Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Policy and Standards on Secure and Efficient Decarbonisation of Energy System
Period when the underpinning research was undertaken:	2005 - 2020
Details of staff conducting the underpinning research from the submitting unit	

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
Professor Goran Strbac	Professor in Electrical Energy Systems	2005 - present

Period when the claimed impact occurred:	1 Aug 2013 – 31 July 2020
Is this case study continued from a case study submitted in 2014?	No

1. Summary of the impact

Professor Strbac and his team have created a modelling and optimisation framework to evaluate energy network designs under various scenarios of carbon-emission limit, supply security, demand growth and technology costs. The impact of this research is:

1. to inform and influence government energy policy for decarbonisation of electricity, gas, heat and transport sectors through the Department of Business, Energy and Industrial Strategy (BEIS) in its *Clean Growth Strategy* (October 2017), and through the Office for Gas and Electricity Market (OFGEM) in its *Smart Systems and Flexibility Plan* (July 2017);
2. to inform the Committee on Climate Change (CCC) in their report "*Net-Zero Technical Report*" (May 2019), produced at the request of the Secretary of State to inform her policy initiative, which made twenty-three references to Strbac's research;
3. to enhance the design standards (March 2019) created by the Electricity Networks Association's (ENA) Distribution Code Review Panel (DCRP) for electricity networks, which have been re-written to include new approaches to providing resilience and security of supply through flexibility of control rather than asset redundancy;
4. to result in GBP100,000,000 savings in investment costs for UK Power Networks ahead of changes in ENA standards through new design principles based on Strbac's research findings, with similar savings by other distribution network owners.

2. Underpinning research

Prof Strbac is known for creating optimisation methods that identify least-cost means to plan electricity networks and generation infrastructure. Through a series of ESPRC-funded projects, he and his team have made important advances so that traditional energy system planning can be replaced with methods that facilitate net zero-carbon emissions in electricity and beyond. His new optimisation methods identify energy infrastructure designs across energy vectors of electricity, gas, heat and transport energy. The research identifies the roles and value of new control paradigms, new technologies, consumer flexibility and interactions between vectors. These insights enable deep decarbonisation at least cost. Three advances in the underpinning research are critical to this.

Accommodation of Temporal and Spatial Interactions

Strbac has demonstrated that the least-cost system design can only be obtained through optimising a "whole-system" model that considers, simultaneously, interactions across a wide range of time-scales and across length-scales. He has identified judicious approximate representations and archetype networks can make this problem computationally tractable.

The *time-scale* challenge is that decadal investment horizons include consideration of assets needed for second-by-second demand-supply balancing in the most difficult half-hour of the most difficult year. The *spatial-scale* and *asset-type* challenge is that a national electricity system might achieve demand-supply balance through provision of network assets for street-level access to electric vehicles or international interconnection to countries with complementary renewable portfolios to trade energy or network services with other countries.

The key scientific contribution is the computationally-efficient fine-grained representation of energy network in both time and space within the whole-energy system optimisation models of [R1]. In order to manage real-time variability in renewable generation, appropriate levels of 'reserve' are scheduled by the developed system optimisation model. This required approximating, through linear constraints in mixed integer programming, the uncertainty over renewable generation and the operational constraints of conventional generation (e.g., start-up and no-load costs) [R2]. Extra "frequency response" is also need as physical inertia decreases. The differential equations governing this were approximated by algebraic relationships calibrated against detailed transient-response simulations [R3]. Fine spatial granularity is needed to capture the different characteristics urban, semi-urban, semi-rural and rural distribution networks. Cost-functions representing the statistical distribution of network reinforcement costs were identified for reinforcement driven by the growth in peak-demand (from EV charging, heat pumps etc.) [R4]. The accuracy of both time and spatial approximations through linear algebraic models has been demonstrated through comparison with accurate, but much more complex, non-linear, mixed-integer and dynamic models. Through this, Strbac's model captured, for the first time, the interactions across different time scales and across different asset types and allowed quantification of the value of emerging technologies such as distributed energy storage and price-responsive demand. This expansion of the model to be "whole system" opened up assessment of how technologies that bring flexibility (such as energy storage) can create more economically efficient operation of networks and reduce long-run investment in the energy infrastructure from street to national level [R1].

Multi-Vector Energy Systems

With attention turning to de-carbonisation of building heating and transport, Strbac created models of the interactions between electricity, gas and heat energy vectors and interaction with transport energy provision [R5]. The computational challenge for integrating these other energy vectors into the whole-electricity system model [R1] is the complex non-linear operational characteristics of combined heat and power (CHP) plant and large-scale heat pumps. Piece-wise linear algebraic approximations have been formed and calibrated against detailed models to balance modelling accuracy and computational efficiency.

These models show that district heat networks and hybrid heating can provide flexibility in operation that can be exploited in the electricity system to increase the volume of renewable energy that can be accommodated. The insight gained was that increasing investment in heating infrastructure beyond that if heat is considered alone delivers cost savings in the electricity system that yield a lower overall cost across the combined system.

Security-Driven Design

Avoidance of "power cuts" has, in historic terms, been achieved through "design rules" on redundancy provision. Strbac's security-driven design [R6] is a new framework in which demand-side response, distributed generation and energy storage technologies [R1] have their contribution to security quantified. His team analysed traditional network reinforcement and security through non-network technologies in terms of "Expected Energy Not Supplied" and "Equivalent Firm Capacity" to provide a fair basis of comparison. [R6] shows that using these "non-network" assets instead of redundant substation assets is more cost-effective.

3. References to the research

[R1] Pudjianto D, Aunedi M, Djapic P and **Strbac G**, "Whole-Systems Assessment of the Value of Energy Storage in Low-Carbon Electricity Systems", IEEE Trans. on Smart Grids, (5) 2, 1098-1109, 2014. https://doi.org/10.1109/TSG.2013.2282039

[R2] Sturt A and **Strbac G**, "Efficient Stochastic Scheduling for Simulation of Wind-Integrated Power Systems", IEEE Trans. Power Syst., (27) 323-334, 2012. https://doi.org/10.3389/fenrg.2015.00036

[R3] Teng F, Aunedi M, Pudjianto D and **Strbac G**, "Benefits of demand-side response in providing frequency response service in the future GB power system", Frontiers in Energy Research, (3), 2015. https://doi.org/10.3389/fenrg.2015.00036

[R4] Gan CK, Low SY, Pudjianto D and **Strbac G**, "Techno-economic appraisal of alternative distribution network design options", IEEE International Conference on Power and Energy (PECon), Publisher: IEEE, Pages: 829-833, 2012. https://doi.org/10.1109/PECon.2012.6450332

[R5] Qadrdan H, Ameli H, **Strbac G**, and Jenkins N, "Efficacy of options to address balancing challenges: Integrated gas and electricity perspectives," Appl. Energy, (190), 2017. https:// doi.org/10.1016/j.apenergy.2016.11.119

[R6] Djapic P, Tindemans S and **Strbac G**, "Comparison of Approaches for Quantifying Demand Side Response Capacity Credit for the Use in Distribution Network Planning", IET Conf. on Resilience of Transmission and Distribution Networks, 2015. https://doi.org/10.1049/cp.2015.0877

4. Details of the impact

(I1) Informing policy for decarbonisation of the GB energy system

Strbac's team used the fine temporally and spatially resolved model reported in [R1] to compare the cost of a network using storage [R2] and demand-side action [R4] to one without, to generate the evidence in a commissioned report "*Delivering future-proof energy infrastructure*" by Imperial and Cambridge for the National Infrastructure Commission (NIC) published in February 2016. The report identified that a smart grid paradigm would save approximately GBP8,000,000,000 per year from 2030 onward compared to a conventional network. The NIC's own report on "Smart Power" [E1] in May 2016 quoted Imperial's report as references 7, 9, 12, 15, 26, 30, 36, 39, 69 and 84 in setting out their recommendations to government for infrastructure development.

BEIS commissioned Imperial College and the Carbon Trust to provide evidence on the role and value of system flexibility to plan for the future of Great Britain's energy system. Strbac's team again used the model reported in [R1] to make this assessment. This evidence, which was made public in a report "*An analysis of electricity system flexibility for Great Britain*" of November 2016, demonstrated that these forms of flexibility can provide an 'option value', whereby small investments in flexibility can postpone decision-making on large infrastructure investments, hence reducing the need to make decisions with potentially high regret outcomes. A specific finding (Executive Summary, page 3) was "*The UK could save £17 to 40 bn across the electricity system from now to 2050 by deploying flexibility technologies*" has been highly influential. (Note, NIC quotes annual savings but this report quotes total savings.)

Following assessment of the report to BEIS, OFGEM published its plan for upgrading UK energy systems [E2a] (July 2017) which cites the report (on pages 4 and 5) to support estimates of cost savings for UK of up to GBP40,000,000,000 by deploying technologies such as energy storage technologies that bring flexibility. The OFGEM report [E2a] picks up two more examples of Strbac's work when, on page 10, it says that *"Many of* [the proposed actions] *build on the actions identified in a number of recent studies on smart energy, including the National Infrastructure Commission's 'Smart Power' report … and the recently published Committee on Climate Change annual progress report to Parliament*". The first report is [E1], for which the technical evidence was Strbac's commissioned report for NIC. The second report is [E2b] for which Strbac was again commissioned to provide technical evidence [E2c]. [E2b] has a break-out box on page 61 on system impacts of renewables and flexibility that is based on [E2c].

OFGEM's proposed actions (summarised on page 22 of [E2a]) are to improve the market framework, catalyse innovation and re-shape network operator roles for a transition to a smart and more flexible energy system with government committing GBP70,000,000 to support smart energy technologies in response to recommendation 1.9. For the first time, topics such as "whole-system approach" and "planning under uncertainty" are part of the regulatory framework, driven by the evidence in Strbac's report to BEIS of the cost savings achievable. OFGEM confirm in a letter [E2d] the importance of Strbac's work in the regulatory framework known as RIIO-2 and in the Smart Systems and Flexibility Plan which is [E2a].

Strbac's calculation of a saving of GBP17,000,000,000 to GBP40,000,000,000 through smart flexible systems is also cited on page 99 of the "*The Clean Growth Strategy*" published by BEIS in October 2017 [E3]. [E3] cites Strbac's report to BEIS on page 99, and that in turn cites Strbac's report to NIC for the valuation.

(I2) Uptake by Committee on Climate Change (CCC)

The CCC was established by the Climate Change Act 2008 with a duty to advise the UK government and governments of Scotland and Wales on carbon budgets and to report to parliament annually on progress against those budgets. There was an imperative in 2017 to find evidence on minimum-cost pathways for heat decarbonisation and Strbac was commissioned to provide system cost estimates from his models to support the CCC's work which was published as a report "Analysis of alternative UK heat decarbonisation pathways" to CCC in September 2018.

(a) Strbac's team was asked to analyse pathways for decarbonising building and industrial heating. In Strbac's report for the CCC, the whole-energy system model described in [R1] and its multi-vector extensions [R5] was used to analyse: (i) conversion of the gas grid to low-carbon hydrogen, (ii) electrification of heat with heat pumps and resistive heating and (iii) hybrid use of heat pumps and biogas boilers. Subsequently, the CCC's own report on hydrogen in low-carbon economy [E4a] uses Strbac's modelling and findings on system costs for thirteen of the figures in the report and as support for specific conclusions such as "*A hybrid heat pump pathway based on methane as the residual gas has lower costs than other decarbonisation pathways based on the results of the Imperial College optimisation modelling*" (Page 33). The work is also cited (as an unpublished draft) in [E4b] (page 113) to compare costs of pathways.

(b) Secretary of State for BEIS requested CCC to report on "setting a date for achieving net zero greenhouse gas emissions from across the economy" in October 2018. This became the report "Net Zero: The UK's contribution to stopping global warming" of May 2019. Strbac and Vivid were commissioned, in turn, to write a report on "Accelerated electrification and the GB electricity system" published later in 2019. The report, together with Strbac's report to CCC, are major sources (quoted 23 times) of material for Chapter 2 "Power and Hydrogen Production" of the CCC's "Net-Zero Technical Report" [E5].

(I3) Fundamental review of distribution network design standards

Strbac was appointed a member of Working Group P2 of the DCRP, an industry and OFGEM body responsible for standards that apply to distribution network companies. Strbac's team, working through the Energy Network Association (ENA), used the methods reported in [R6] to provide evidence on the cost-effectiveness of the historical network design standards which was published by ENA as "*Review of Distribution Network Security Standards*" in March 2015. The report demonstrated the use of a new concept that enables network planners to directly compare conventional network reinforcement and non-network solutions including energy storage, embedded generation and demand-side response. These findings were used to recommend an update to the framework specified in Engineering Report 130 (EREP 130). [E6a] is the notice of that recommendation, and in Section 2 as one of five proposed changes it states, "*Update the F factors for assessing the contribution to security from Distributed Generation … based on work carried out for ENA by Imperial College London*" with Strbac's report to ENA called up as Appendix 4. The agreed Code change, Issue 3 of EREP 130, was published August 2019 [E6b]. Strbac's report appears as reference N9 in [E6b] and is cited 14 times including in Annex G which serves as a guide to application of the method within the standard.

(I4) Uptake by UK Power Networks

UK Power Networks have used the signalled change in distribution code [E6a] to begin using the concepts in Strbac's report to ENA and has contracted control services from distributed energy resources as a substitute for network reinforcement [E7]. This has reduced their overall costs while maintaining security of supply. Savings made against investment plans previously agreed with the regulator OFGEM, are retained in part by UKPN and the wider public benefits from a reduced network cost component in their electricity bills. The estimated benefit is GBP100,000,000 [E7].

5. Sources to corroborate the impact

[E1] National Infrastructure Commission, "Smart Power", 4th March 2016. PDF archived here.

[E2a] Ofgem, "Upgrading Our Energy System: Smart Systems and Flexibility Plan", July 2017. PDF archived here.

[E2b] Committee on Climate Change, "Meeting Carbon Budgets: Closing the Policy Gap" Report to Parliament, 2017. PDF archived here.

[E2c] Pöyry and Imperial College, "Roadmap for flexibility services to 2030", 2017. PDF archived here.

[E2d] Director of Energy Systems Management and Security, OFGEM. Letter stating impact of Strbac's work on regulatory framework RIIO-2 and the Smart System and Flexibility Plan [E2a]

[E3] BEIS, "The Clean Growth Strategy: Leading the Way to a Low Carbon Future", October 2017. PDF archived here.

[E4a] The Committee on Climate Change, "Hydrogen in a low-carbon economy", Nov 2018 (References to "Analysis of alternative UK heat decarbonisation pathways" appear on pages 9, 14, 26, 28, 31, 32, 33, 34, 35, 36, 48, 49, 50, 70, 74, 78, 80, 81, 82, 84, 85, 86, 87, 95, 98, 99, 103, 105, 107, 108, 110 and 111) PDF archived here.

[E4b] The Committee on Climate Change "Reducing UK emissions - 2018 Progress Report to Parliament", June 2018. PDF archived here.

[E5] Committee on Climate Change "Net Zero Technical Report", May 2019. PDF archived here.

[E6a] DCRP DCRP/MP/19/02 - "Revision of Engineering Report (EREP) 130 - Guidance on the application of P2, Security of Supply", Final Modification Report, March 2019. PDF archived here.

[E6b] Electricity Networks Association "Guidance on the application of Engineering Recommendation P2, Security of Supply", Engineering Report 130, Issue 3, August 2019. PDF archived here.

[E7] Letter from the Director of Asset Management, UK Power Networks, stating the impact of Strbac's work on investment costs for network reinforcement in UKPN distribution licence areas.