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Lost Generation: System Resilience and Flexibility

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Abstract—Whole energy system modelling is a valuable tool to support the development of policy to decarbonise energy systems, and has been used extensively in the UK for this purpose. However, quantitative insights produced by such models methods necessarily omit potentially important features of physical and engineering reality. The authors argue that important socio-technical insights can be gained by studying critical events such as the loss of 2.1 GW generation from the electricity system of Great Britain in August, 2019. The present paper uses this event as a starting point for a discussion of the need for additional tools, drawn from the System Architecture literature, to support the design and realisation of future fully decarbonised systems with high penetrations of renewable energy, capable of providing high levels of resilience and flexibility.

Keywords—energy system modelling, resilience, flexibility, governance, storage, energy system architecture.

INTRODUCTION

The UK Government has progressively strengthened its commitment to reducing GHG emissions, from 60% (CO_2 only) in 2003, to 80% in 2008, and, in 2019, to net-zero by 2050 [1]. Much of the UK's energy research effort over this period has been devoted to inform policymakers of the technological options and pathways for transforming the energy system to meet these targets at least cost. While a diversity of energy system models exist, only a sub-set are being utilised in policy making [2]. While quantitative insights generated by these models have been useful, they have tended to lag behind some key technical developments, such as the emergence of low cost PV and offshore wind [3, 4], and they do not clearly resolve details relating to system configuration and operational performance that might facilitate or impede deployment.

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The aim of this paper is to explore qualitative insights that emerge from the study of the power outage that occurred in mainland Britain on the 9th August 2019. Recently published technical analysis of this event confirms the part played by technical and regulatory issues associated with the increasing penetration of renewables. The initial analytic focus is on the problem of ensuring the flexibility, resilience and stability of the electricity system in the context of rapid evolution of the whole Energy System. The results of the exploration suggest the need to complement modelling with a rich understanding of the technical and socio-technical landscape of the real-world in the formation of policy for decarbonising complex economies.

I. DEFINITIONS

Flexibility and resilience are key concepts in this paper. The International Energy Agency defines energy system flexibility as "the ability to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales" [5].

The UK Energy Research Centre, UKERC, defines energy system resilience as "the capacity of an **energy system** to tolerate disturbance and to continue to deliver affordable **energy** services to consumers. A **resilient energy system** can speedily recover from shocks..." [6]. Defined thus, resilience is a subset of flexibility.

II. THE EVOLUTION OF THE UK ELECTRICITY SYSTEM

Key features of the UK electricity system had emerged by the early 1940s. Most importantly, the national grid was in place, interconnecting all major generators and conurbations, and the broad principles of its operation were understood:

- the merit order, ensuring that only the cheapest power stations would be operated;
- the use of multiple layers of reserve capacity to maintain system stability over time periods from seconds to hours;
- guaranteeing longer term stability by the use of energy stores distributed throughout the UK electricity system

and the wider energy system, in the form of stockpiles of fossil fuels. As an example, stocks of up to 20 million tonnes (140 TWh_{th}) of coal were maintained at coal fired power stations, which dominated electricity generation until the early 1990s. These fossil fuel stocks were complemented by much smaller but critically placed and tightly coupled stores of thermal energy in boilers and rotational energy in the form of turbo-alternators at essentially all power stations.

This model continued into the 21st Century, only changing significantly in the last 5 years. In 2018, the proportion of renewable energy generation amounted to 33% of UK total electricity supply, up by almost 4% on the previous year [7]. Most of it was connected at the level of the transmission system, but significant amounts of PV and some onshore wind were integrated at the level of the distribution system (voltages of 132 kV and below). The growth of renewable generation has posed a new challenge for the Electricity System Operator (ESO), National Grid, the 14 distribution network operators (DNOs), and the regulator, Ofgem (Office of Gas and Electricity Markets), of managing and regulating systems that were originally designed around unidirectional and predictable power flows [8].

The breakthrough in prices of electricity from offshore wind that occurred in Europe between 2016 and 2018, and even more dramatic breakthrough in the price of PV electricity that has occurred globally, make it all but certain that strategies for decarbonising electricity generation, and for electrifying some or all sectors of demand that are still dependent on fossil fuels, will be dominated by these two forms of generation for the foreseeable future. The result will be a significant expansion of electricity grids, a reduction in capacity factors, an increase in supply side volatility coupled with qualitative changes in periodicity, and the need to integrate new forms of storage to replace fossil fuel stores that, both by design and as a matter of convenience, facilitated the operation of many electricity systems, and energy systems more generally, throughout the 20th Century.

III. Critical Event (9 Aug 2019 outage)

On the 9th August, 2019, the electricity grid of mainland Britain (GB) suffered the almost simultaneous failure of a wind farm and a gas-fired power station that left up to a million homes, rail networks and businesses without power. The Energy Emergencies Executive Committee was asked by the UK regulator, Ofgem (Office of Gas and Electricity Markets) to investigate the cause of power cuts [9]. Enforcement action in the form of fines were subsequently imposed on generators and the ESO for various breaches of rules [10]. The incident was of a scale that would be expected in countries such as the UK roughly once in every 10 years.

A. The causes and nature of the outage

The primary cause of the outage was a lightning strike to an overhead transmission line and a near simultaneous loss of an offshore wind farm and one of two units at gas-fired power station (the second unit was also subsequently lost). This loss caused the system frequency (nominally 50 Hz) to drop to 48.8 Hz, below the statutory lower limit of 49.5 Hz. To arrest the fall of frequency, the Low Frequency Demand Disconnection (LFDD) protocol was triggered, leading to the disconnection of approx. 900 MW of demand, equivalent to over 1 million customers.

Further investigation showed that approx. 550MW of embedded generation also disconnected either as part of the Low Frequency Demand Disconnection (LFDD) scheme or via another, as yet unidentified mechanism. Significantly, embedded generation began to disconnect at 49 Hz, well within the extended 47-52 Hz operating range of the GB grid, and well within the frequency range set by current versions of regulations governing the connection of embedded generators to the electricity distribution system. The total loss of generation on the 9th August amounted to around 2.1 GW, around 1.5 times the initial loss of wind farm and gas-fired power station, and more than double the 1 GW of reserve capacity held by the ESO, under the Security and Quality of Supply Standards (SQSS).

Although electricity supply was fully restored within 45 minutes, a number of essential services such as rail transport, hospitals, water and oil were disrupted for longer periods. Rail services were badly hit, with delays of many hours to some services. More than 22 trains could not be restarted by train crews following the restoration of power, and had to be reset by technicians. Delays were compounded by the complexity of the restart process, the limited number of available technicians, and the fact that these technicians had to drive to the affected trains. 371 services were cancelled, 220 were part cancelled and 873 services were delayed [11].

B. Implications:governance and engineering solutions

The aim of the ESO is to ensure the supply of electricity to all connected consumers, by maintaining sufficient reserve capacity to deal with a wide range of potential disruptions. On this occasion, the reserve was insufficient to stabilise grid frequency and avoid disconnections. A significant factor in the outage appears to have been interactions between governance and engineering systems associated with embedded generation.

While regulations for connection of embedded generators have been repeatedly updated, it has become clear that as of 9th August 2019, embedded generation reduced rather than increased the stability of the electricity system. At the time of writing, the causes of the disconnection of 300 MW of embedded generation are still not understood, but they may reflect i) a combination of limited operational data due to lack of monitoring of large numbers of microgenerators, ii) the presence of multiple layers of infrastructure between the sites of the initial losses on the high voltage transmission system, and locations of embedded generation deep within the low voltage distribution system, and iii) the possibility that an unknown proportion of embedded generation was operating according to superseded versions of relevant codes.

C. The role of demand-side systems in resilience

A key observation from the 9th August outage is that, although the electricity system recovered within 45 minutes, disruption continued in demand-side systems for much longer. The features of demand-side systems that are likely to have contributed to extended periods of disruption include:

- they are not governed by performance and operating regulations analogous to those that apply to the electricity system, and which were generally followed on the 9th August, ensuring the recovery of that system;

- compared with the electricity system, demand-side organisations employ relatively few technicians and engineers who are capable of restoring end-user systems following disruption;
- technological change in end-user systems had introduced additional latent failure modes that only became apparent as the events of 9th August played out [12,13];
- failures in multiple end-user systems interacted – e.g. technicians who were driving to stopped trains were further delayed by failed traffic lights; this is a specific example of a general principle, that the more extensive the primary disruption to a complex system, the greater the probability of such interactions [12,14].

This event and the ensuing disruption shows that resilience is a property not just of the electricity system, but ultimately of the whole society, and that it can be strengthened or eroded by ongoing technical, regulatory and sociotechnical change, in ways that may only be revealed when a significant primary failure takes place.

IV. Flexibility in decarbonised energy systems

The foregoing illustrates the need and means to ensure flexibility and resilience of electricity systems and, more generally, energy systems over periods of seconds to minutes. The likely domination of renewable energy in a future decarbonised UK energy system will require consideration of flexibility out to periods of years and decades due to long term variability in weather wind and solar availability. Recent analysis suggests that integration of 100s of GW of renewable electricity capacity into the system will require the addition of 50-100 TWh of energy storage (subject to detailed examination of trade-offs with increased trans-European transmission and excess renewable generation capacity), in order to deal with variability in demand and renewable electricity output over inter-decadal timescales.

Achieving an appropriate disposition of energy storage through the energy system will therefore be a strategic necessity. But the task of thinking through the implications of these different roles for storage and their implications for how, where, within what network topologies, and at what scales storage technologies might best be deployed and integrated within the evolving system has so far been largely overlooked by both energy research and energy policy communities.

V. Existing tools to support Energy System thinking

Academic and policy discourses around UK energy policy and decarbonisation strategy have been dominated over the last 20 years by a small number of whole energy system models, in particular MARKAL, UKTM and ESME [2,15,16]. While the sophistication and spatial and temporal resolution of these models has steadily increased, they are still below the level needed to shed light on operational questions posed by new energy systems, or to resolve issues relating to energy system topology and cross-vector integration [17]. Models, such as WeSIM [18], IWES [19] and ESTIMO [20] with significant spatio-temporal capability are designed primarily to provide operational snapshots of future energy systems, but are not designed to model the long-term evolution of the whole energy system [21]. Operational models run by the energy system operator, National Grid, provide highly detailed insight into current electricity and gas grids, but are also not designed to model the evolution of the whole energy system.

Adding new capabilities to models is technically and intellectually demanding, and the pace of development is necessarily constrained. With respect to the development of Whole Energy System Models, there has been a tendency to add technologies and novel energy conversion pathways only when they are perceived to be required by new policy goals. Models have therefore been limited by policy ambition. At the same time, there has been a tendency for interpretation of models and wider policy discourse to be limited by and to the conceptual structure of, and results emerging from the models themselves.

The result has been a tendency in the UK to conceptualise the problem of developing decarbonisation strategies mainly in terms of the use of whole energy system models to find optimal mixes of energy conversion technologies and energy vectors – for example electrification of heat through individual heat pumps, versus a gas grid (repurposed to carry H_2 rather than natural gas), versus heat networks.

The large cost of decarbonising the UK energy system – the gross cost is estimated to be of the order of £1tn [1] – makes the pursuit of synergies between technologies and energy vectors essential, but the rapidly reducing window of time within which decarbonisation has to be achieved, makes the task of realising such synergies progressively harder.

Uncertainty is a key problem for energy system modelling. In much of the modelling literature, this has typically been conceived as stochastic uncertainty in input data. But despite the complexity and indeterminacy of the underlying problem the uncertainties are not strictly stochastic. They are to a large extent associated with (necessarily) incomplete libraries of energy conversion pathways, the presence of multiple potential interactions – positive and negative – between actual electricity, heat, transport and storage technologies, high recent and projected rates of innovation and learning, and the predictable trajectory of the UK's official carbon target.

A consequence of all of the above, is that the pace of change in the real world has thrown up both problems and opportunities faster than they can be addressed by academic energy researchers and policy makers, with the tools currently available.

VI. The need for new tools to support Energy System thinking

Comparisons are sometimes made between the task of decarbonising the UK economy and historic undertakings such as the Manhattan and Apollo Programmes [22,23]. At a total cost of something like US $(2019) 150 billion, Apollo turns out to have have been roughly an order of magnitude cheaper than the projected cost of decarbonising the UK energy system, and at eleven years, to have been significantly shorter.

The comparison with Apollo yields a number of insights. One of the most important differences relates to the life cycle of the two systems. While each Apollo mission lasted a few days, the UK energy system has existed in something like its current form for more than a century. It represents an endowment with individual sub-systems up to half a century old. A key distinction between Apollo and the decarbonisation of the UK energy system, is that the former was entirely optional. While expensive, Apollo was only ever incidental to the survival of the US economy. In contrast, the UK energy system is absolutely critical to the UK's continued existence as an industrialised country – indeed to its survival as anything other than a subsistence economy. The designers of Apollo started with a blank slate. In contrast, and though to some extent de-risked by high levels of modularity and redundancy within the energy system, the task facing the UK is the equivalent of re-engineering its own life support system, in flight.

A. System Architecture

A key contribution to the success of the Apollo programme was made by an entirely new discipline, that of System Architecture [24,25]. In the early years, the complexity of the programme proved almost unmanageable. Strategic decision-making was made possible by using the concepts and methods developed within this emerging discipline to organise the emerging complexity, and to enable hundreds of thousands of people from tens of thousands of companies and universities, and dozens of disciplines, to comprehend their own roles and objectives sufficiently clearly to collaborate effectively on the common endeavour. These new concepts and methods did not supplant the practices, tools and methods of engineering and physics; rather they coordinated and guided them, and provided a conceptual structure within which to interpret their results. Within the discipline of System Architecture, the function of models is to support decision making, not to supplant decision makers. As Crawley et al. put it:

> "We will show that there are applications for which the complexity of the architecting problem may be usefully condensed in a model, but it is important to remember that no model can replace the architect - accordingly, we emphasize decision support." [24:21]

Crawley et al. describe the objectives of good architecture as being to meet stakeholder needs, deliver value, to integrate easily, evolve flexibly and to operate simply and reliably. They go on to state:

> "The role of the architect is to resolve ambiguity, focus creativity, and simplify complexity. The architect seeks to create elegant systems that create value and competitive advantage by defining goals, functions, and boundaries; creating the concept that incorporates the appropriate technology; allocating functionality; and defining interfaces, hierarchy, and abstractions to manage complexity."

B. Energy System Architecture

The process of System Architecture begins with identification of stakeholders and characterisation of needs and requirements. Eyre et al. have defined the goals of energy policy as being to produce "a secure, affordable, and sustainable energy system" [26].

A possible expanded list of requirements for such a system could be:

- sustainability
- resilience
- flexibility
- evolvability
- cost
- equity

The authors note that among the questions posed by this list is whether there is an implicit or explicit rank order among requirements. In the context of historically unconstrained systems such as Apollo, Crawley et al. describe the process for moving on from a initial list of goals to begin with work to reduce such ambiguity, followed by:

- proposing and developing concepts
- identifying key metrics and drivers
- conducting highest level trades and optimisation
- selecting a concept to carry forward, and perhaps a backup
- thinking holistically about the entire product life cycle
- anticipating failure modes and plans for mitigation and recovery [24:193].

This process has to be rethought for energy systems. One of the features of very complex systems such as energy systems, is that it may be technically impossible to identify failure modes in advance. In the case of the 9th August outage, the possibility that brand-new, IT-equipped trains would take hours to restart following an outage that lasted less than hour, appears not to have been foreseen. It would be unreasonable to expect that 2019 will have seen the last major energy system failure whose ultimate causes can be traced back to decades of innovation in multiple systems both inside and outside the energy system itself. Innovation has the potential to change everything, and not just the thing that is the object or product of the innovation.

More generally, in complex and long-lived systems, it may be impossible to define any unique and stable set goals, concepts or metrics in advance. This is certainly the case for energy systems, for which e.g. the goal of sustainability might be less than 30 years old, and the idea that this goal might include the sub-goal of complete decarbonisation, even more recent. With respect to concepts, the palette of technologies by which a system architect might seek to realise the goals of the UK energy system has been transformed within the last 5 years, in ways that are already affecting decisions about the architecture of this system. Similarly, with respect to metrics, we observe that greenhouse gas emissions have gone from being irrelevant as little as 25 years ago, to critical now, but that their relative importance is likely once again to decline, as the energy system decarbonises over coming decades.

All of the above limits our collective ability to describe future energy systems with a level of detail and certainty that would allow the trajectory of their development to be uniquely defined. This in turn explains our inclusion of evolvability among our key requirements for the UK energy system. The process of energy system architecting will need to be continuous, driven by emerging needs, constrained by endowment, enabled by new technology.

C. *The role of architecture in flexibility and resilience*

The complete decarbonisation of the UK energy system will require change of technologies, configurations, regulatory and governance structures, and operating practices at all levels. Change will involve all existing energy vectors, greater cross-vector integration, the production of hydrogen and of synthetic fuels, and integration of new forms of storage. Extension of electrification of heat, road transport and industry will offer new possibilities for demand-side management. All of this will provide multiple opportunities for increasing resilience.

Deployment of energy storage impacts, and is impacted by the evolution of energy system functionality and topology. System architectural thinking will be needed to determine what types of storage to deploy, how to control them and where to place them in the evolving energy system. The fact that energy storage displays significant economies of scale is an argument for integration of relatively small numbers of large stores in association with gas, electricity and heat distribution systems. But in principle, local electricity and other high-exergy stores with an aggregate capacity several orders of magnitude smaller than needed to deal with inter-decadal variation at the whole system level, could also significantly increase flexibility and resilience, by dealing with local supply-demand imbalances, backing up essential sub-systems such as communications, banking and transport (see earlier discussion of the 9th August outage), allowing islanding and by providing local black-start capability across the country (it is possible that the whole UK electricity system will never fail, but it would be unwise to plan on this basis).

D. *The role of storage in reducing cost and improving operability and comprehensibility*

The system architecture perspective helps to identify further functions of storage, with potential implications for infrastructure costs and investments. Stores at intermediate nodes in the energy system act as low pass filters on energy transfers. At the crudest level, such stores allow buffering of the energy supply system from variations in demand, and vice versa. Stores at intermediate nodes and co-located with energy conversion systems, allow increased load factors on infrastructure throughout the system.

An additional and potentially critical function of such low pass filters would be partial compartmentation of an otherwise increasingly complex energy system, with respect to operability. In a dynamic and interconnected system with significant capability for inter-temporal shifting of energy, the operator of each sub-system needs to maintain models of the current and likely future states of adjacent sub-systems. Stores between sub-systems allow these models to be simpler and to operate at lower temporal resolution. This in turn simplifies the tasks of regulators and the communities of practice that are responsible for individual sub-systems and increases the overall comprehensibility of the energy system. This, as we have seen, is a critical function of good system architecture.

VII. CONCLUSIONS

Using insights gained from analysis of a recent electricity outage, this paper has explored two key issues, resilience and flexibility, in the context of the decarbonisation of the UK energy system. We argue that, while whole energy system models have a significant role to play in energy policy formation, they are insufficient to support the design of a fully decarbonised energy system with a large renewable energy fraction. We have shown how additional tools and methods, drawn from the System Architecture literature, can complement existing energy system models, guide modelling and support decision-making to achieve net-zero emissions.

Introducing the tools and concepts of system architecture energy research and policy making will help the UK meet the following challenges:

- coordination between supply and demand sectors of the economy;
- coordination across multiple levels within the electricity system and between the electricity system and other energy vectors;
- coordination across time, balancing investments made in the near term, using the products of existing carbon intensive means of production, to jointly minimise i) costs of existing energy systems and emerging zero carbon systems and infrastructure, and ii) cumulative future greenhouse gas emissions;
- reviewing and renewing system regulation and governance;
- coordination within and between the communities of practice who will be responsible for building, commissioning and operating the multiple sub-systems of the evolving energy system.

In a task of such complexity, the organising principles of System Architecture are likely to prove essential.

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