Weynants, A., & Sprooten, J. *Enhanced, risk-based system development process: a case study from the Belgian transmission network.* 20th Power Systems Computation Conference (PSCC), Dublin, 2018. https://doi.org/10.23919/PSCC.2018.8442756

R4 **Dyśko, A.**, **Tzelepis, D.**, **Booth, C.**, Pollock, J., & Hill, D. (2018). Practical risk assessment of the relaxation of LOM protection settings in NIE Networks' distribution system. *The Journal of Engineering, 15*, 1335-1339. https://doi.org/10.1049/joe.2018.0203 [REF2]

R5 **Yu, M.**, **Dyśko, A.**, **Booth, C.**, **Roscoe, A.J.**, Zhu, J., & Urdal, H. (2015). *Investigations of the Constraints relating to Penetration of Non-Synchronous Generation (NSG) in Future Power Systems*. Protection, Automation & Control World Conference (PACWorld). Glasgow, UK. https://strathprints.strath.ac.uk/53806/

R6 **Yu, M.**, **Roscoe, A.J.**, **Dyśko, A.**, **Booth, C.**, Ierna, R., Zhu, J., & Urdal, H. (2016). Instantaneous Penetration Level Limits of Non-Synchronous Devices in the British Power System. *IET Renewable Power Generation, 11(8)*, 1211-1217. https://doi.org/10.1049/iet-rpg.2016.0352

Notes on the quality of research: Key outputs above were peer-reviewed before publication or conference presentation. The underpinning research body has been supported by a total of GBP1,206,728 of funding, peer-reviewed funding from Government, and funding from industry subject to strict criteria set by the electricity regulator, including from National Grid (e.g. Booth, Dyśko, Roscoe. Control and protection challenges in future converter dominated power systems, National Grid, 01/10/2013-30/09/2016, GBP263,594.00) and directly from Ofgem (Bell, Ault, McDonald, Kockar, 'Project TransmiT' review of transmission charging, 2010-2011, GBP60,000).

4. Details of the impact

Research led by Dyśko and Bell, implemented through technical advisory roles and collaboration with key stakeholders in Great Britain and Europe, has led to improvements and benefits affecting:

- National Grid Electrical System Operator, the organisation which operates the high voltage electric power transmission system for Great Britain, the European Network of Transmission System Operators for Electricity and ELIA, the electricity system operator in Belgium.
- Ofgem, the Office of Gas and Electricity Markets, a non-ministerial government department with a remit to encourage competition between energy providers and protect consumers, and

which oversees legal obligations, industry codes and engineering standards including the Security and Quality of Supply Standard, the Distribution Code and associated Engineering Recommendations, the Grid Code and Transmission Network Use of System charging methodology.
- All renewables operators who provide low carbon power to the GB system, and consumers who gain from lower costs in electricity transmission networks, stable and secure supplies of electricity, and an increasing mix of low carbon energy from renewables.

Improved decision making on expenditure and long-term investment in power networks

The Security and Quality of Supply Standards (SQSS) sets out legal obligations on the transmission network licensees for planning and operating the GB transmission network. The Head of Networks (NG ESO) confirms that Bell's research [**R2**] led to the split of 'economy driven' from 'reliability driven' planning criteria in the SQSS in November 2011 [**S1**]. From August 2013 these standards continued to define the legal obligations on the transmission network licensees and guide the level of capital expenditure by network owners. This is estimated by Ofgem to be over GBP6,300,000,000 in the period 2014 – 2021. The SQSS also dictates what the Electricity System Operator (ESO) must spend on 'balancing services' to ensure stable operation (more than GBP1,200,000,000 in 2019-20).

Bell's contribution to SQSS revision, with *'an associated clearer focus on economic appraisal*' [**S1**] led to the institution of a new process, the 'Network Options Assessment' (NOA), to determine the ESO's long term investment plans for the GB transmission network. In 2016, ESO implemented software to model GB and European energy markets (including growth in renewable generation), and in 2017 Bell was appointed to review the modelling tool's configuration and benchmarking. NG ESO Head of Networks [**S1**] states that '*the expert advice and challenge by Bell and team to review the system set-up, assess and validate assumptions, and critique a back-casting report has provided the ESO with confidence to not just implement the software but to expand its use through … projects which are key to enabling the GB energy system to run carbon free.'* Following Bell's review, the NOA process in its most recent iteration has been used to assess the benefits of potential investments across a broad range of demand/supply scenarios, to justify GBP183,000,000 spend in FY21/22 and inform plans for a potential spend of GBP13,900,000,000 across the next decade [**S1**].

Research by Bell and Bukhsh [**R3**] was applied in the Network Innovation Allowance (NIA) project with NG ESO from October 2019 onwards to further enhance the NOA process and '*to assess significantly more future scenarios for generation and demand than currently feasible using existing tools and techniques'* and allow *'more informed investment and operational decisions to ensure a secure, economic and efficient electricity grid'* [**S1**]. NIA project activities have enabled NG ESO to plan with greater flexibility *'as the network is moving away from historic 'Winter Peak' concerns to lightly loaded summer periods providing greater reactive needs; this has been exacerbated during the COVID pandemic with lower than average demands. For context, the ESO spent ~£70m on voltage related constraints since April 2020.*' [**S1**]. Bell's research and advice on network innovation were also instrumental in persuading the Gas and Electricity Markets Authority (GEMA, the governing body of Ofgem) to make a GBP600,000,000 package of innovation funding available to the sector in December 2020 for the period 2021 to 2026 [**S3**].

The Head of Power System Planning for the Belgian transmission system operator, Elia [**S2**], confirms that a research partnership with Strathclyde was used in 2017 to '*improve Elia's investment strategy, helping to ensure the consumers have a reliable supply of electricity and increasing the hosting of new, low carbon sources of electricity in the grid*' with improvements to their system development and investment planning process. This approach has been adopted by Elia to allow better targeting and justification of network investment in Belgium's electricity network.

Capital investment of GBP820,000,000 in the Beauly-Denny overhead power line was also informed by Strathclyde research [**R1**], cited in the Technical Assessor's report in the public inquiry into this development (2007) and which addressed key technical requirements of construction and economic cost, which were critical to the approval process [**S4**]. The Beauly-Denny line is a 220km overhead line along the north south axis of Scotland's electricity network, replacing over 800 pylons which were constructed in the 1950's. Overhead line works began in 2014, with power transmitted along the line from Nov 2015 onwards, enabling renewable generation and export of wind power from the North of Scotland to the rest of GB, and avoiding excessive electricity market costs.

Bell was also engaged by Ofgem as technical advisor to its enquiry into the August 9th, 2019 electricity supply interruptions in which supplies to 1.1 million consumers were lost, advising on key engineering issues and potential breaches of licence obligations by the ESO and generators [**S3**]. The enquiry established that two large power stations did not remain connected after a lightning strike, and the owners of these stations subsequently agreed to make a voluntary payment of GBP4,500,000 each into Ofgem's redress fund.

Fairer charging for use of the GB transmission network

Electricity generators and suppliers pay annual 'Transmission Network Use of System' (TNUoS) charges to recover the costs of the networks owners' provision of transmission assets. The total cost of electricity transmission network infrastructure to be recovered through TNUoS charges is around a few billion pounds annually; in 2019/20, it was GBP2,840,000,000 [**S3**]. With significant amounts of new and low-carbon generation required to connect to GB electricity networks to meet low carbon targets, in 2009 Ofgem initiated Project TransmiT to consider whether the existing charging arrangements were fit to meet the challenges of the future [**S1**]. Four 'academic reviews' were commissioned by Ofgem at that stage, and the Deputy Director, Networks (Ofgem) confirms that '*Prof Keith Bell led one of the academic reviews and was the main author of the associated report. The report and its recommendations were a critical influence on Ofgem's thinking on the subject of reform of the transmission network charging arrangements in 2011-14 when arrangements that still apply now were put in place*.' [**S3**].

Bell's main recommendation was based on his research on wind outputs and the drivers for network investment [**R2**]. He proposed a split of TNUoS charges into a 'peak-related' component (only paid by non-intermittent generators, such as gas plants) and a 'year-round' component (paid by all generators in proportion to their 'capacity factor'). This change was approved by Ofgem in July 2014 and implemented in April 2016, removing a major barrier to competition, and reducing charges paid by geographically remote operators such as wind farms, while retaining a cost-reflective signal from these locations. Ofgem's impact assessment estimated a benefit to wind generators in the North of Scotland in 2014 of £13/kW, (equating to GBP24,000,000 for generators there) [**S5**]. Speaking at the time, Ofgem stated: '*We consider this to be a significant improvement to the existing approach … it is low carbon plants in particular that are currently being inappropriately charged and hence face an undue barrier to entry in some parts of the transmission system where there is significant potential for the deployment of renewables (e.g., the north of Scotland).*' [**S5**] Since 2014 the Project TransmiT report remains *'a 'go to' reference for the industry, clearly setting out the main principles that should be considered when setting regulatory arrangements for the electricity network and the levying of charges to recover the network's cost'* [**S3**]. In their Impact Assessment [**S5**] Ofgem estimate the total benefits of the changes to TNUoS charging over the period 2014-2030 to Net Present Value to consumers of GBP3,800,000,000.

Ensuring safe and stable operation of the GB electricity network

Loss of Mains (LoM) or 'islanding' occurs when part of the network (incorporating generation) loses connection with the rest of the system, potentially causing a safety hazard. The problem increases as more distributed renewable energy generation is connected to the grid, and Ofgem set up two working groups (2013-2016) to address this issue and adapt Engineering Recommendation (ER) G59, a key document governing the connection of all but the smallest distributed generation in the electricity network.

The Chair of Distribution Code Review Panel [**S6**] confirms that Dyśko was the lead technical expert on the working groups that addressed the risks, costs and benefits associated with changing the existing settings of LoM protection, with Dyśko's research expertise [**R4**] critical in confirming that additional safety risk resulting from relaxation of the LoM protection settings was tolerable [**S1**]. The case for change was subject to scrutiny by the Distribution Code Review Panel of Great Britain and by the Health and Safety Executive before sign off by Ofgem. In December 2017 Ofgem published modifications to the Distribution Code and ER G59, to reduce losses of generation following transmission faults and prohibiting the use of voltage vector shift (VS) devices as an alternative to established LoM protection [S7]. This led to a programme of 'vector shift protection removal' which began in mid-2018 and will result in the eventual application of new LoM protection settings to 50,000 distributed generation sites in Great Britain. The Chair of Distribution Code Review Panel also notes that that the change to the Distribution Code and ER G59 were '*an essential underpinning of the path to decarbonize GB's electricity system and would not have been possible … without the rapid research, development and implementation of (Dyśko's) risk assessment analysis.'* [S6]

Referring to the change of codes, the Network Operability Manager of National Grid ESO stated: '*The result is a network management benefit which gives much more flexibility before generators disconnect. It will mean we'll be able to operate the grid more efficiently and safely than ever before.*' [S8] The economic importance of the change is that UK renewable generation is no longer shut down in an 'over cautious' manner in order to balance the grid. Given that renewable operators are paid by NG ESO to shut down generation, these changes to distribution codes and ER G59 enable a significant reduction in costs for NG ESO, without risking instability or reduction in renewable generators' output. This was confirmed by NG ESO's Head of Networks: '*This leads to a significance reduction in operational costs – estimated at GBP150,000,000/annum in 2019 but will increase in the future; an increase in the percentage of energy from zero carbon; and an overall increase in the security of supply in GB*.' [S1]

EU and UK planning for 2030 targets for renewables in power systems

Through a 3 year collaborative project with NG ESO, Strathclyde researchers addressed issues of lack of 'system strength' and instability when thermal generation is replaced partially or wholly by renewables, [R5, R6]. In 2016, they conducted the first assessment of the impact of the converter control approach on the GB system, with a virtual synchronous machine or Grid Forming Converter (GFC), to regulate the frequency and voltage of the system using power from wind turbines. As a direct result of this research, the European Network of Transmission System Operators for Electricity (ENTSO-E) and the EU power community accepted that some of their mandatory network codes were not sufficient to ensure stable operation of power systems in countries with the highest wind and solar energy penetration [S9]. ENTSO-E and Strathclyde researchers worked on two Implementation Guidance Documents in Autumn 2017, to provide advice to 34 European countries on when to go beyond their mandatory requirements and, for the first time, laid down draft definitions for grid-forming converters and fast fault current infeed [S9]. In Britain, NG ESO responded to Strathclyde's recommendations to ENTSO-E with the implementation of Grid Code modifications GC0100 and GC0101 in May 2018 and set up an expert group to assess the technology of grid-forming converters, in particular virtual synchronous machines, and develop further changes to the Grid Code [S1].

In collaboration with renewables operators, a world first trial of the GFC control strategy took place at a wind farm in Scotland in 2019 [S9, S10]. The trial demonstrated that a wind farm can restore power in the event of a total or partial shutdown of the electricity transmission system, potentially removing reliance on coal and gas for this aspect of stability of supply. The CEO of Scottish Power Renewables considered this to be an '*example of collaboration and innovation to deliver something exceptional that will change how renewables interact with the grid forever.'* [S10].

Sources to corroborate the impact

S1 Corroborating statement from Head of Networks, Chief Engineer, NG ESO, dated Feb 2021.
S2 Corroborating statement from Head of Power System Planning, ELIA, dated Dec 2020.
S3 Corroborating statement from Deputy Director Networks, Ofgem, dated Feb 2021.
S4 Beauly-Denny Public Inquiry: Report of the Technical Assessor.
S5 Project Transmit Impact Assessment of industry's proposals (CMP213) to change the electricity transmission charging methodology. https://bit.ly/3lpKCwb
S6 Corroborating statement from Chair of Distribution Code Panel (2015), dated Dec 2020.
S7 Ofgem decision paper on Modification DC0079 – Frequency Changes during Large Disturbances and their Impact on the Total System. https://bit.ly/3bLI60a
S8 National Grid ESO. *Keeping the grid stable – what is Loss of Mains Protection?* https://bit.ly/3bOauyz
S9 Corroborating statement from Technical Consultant for ENTSO-E, dated Dec 2020.
S10 ScottishPower. *Global First for ScottishPower as COP Countdown Starts*. https://bit.ly/3ljENQW