Institution: Imperial College London Business School		
Unit of Assessment: C17 Business and Management Studies		
Title of case study: Informing decisions and debate on low-carbon electricity		
Period when the underpinning research was undertaken: 2011-2017		
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:**
Richard Green	Professor of Sustainable Energy Business	09/2011 - Present
Iain Staffell	Lecturer in Sustainable Energy Systems	11/2015 - Present
Period when the claimed impact occurred: October 2013 onwards		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

When the European Commission decided to give State Aid Clearance for a 35-year, £70 billion, contract with the Hinkley Point C nuclear power station (now under construction), our economic modelling provided a key part of the evidence base. We showed the proposed UK government intervention would change the electricity industry's investment decisions, thus meeting one of the three tests set in EU law.

Our improvements to wind production estimates for electricity modelling have informed UK policymakers and the open source "Renewables.Ninja" wind output simulation data is used around the world, including for the International Energy Agency's flagship World Energy Outlook.

We contribute to public debate through the Drax Electric Insights website and quarterly newsletter, providing data and analysis for Britain's power system, frequently quoted in the UK media.

2. Underpinning research (indicative maximum 500 words)

Green and Staffell are researching the best way to decarbonise electricity generation, an essential step in meeting net-zero targets. In particular they have a longstanding collaboration to develop economic-engineering models of the power system that are realistic but flexible and fast-solving and apply them to policy-relevant problems. They build optimisation models and simulations that impose the equilibrium conditions of profit-maximising firms in a competitive market, using linear or non-linear programming. The economics of dispatching (using) power stations variable cost "merit order" are well-known, but the research challenge is to choose which costs, constraints and heuristics to include in a specific implementation, trading off accuracy against solution speed. The research aims to develop sufficiently accurate models that can be run easily enough to allow numerous scenarios to be tested, including the impact of different government policies and exogenous factors such as fuel prices.

Because an annual model solves quickly, successive individual years can be simulated in turn to calculate generators' expected lifetime profitability. Another module adjusts investments to avoid unprofitable projects, and the cycle repeats until a long-run equilibrium is reached. The combined model is documented in **3.1**, the report produced for the European Commission, which shows results from a range of scenarios, both with and without the proposed government support for nuclear stations. Several sensitivity analyses were run to ensure that the results would be robust enough for use in a significant policy decision. The model has since been extended in **3.2**, which uses the model to show the impact of different levels of investment in renewable generators (wind and solar) and alternative carbon price trajectories on investment and closures of fossil-fuelled generators. Reference **3.3** shows the model-design approach in action, modifying a model based simply on the variable cost of electricity generation to include the cost of starting up each plant. This produces noticeable changes in the optimal mix of power station types, closer to the results of more comprehensive (and frequently unwieldy) black-box models, but far easier to explain. In another strand of this research (**3.4**), we showed that using a relatively small number of daily load profiles, selected through k-means clustering, could produce predictions of key variables (such as annual average prices and outputs) that were close to those from a full 8,760-hour model but took less than 2% of the time to run.

Models of modern electricity systems need estimates of wind turbine outputs, and we have worked to improve these. Wind speed data from NASA's MERRA satellite reanalysis is interpolated to the location of a wind turbine and extrapolated to its hub height. The manufacturer's power curve shows how the turbine output depends on this wind speed; **3.5** shows how the modelled wind speed is scaled so that the modelled output matches available data. That study used variations between actual and modelled outputs over time as to calculate the rate of wind farm performance decline, a then-controversial topic. Further research (**3.6**) improved the techniques and calculated wind speed scaling factors that could be applied worldwide.

This work inspired us to obtain an EPSRC grant on the contribution wind could make to Britain's decarbonisation. **3.7** compiled publicly available data to chart the progress made from 2009 to 2016, analyse the contribution already made by renewable generation and carbon prices, and draw attention to the challenges ahead. The data used are the foundation of the information and analysis website Drax Electric Insights, discussed below.

3. References to the research (indicative maximum of six references)

3.1 https://goo.gl/StJyso ([Report] The Impact of Government Interventions on Investment in the GB Electricity Market)

3.2 https://doi.org/10.1093/oxrep/grw003 (Green, R.J. and I. Staffell (2016) "Electricity in Europe: Exiting Fossil Fuels?" *Oxford Review of Economic Policy*, vol. 32, no. 2, pp 282-303) (38 WoS citations)

3.3 http://dx.doi.org/10.1109/TPWRS.2015.2407613 (Staffell, I and R.J. Green (2016) "Is there still merit in the Merit Order Stack?" *IEEE Transactions on Power Systems*, Vol. 31, No. 1, pp. 43-53) (19 WoS citations)

3.4 http://dx.doi.org/10.1109/TEM.2013.2284386 **(**Green R.J., I. Staffell I and N. Vasilakos (2014), "Divide and Conquer? k-Means Clustering of Demand Data Allows Rapid and Accurate Simulations of the British Electricity System", *IEEE Transactions on Engineering Management*, Vol. 61, pp. 251-260) (53 WoS citations)

3.5 https://doi.org/10.1016/j.renene.2013.10.041 (Staffell, I. and R.J. Green (2014) "How does wind farm performance decline with age?", *Renewable Energy*, vol. 64, pp. 775-786) (172 WoS citations)

3.6 https://doi.org/10.1016/j.energy.2016.08.068 Staffell, I. and S. Pfenninger (2016) "Using bias-corrected reanalysis to simulate current and future wind power output", *Energy*, vol. 114, pp 1224-39 (257 WoS citations)

3.7 https://doi.org/10.1016/j.enpol.2016.12.037 Staffell, I. (2017) "Measuring the progress and impacts of decarbonising British electricity" *Energy Policy*, vol. 102, pp 463-75 (40 WoS citations)

References 3.2-3.7 were published in peer-reviewed journals; Green was PI and Staffell a Co-I on EPSRC project EP/N005996/1 for further work on our wind power estimates *(inter alia)*.

4. Details of the impact (indicative maximum 750 words)

Our work is informing policymakers considering alternative strategies for decarbonising electricity; better decisions lead to savings in both emissions and costs to consumers. We have influenced policy and debate, specifically for nuclear power and wind power and also provided public information on the power system as a whole.

Impact Strand 1: Hinkley
This research helped to inform an EU policy decision with significant consequences for the UK government and for decarbonisation policy in the UK. The UK government requested State Aid clearance to support the proposed nuclear power station at Hinkley Point in Somerset, and the European Commission could only approve this after "in depth analysis of… the likely impact of the aid… [This required] specialised knowledge of electricity markets which was not available inside the Commission" (**5.3**). Our existing research allowed us to do this essential analysis to the tight timetable required.

A key legal test is whether State Aid is actually needed to change the decision of the party receiving it. Economic analysis to show whether a project would be viable without the Aid was carried out for DG Comp of the Commission by Professor Green and Dr Staffell, drawing on their research at Imperial (**3.2-3.4**). We ran our model of the GB wholesale electricity market (**3.2**) under a range of government policies and other input assumptions supplied by the Commission, liaising closely with DG Comp.

The Commission published its initial decision on 18 December 2013, announcing that a full investigation would be required. The initial decision (**5.1**) summarised the Imperial report (published as **3.1**). "The report was an important part of the evidence base that DG Comp drew on" (**5.3**). The report showed (**5.1**, Table 3) that without government assistance, new nuclear stations would not be profitable until the 2050s. With the government's proposed contract structure, a substantial number of new stations might enter the market during the 2020s. To quote the decision (para 408), "based on the Expert Opinion, CfD policies are effective at stimulating early nuclear investment." Electricity prices and other generators' profits would be affected by the contract. In other words, "the Expert Opinion therefore confirms that the [contract] can have substantial distortive effects on competitive conditions."

The Imperial report thus set key parameters for the subsequent stage of the process. To quote the Commission, "the research showed how different contract designs could affect the impact of the aid […] and we drew on this once we started to discuss modifications to the proposed aid with the government and the company". The Commission "found it very useful to have quantified results as the background to those discussions" (**5.3**, **5.5**). The final decision (**5.2**) was published on 8 October 2014, and approved the aid, with some of the modifications that had been discussed.

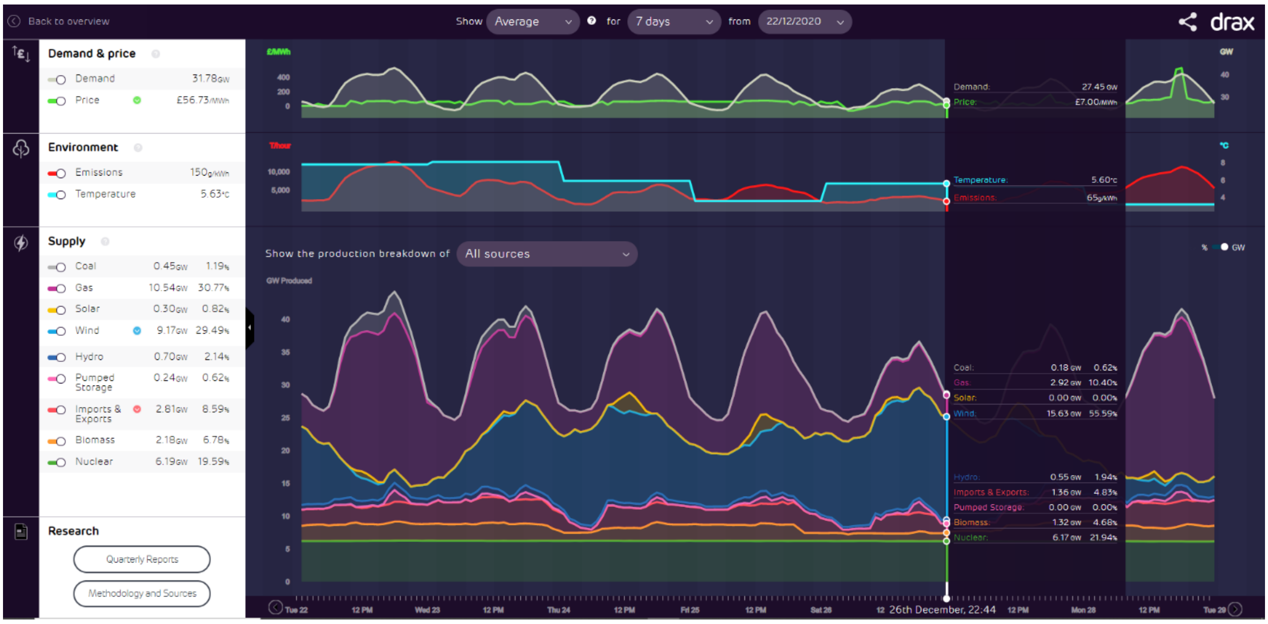
EdF expect that the station will generate up to 25,000 jobs during its construction and save 600 million tonnes of CO_2 emissions over its lifetime (**5.4**). This represents 18 months of current UK net CO_2 emissions from all sources and is a significant contribution towards meeting the legally binding net zero commitment while providing stable supplies of electricity to the benefit of British firms and households. To quote the Commission (**5.3**), "Without the research by Professor Green and Dr Staffell, we would not have been able to carry out a proper assessment of the aid to the demanding timetable required; without our clearance, the UK government would not have been able to grant the aid, and no station would now be forthcoming."

Impact Strand 2: Renewables Ninja
Our work on wind farms has informed policy and business users around the world. Our research on wind farm degradation was presented in committee evidence to the House of Lords (**5.7**). BEIS modellers used it, raising their estimates of wind costs. The Virtual Wind Farm model created in this research is at the heart of the Renewables Ninja (**5.6**), an open-source website for simulating the hourly output of a wind farm, or a solar panel, anywhere in the world. The solar work was done by Dr Stefan Pfenninger, then an Imperial PhD student, working with Dr Staffell. More than 2

million wind simulations have been run since 2016. Registered commercial users include major energy companies and policy bodies (**5.8**). The International Energy Agency's modelling for its widely read and influential flagship World Energy Outlook has used its data since 2016 (**5.9**). In 2019, the IEA's Offshore Wind Outlook (**5.10**) included analysis of the world-wide potential for offshore wind, based on the Renewables Ninja. The estimated potential output of over 18 times the current global demand for electricity was widely reported by general and specialist media.

Impact Strand 3: Drax Electric Insights

We have contributed to public debate on the electricity system by creating Drax Electric Insights, funded by but editorially independent of the UK electricity company. This website (**5.11** and below) was created in 2016 and shows publicly available data on the power system since 2009 in a user-friendly form; a quarterly report with analysis is widely distributed. The website and reports are frequently quoted by UK broadsheets and other media (**5.12**), including The Financial Times (4 times), The Guardian (9), The Independent (5), The Telegraph (2) and The Times (6). The website has received over 750,000 visits by 170,000 users (5.13), and mentioned in almost 10,000 web pages.



5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 http://ec.europa.eu/competition/state_aid/cases/251157/251157_1507977_35_2.pdf European Commission (2013) Decision to Initiate the Formal Investigation Procedure

5.2 http://ec.europa.eu/competition/state_aid/cases/251157/251157_1615983_2292_4.pdf European Commission (2014) Letter to the Member State on the Commission Decision

5.3 Supporting letter of support from DG Competition of the European Commission

5.4 Supporting letter from EdF Energy

5.5 Supporting statement from Department for Business, Energy and Industrial Strategy

5.6 http://www.renewables.ninja Renewables Ninja website for renewable energy simulations.

5.7 (Evidence given to the Science & Technology Committee [Lords] Inquiry on *The Resilience of Electricity Infrastructure*, HL121 of 2014-15, Evidence pp. 256-9) https://old.parliament.uk/documents/lords-committees/science-technology/Resilienceofelectricityinfrasrtucture/Resilienceofelectricityinfrastructureevidence.pdf

5.8 List of commercial users of the Renewables Ninja

5.9 World Energy Outlook 2016 (see page 502) https://webstore.iea.org/download/direct/202 IEA

5.10 IEA Offshore Wind Outlook 2019 https://www.iea.org/reports/offshore-wind-outlook-2019 (see pp. 48-54 and visit the actual website for the geospatial analysis https://www.iea.org/reports/offshore-wind-outlook-2019/geospatial-analysis)

5.11 Drax Electric Insights website with graphs and analysis: http://www.electricinsights.co.uk/

5.12 Drax Electric Insights: main mentions in UK and overseas media

5.13 Supporting letter from Drax Group plc