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Lost generation: Reflections on resilience and flexibility from an energy system architecture perspective

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HIGHLIGHTS

- Emergent phenomena can affect energy system resilience.
- A System Architectural perspective is therefore needed to support decision-making.
- High rates of change will make evolvability a desirable property of energy systems.
- A definition of evolvability is offered.

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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 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 on 9th August 2019, in conjunction with literature on the behaviour of complex systems. Among these insights is the idea that models of the operation and evolution of energy systems can never be complete. Both system behaviour (operation) and the emergence and evolution of structure in such systems are formally uncomputable. This provides 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. Desirable properties of System Architectures, including current and future Energy System Architectures, are discussed. These include resilience and flexibility, for which there is an extensive literature. They also include the properties of comprehensibility, which helps to make complex systems easier to operate, and of evolvability, for which a working definition is offered.

1. Introduction

Energy policy in the UK has been dominated by the issue of the decarbonisation of the energy system since the turn of the century. Over this period, the UK Government has progressively strengthened its commitment to reducing greenhouse gas emissions, from an initial commitment of 60% (CO_2 only) in 2003 [1], to 80% in 2008 [2], and, in 2019, to net-zero by 2050 [3]. Much of the UK's energy research effort over this period has been devoted to informing policymakers and other stakeholders of the technological options and pathways for transforming the energy system to meet these targets at least cost. This strand of research has been dominated by teams using optimising whole energy system models drawn from the TIMES family – MARKAL before 2003 and UKTM since [4,5]. While quantitative insights generated by these models have played a significant part in the development of policy, they have tended to lag behind some key technical developments, such as the emergence of low cost PV and offshore wind [6,7] and the models themselves do not explicitly resolve some important questions relating to the interaction between system configuration and operational performance that might facilitate or impede deployment.

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A second group of models has been developed to explore operational questions arising from the transformation of the UK energy system from one dominated by fossil fuels to one dominated by primary electricity generated by wind and solar. Often referred to collectively as dispatch models, these have until recently played a less important role in formulation of policy. Examples include WeSIM [8], IWES [9] and ESTIMO [10].

Largely absent from the energy research literature of the last two decades has been work that uses tools and concepts from the System Architecture tradition, as developed over the last 60 years, originally in the context of the aerospace industry [11–13].

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, and to reflect on their implications for the future of the energy system and in particular, for the tools and methods that will be needed to support the design and realisation of future fully decarbonised systems with high penetrations of renewable energy, that will be capable of satisfying the requirements of stakeholders. Recently published technical analysis of the 9th August outage confirms the part played by technical and regulatory issues associated with the increasing penetration of renewables. The initial analytic focus of the paper 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.

While the authors note the burgeoning literature on the impact of high penetrations of renewable energy on electricity system stability [14], much of this focuses on the technical problems of frequency control, rather than System Architecture. It appears likely that, in the long term, integration of large amounts of battery storage coupled with high frequency digital control of output of renewable energy systems – which will be partloaded for much of the time – will tend to make frequency control more, rather than less manageable. But the structural questions will be less easy to resolve.

The results of the work described here therefore 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. This insight opens the door to a discussion of the role of System Architecture tools and concepts in the development and implementation of decarbonisation strategies over the coming three decades and the ongoing evolution of net-zero carbon energy systems through the remainder of the century.

2. 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” [15].

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…” [16]. Defined thus, resilience is a subset of flexibility.

At this point, it is useful to define a third energy system property, evolvability. Little has been written on this subject to date with respect to energy – one of the few references is provided by Scamman et al. [5] Its importance is asserted in the System Architecture literature [13], and attempts to define it have been made by authors from a variety of fields [17,18,19]. In the context of energy systems, the authors have tentatively defined evolvability in terms of the costs associated with seizing unexpected opportunities, or of avoiding or mitigating unexpected threats or disappointments. The importance of evolvability emerges from the inherent unpredictability of the future trajectory of the energy system and the certainty that the future will contain the unexpected.

3. The evolution of the UK electricity system

Key features of the modern UK electricity system had emerged by the early 1940s [20]. Most importantly, the national grid was in place, interconnecting all major generators and conurbations, and the broad principles of its operation had been developed:

- 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 months;
- the guaranteeing of 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 (c.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 sufficient to allow power stations to operate for periods of months without being resupplied. They 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, supporting a wide spectrum of flexibility and resilience mechanisms. Similar arrangements have obtained in more or less all countries with electricity grids dominated by fossil-fired generation, driven by the high levels of reliability of inter-connected systems with multiple independent dispatchable power stations and the low cost of maintaining large stocks of fossil fuels.

This model continued into the second decade of the 21st century, only changing significantly since 2015. In 2018, the proportion of renewable energy generation amounted to 33% of UK total electricity supply, up by almost 4% on the previous year [21]. 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, flexible and predictable power flows from dispatchable generators [22].

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 is likely to be a significant expansion of electricity grids, a reduction in capacity factors for generation and transmission assets, an increase in supply side volatility coupled with qualitative changes in periodicity with emerging diurnal, annual and inter-annual variability, and the need to integrate new forms of storage to replace fossil fuel stores that, both by design and as a matter of convenience, have facilitated the operation of many electricity systems, and energy systems more generally, throughout the 20th Century.

4. 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 rail networks, businesses and up to a million homes 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 [23]. Enforcement action in the form of fines was subsequently imposed on generators and the

ESO for various breaches of rules [24]. The incident was of a scale that would be expected in countries such as the UK roughly once in every 10 years.

4.1. The causes and nature of the outage

The investigation showed the primary cause of the outage to be a lightning strike to an overhead transmission line, and 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 (in the UK, 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 approximately 550 MW 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 [25]. The total loss of generation on the 9th August amounted to around 2.1 GW, around one-and-a-half 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). The main features of the course of the outage are presented in Fig. 1.

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 part-cancelled and 873 services were delayed [27]. Much of the immediate news footage of the outage focused on crowds of passengers at mainline stations, and on those who did not arrive at their destinations until the early hours of the following day [28].

4.2. Implications:governance and engineering solutions

The overarching strategic objective of the ESO, National Grid, is to ensure a continuous 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. Significant factors in the outage appear to have been interactions between electricity supply and demand-side systems, and 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 fully understood, but they appear to 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. Indirect support for this last suggestion is provided by a recent call from the ESO and the Energy Networks Association for operators of embedded generation to upgrade their systems to improve network resilience. An industry publication noted subsequently that, "Loss of Mains protection exists to ensure generators shut down safely when needed. However, those connected to the grid before February 2018 are set at levels where minor network disturbances can cause them to trip off…" [29]. Rather than making the electricity system more resilient, as some have uncritically argued, if operating under such restrictions, distributed generation may undermine it [30].

4.3. 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;
- 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 [31,32];
- 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 [33–35].

An obvious conclusion from the above description of the 9th August outage is that while the electricity system itself proved to be sufficiently resilient to limit the initial cascade of failure, the same could not reasonably be said of demand-side systems. This in turn shows that resilience is a property not just of the electricity system, but ultimately of the whole energy system,[1] 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.

5. Flexibility/resilience in decarbonised energy systems

The foregoing illustrates the need for and means by which flexibility and resilience of the GB electricity system is currently ensured over periods of seconds to minutes. The likely dominant role of renewable electricity in any future decarbonised UK energy system will require consideration of flexibility out to periods of years and decades due to long term variability in weather, and wind and solar availability.

Recent analysis suggests that integration of hundreds of GW of renewable electricity capacity into the UK energy system will require the addition of tens of 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 appropriate provision of energy storage throughout the energy system will therefore be a strategic necessity. But the task of systematically 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 until recently

[1] Indeed, of the whole of society.

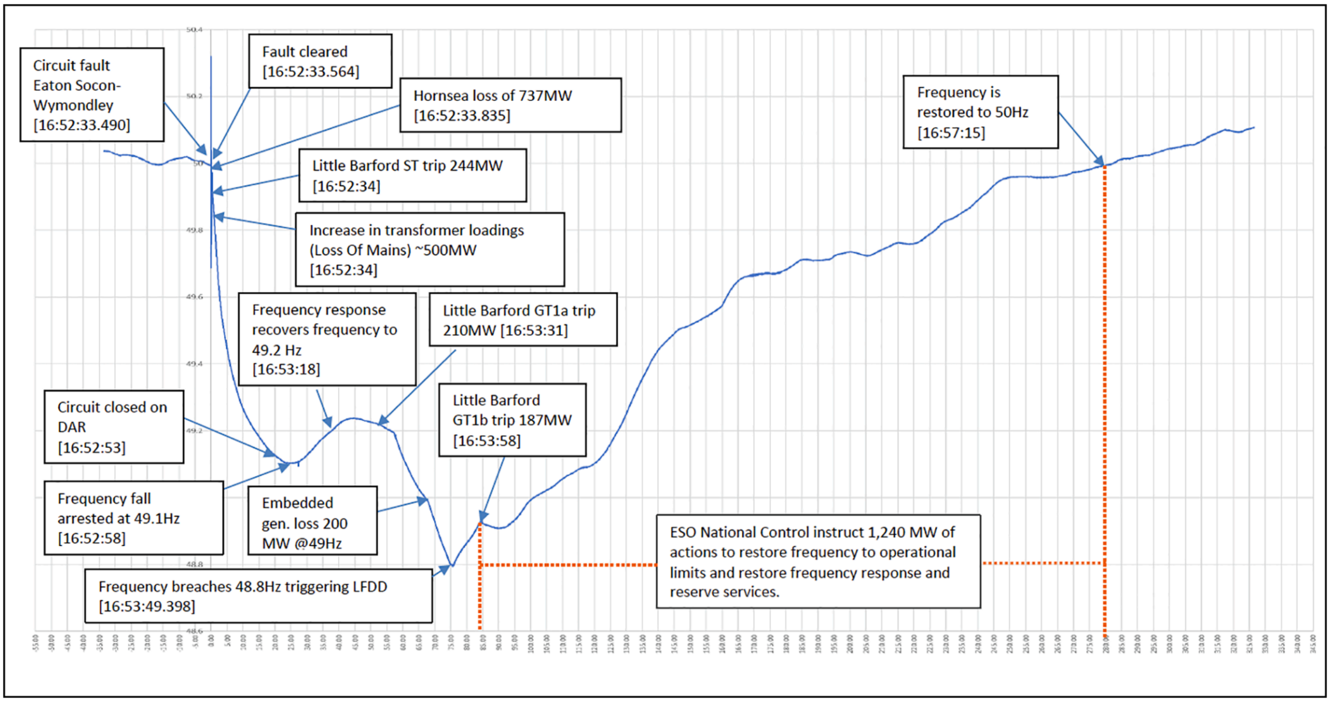

Fig. 1. Anatomy of the 9th August outage. Annotated Frequency Trace of Event - time axis in intervals of 5 seconds [26].

been largely overlooked by both energy research and energy policy communities.

6. Existing analytical tools to support energy system development

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 [36]. 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 [37]. Models, such as WeSIM, IWES and ESTIMO mentioned earlier, 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. Operational models run by the energy system operator, National Grid, provide highly detailed insight into existing 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 integrate novel energy conversion pathways only when they are perceived to be required by new policy goals. Models and modelling have therefore been limited by policy ambition, which in turn has lagged behind climate science. 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 structures embedded in, 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 hydrogen 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[3] – 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, through the evolution of tightly coupled bundles of technology, progressively harder.

The emergence, not just of new technologies, but of new bundles of technologies has been a feature of all previous energy system transitions. A bundle initially consisting of steam, coal mining and iron smelting, and subsequently including railways, was at the heart of the first Industrial Revolution [38]. The transition from coal to oil was driven by the internal combustion engine in terrestrial transport, shipping and aviation. In each case, these technology bundles formed part of wider military, political, economic and cultural structures. It appears likely that a transition to a largely renewable energy economy will be driven by wind and PV in conjunction with new and existing energy storage technologies, long distance electricity transmission, and electrification of end-uses [39].

Uncertainty is perceived as a key problem for energy system modelling. In much of the modelling literature, this has typically been conceived as stochastic uncertainty in techno-economic input data. But despite the complexity and indeterminacy of the underlying problem the uncertainties are not strictly stochastic. They are to a large extent also 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, many of which are parameterised rather than modelled explicitly, high recent and projected rates of innovation and learning, and the predictable but largely unpredicted trajectory of the UK's official carbon target. All of this is compounded by the size and dimensionality of search spaces, non-linearity of a number of techno-economic variables, lack of quantitative metrics for key concepts and the profound difficulties associated with reducing socio-political aspects of the problem to computable form.

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

7. 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 [40,41]. At a total cost of something like USD(2019) 150 billion, Apollo turns out to have been roughly an order of magnitude cheaper than the projected cost of decarbonising the UK energy system, and at eleven years, to have a been significantly shorter undertaking.

The comparison with Apollo yields a number of additional insights. One of the most important differences relates to the life cycles of the two systems. While the longest Apollo mission lasted just twelve 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, for example, power stations, 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 both expensive and a magnificent technical achievement, 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 something approaching 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 now facing the UK is the equivalent of re-engineering its own life support system, in flight[2].

7.1. System architecture

A key contribution to the success of the Apollo programme was made by an entirely new discipline, that of System Architecture [12,13]. In the early years, the complexity of the programme proved almost unmanageable, as a result of the difficulty of choosing between multiple possible mission architectures. Lack of consensus on mission architecture, in turn made it impossible to define and focus engineering teams on technical development programmes. Strategic decision-making, and therefore technical progress 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." [13:21]

Crawley et al. describe the objectives of good architecture as being to deliver value by meeting stakeholder needs, 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."

[2] Apollo 13 comes to mind.

In the context of the engineering of complex systems including but not limited to Apollo, Crawley et al. describe a process for reducing such ambiguity in an initial list of goals, to be followed by the following steps:

- 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 [13:193].

Although these steps will need further elaboration before being applied to energy systems, they provide a starting point for development.

7.2. Energy system architecture

A feature common to all complex systems is that they display structure which cannot be predicted from bottom-up analysis [42–45]. Among the reasons for this, is that almost all real-world systems are non-linear and the trajectories of non-linear systems are exquisitely sensitive to the numerical values of starting conditions. The large-scale structure of such systems therefore needs to be understood on its own terms. The term "architecture" is used to describe such structure in disciplines as diverse as cell biology, zoology, software design, and multiple branches of engineering. That the term is applied both to naturally occurring systems and human artefacts is striking; the main difference is that the verbal forms, "to architect", and "architecting", tend to be reserved for the latter. The extension of the term to energy systems is therefore an obvious step. Despite this, there are few references to Energy System Architecture in the energy research literature [5,46]. The present authors have tentatively defined Energy System Architecture as "the spatial, topological and functional organisation of energy generation, conversion, transmission, distribution, storage, end-use and regulatory systems within the whole energy system".

As noted above, the formal process of architecting a system 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" [47].

Combining this with a review of literature led the authors to set out the following expanded list of requirements for the energy system [5]:

- sustainability (primarily with respect to climate)
- resilience
- flexibility
- evolvability
- cost
- equity

A workshop and series of interviews undertaken subsequently, by the authors, with a range of stakeholders, have confirmed that resilience, flexibility and cost are widely seen as key requirements for any UK future energy system. While equity (or fairness) is also seen as an important requirement, it is, in the main, viewed as being adequately addressed if system cost is kept low. In contrast, the concept evolvability is sufficiently new as to be almost absent from the energy research discourse, and there is no consensus on the meaning of the term among stakeholders.

With respect to resilience, 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 electricity system failure whose ultimate causes can be traced back to decades of innovation in multiple systems both inside *and* outside the energy supply and distribution system. Innovation has the potential to change everything, and not just the thing that is the object or product of the innovation.

The 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. Increased electrification of heat, road transport and industry will offer new possibilities for demand-side management to support the electricity grid. Examples include making use of storage capacity of vehicle batteries and of heat stored in the fabric of homes equipped with heat pumps to provide real/virtual electricity storage to support the grid. Perhaps less familiar are the opportunities presented by district heating systems to integrate multiple forms of heat, electricity and fuel storage [48]. All of this will provide multiple opportunities for increasing flexibility and resilience, at the same time as potentially introducing new mechanisms for failure.

More generally, in complex and long-lived systems, it may be impossible to define any unique and stable set of goals, concepts or metrics in advance. This is certainly the case for energy systems, for which e.g. the goal of sustainability is no more than 30 years old, and the idea that this goal might include the sub-goal of complete decarbonisation (net zero), much more recent. The importance of this lies in the fact that energy system architecture and technology mix turn out to be highly sensitive to the level of decarbonisation required. This sensitivity has been compounded by the fact the UK energy modelling and policy community have been largely unprepared for the consequences of the step change from 80% decarbonisation to Net Zero. 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.

Evaluation metrics for technology selection have also evolved over time. We observe that emissions intensity has gone from being irrelevant as little as 25 years ago, to critical today; but this is unlikely to be the end of the process. With respect to many decisions to be made over the coming three decades, the importance of carbon intensity is likely once again to recede, since all choices now need to be compatible with a net-zero emissions outcome[3]. In this sense, the net-zero target has significantly simplified decision making.

All of the above is indicative of the 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. One of the key insights of the present paper is that the process of energy system architecting will therefore need to be continuous, driven by emerging needs, constrained by endowment, enabled by new technology. This in turn explains our inclusion of evolvability among key requirements for the UK energy system, despite the fact it is not yet recognised or clearly understood by the majority of stakeholders.

[3] Of course, not everything can be zero carbon. It then becomes important to handle hard-to-decarbonise processes systematically and consistently, for example by explicitly including the cost of carbon capture in cost benefit analysis. A net-zero target therefore makes realistic and fully-internalised carbon pricing hard to avoid. But we note that, as deployment of zero-carbon technologies gathers pace, carbon pricing will impact on a progressively declining fraction of the economy. Policy analysis needs to distinguish between level at which carbon price is set, which will tend to rise, and the revenue flow associated with it, which will probably peak within 20 years.

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

Apart from the obvious need to strengthen and extend the electricity grid to cope with increased capacity of renewables, it is likely that a combination of new forms of energy storage and significantly increased interconnector capacity will have an essential role to play in facilitating a transition to a fully decarbonised energy system.

The selection and deployment of energy storage technologies, interacting with evolving patterns of energy demand, deployment of new energy conversion systems (e.g. heat pumps and electric vehicles), and development of new and existing energy vectors and combinations of vectors, both depends on, and drives the evolution of energy system functionality and topology.

System architectural thinking will therefore be needed to help 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.

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 and tightly coupled 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 will help to simplify the tasks of regulators and the communities of practice that are responsible for these sub-systems and increase the overall comprehensibility and operability of the energy system. This, as we have seen, is an important function of good system architecture, and one that can become critical in the context of a system failure.

To conclude this section on storage, we reiterate that non-linearity drives the emergence of structure in complex systems – see references in earlier sections. There is no reason to suppose energy systems to be an exception in this respect. The presumption must therefore be that non-linearity, for example with respect to costs and performance of energy stores, will drive differentiation of energy system architectures.

More broadly, the literature suggests that a System Architecture perspective would help us to understand and organise the emergent complexity of the energy system, both operationally and in terms of its evolution, in response to the trajectories of costs and performance of individual energy technologies over time, and as a function of scale and experience.

8. Discussion

In this section, we focus our discussion on factors relating to high current and expected rates of change of individual energy technologies, the energy system as a whole, and of wider non-energy systems, that are likely to contribute to the difficulty of avoiding future energy system failures.

All systems fail, but some failures are more significant than others. Analysis of the statistics of failures of electricity grids show a power-law relationship between size and frequency of failure. Although impossible to derive mathematically, the literature also suggests that economic costs (disruption, lost production etc.) from grid failures rise more quickly than would be indicated by a simple proportional relationship. These two features taken together imply that the expectation value of cost of grid failures as a function of scale is likely to be fat-tailed – in plain language, large scale electricity grid failures matter.

As the foregoing indicates, much of the literature on electricity grid failures is highly mathematical. But system failures have also been studied from a broadly sociological perspective. The causality and overall trajectory of the 9th August outage has many of the features of "Normal Accidents" described by Perrow:

> "Small failures go on continuously in the system since nothing is perfect, but the safety devices and the cunning of designers, and the wit and experience of operating personnel, cope with them. Occasionally, however, two or more failures, none of them devastating in themselves in isolation, come together in unexpected ways and defeat the safety devices – the definition of a "normal accident" or system accident. If the system is also tightly coupled, these failures can cascade faster than any safety device or operator can cope with them, or they can even be incomprehensible to those doing the coping. […] That, in brief, is Normal Accident Theory." [30:356–357]

Perrow goes on to review a number of specific sociological mechanisms that act to make such accidents more likely. These include the roles of culture, language, power relationships, and personal and organisational cost-benefit considerations associated with risk[4]. The mathematical literature taken together with Perrow's analysis suggests the following tentative conclusions:

- High rates of change across the whole energy system may be unavoidable as a consequence of technical development and accelerating pace of deployment of renewable energy systems over coming decades. As a result, latent failures may not emerge early enough in the transition process to make it possible to undertake targeted modifications to technologies or processes in the light of experience;
- The likelihood that failures will be associated with increasingly tight coupling of sub-systems that have been relatively independent until comparatively recently[5];
- Associated with the foregoing, the likelihood that a transition from fossil fuels to renewable electricity as the foundation of future energy systems will result in the formation of new bundles of technologies with high probability of emergent and poorly understood new failure modes, and practical difficulty of recognising what information is vital to system reliability in the context of systemic failure modes that have been built in, but not yet resulted in failure;
- The low probability/high consequence nature of actual and potential failures in energy systems, leading to a potential for moral hazard at the level of governments, organisations and individuals – it may not be in the interest of any given actor to advocate for action to deal with emergent risks, since to do so may be costly, and such risks may not result in failure within a timescale relevant to that actor (for example, expected time-to-failure may exceed the current term of a government, or mean that failure is unlikely before potentially responsible individuals retire);
- The possibility of other organisational, social and cultural barriers to communication of vital information and to acting on such information in the context of rare events with significant consequences.

Two consequences follow from the above. The first is that it may be desirable to implement a strategic approach to resilience in energy systems, for example through heuristics and rules of thumb that appear likely to reduce tightness of coupling between sub-systems and lengthen periods within which responses to failures would need to be implemented. The preceding section on the role of storage in energy systems suggests some specific examples.

The second consequence is that high rates of change constitute an additional reason for expecting energy systems to continue to evolve long after notional deadlines for achieving carbon targets have been reached and passed. Specifically, architectures that are capable of evolution are likely to cope with emergent failure modes more gracefully than architectures that are not, as well as potentially making it easier to to seize new opportunities as they emerge. It is possible that this may eventually lead to stakeholders placing evolvability higher in the rank ordering of energy system requirements.

9. Conclusions

This paper presents an extended reflection on an electricity system outage that occurred in the UK on 9th August 2019 using a perspective drawn from the System Architecture literature. This reflection has enabled us to tease out consequences of the emergent nature of key energy system properties that may not be immediately obvious when seen only through the lens of bottom-up modelling.

Much of the analysis presented here relates to two key energy system properties, resilience and flexibility, in the context of the decarbonisation of the UK energy system. This in turn allows us to draw conclusions with respect to the importance of a third property of complex systems, evolvability.

We argue that, while whole energy system models have a significant role to play in energy policy formation, they are insufficient on their own to support the design of and transition to a fully decarbonised energy system with a large renewable energy fraction. We go on to argue that additional tools and methods, drawn from the System Architecture literature, can complement existing energy system models, guide modelling and support decision-making around the transition to zero carbon.

It appears that introducing the tools and concepts of system architecture into energy research and policy making can 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 stakeholders and the communities of practice who will be responsible for building, commissioning and operating the multiple sub-systems of the evolving energy system.

[4] The latter are often referred to under the heading of moral hazard.

[5] An emergent feature of some models of hybrid car illustrates the principle in microcosm. High power demand for on-board computers needed for engine management, coupled with the fact that such computers may be powered, not from the vehicle's very large main battery, but from a small auxiliary battery, and the fact that a dead computer coupled with the presence of an electrically operated door-opening mechanism, may make it difficult to open the car doors to gain access, mean that such cars may need to be driven or otherwise charged on a weekly basis.

In a task of such complexity, the organising principles of System Architecture are likely to prove essential, helping to frame and organise the direction of bottom-up energy system modelling and interpretation of results, and reveal the implications of technology choices, thereby informing and structuring debate, clarifying goals and supporting collective decision making.

CRediT authorship contribution statement

Robert J. Lowe: Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition. **Lai Fong Chiu:** Conceptualization, Writing - original draft, Writing - review & editing, Funding acquisition. **Steve Pye:** Writing - review & editing, Funding acquisition. **Tiziano Gallo Cassarino:** Writing - review & editing. **Daniel Scamman:** Writing - review & editing. **Baltazar Solano-Rodriguez:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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