Call for Evidence:

Resilience of Electricity Infrastructure

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1. Introduction

Boosting the resilience of UK's electricity infrastructure in the short term (2020) and in the medium term (2030) future is critical for withstanding peaks and pattern changes in demand and sudden shocks in supply. The future UK energy network should go greener to meet the requirements of its climate change targets by applying drastic measures such as decarbonizing its electricity generation, but should also be resilient to unforeseeable external shocks, such as extreme weather events. This leads to the so-called "low-carbon resilient" networks[1], which imposes several challenges in the design and operation of the future UK energy system.

To address these multiple challenges, the Resilient Electricity Networks for Great Britain (RESNET) project is:

- Developing and demonstrating a comprehensive approach to analyse, at a national scale, climate-related challenges in the resilience of the UK's electricity system; and
- Developing tools for quantifying the value of adaptations that would enhance its resilience.

The RESNET project comprises five discrete work packages, ranging from electricity demand and supply scenarios to a systematic resilience analysis of the UK power network, evaluation of adaptation measures, and social responses to these measures. The project is funded by the Engineering and Physical Sciences Research Council (EPSRC) and it is a consortium of Universities and research centres (University of Manchester, Tyndall Centre and Newcastle University), supported by stakeholder partners (National Grid, Environment Agency and Ove Arup).

This letter is a collective response by the RESNET project to the "Call for Evidence: Resilience of Electricity Infrastructure", which summarizes the key findings of the project so far.

2. What is "Resilience of Electricity Infrastructure"?

The electricity infrastructure, as a critical infrastructure, must be reliable during normal conditions and in response to foreseeable threats. In this respect, its design and operation have traditionally been driven by the key reliability aspects of security and adequacy. However, it is becoming increasingly apparent how the critical electricity infrastructure must also be resilient to high-impact low-probability events, such as extremes of weather. In the light of climate change, this is increasingly important as the frequency, intensity and duration of extreme weather events is expected to increase in the future[2].

In this context, *resilience* is defined as the ability of a power system to withstand extraordinary and high-impact low-probability events (sudden shocks) such as extreme weather events, rapidly recover from such disruptive events and absorb lessons for adapting its operation and structure to

[1] Modassar Chaudry, Paul Ekins, Kannan Ramachandran, Anser Shakoor, Jim Skea, Goran Strbac, *et. al.*, "Building a Resilient UK Energy System", UKERC/WP/ES/2009/023, UK Energy Research Center (UKERC), March 2009.
[2] Executive Office of the President, "Economic Benefits of Increasing Electric Grid Resilience to Weather Outages", USA, August 2013.

prevent or mitigate the impact of similar events in the future. According to Cabinet Office, UK[3], and the National Infrastructure Advisory Council (NIAC), USA[4], the key features of resilience are robustness/resistance, resourcefulness/redundancy, rapid recovery and adaptation. Adaptation refers to the measures taken to reduce the vulnerability and build resilience and it can be defined as the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities[5].

However, building highly resilient networks to extreme weather events, and in general to the challenges introduced by climate change, is a difficult task. In addition to the uncertainty associated with future climate projections in key weather variables (e.g. future wind speeds), the high impact of extreme events on the electricity infrastructure may also influence significantly other infrastructures, such as telecommunications and transportation. Thus far, the low probability of severe weather events has made it hard to develop a suitable cost benefit analysis. In addition, large-scale investments for enhancing resilience will require social acceptance of new physical infrastructure and public confidence in energy companies, as well as government policies for attracting investors.

3. Response to Questions

This section provides the collective responses by RESNET project to the questions of interest for the specific Call for Evidence.

Short term (to 2020)

1. **How resilient is the UK's electricity system to peaks in consumer demand and sudden shocks? How well developed is the underpinning evidence base?**

   UK's electricity system can *currently* be considered adequately resilient to peaks in demand and sudden shocks, mostly due to built-in redundancy. However, more variable renewable energy sources penetrating the system in the short to medium term may challenge its ability to deliver sufficient generation capacity at peak times with the current level of reliability, particularly if this occurs simultaneously with greater demand through electrification of heating and transport and the addition of new cooling loads. With increasing impacts of climate change on demand patterns as well as on the frequency and severity of extreme weather events, the resilience of the existing electricity network will likely be compromised. To maintain current levels of resilience and wider performance into the medium and long term, measures will have to be taken to reinforce, upgrade and develop the grid.

[3] Cabinet Office, "Keeping the Country Running: Natural Hazards and Infrastructure," UK, October 2011.
[4] National Infrastructure Advisory Council (NIAC), "A Framework for Establishing Critical Infrastructure Resilience Goals," USA, October 2010.
[5] Intergovernmental Panel on Climate Change (IPCC), "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation", September 2012.

Within the RESNET project, a novel time-series simulation based tool has been developed and applied on a test network for evaluating the resilience of the transmission system to extreme wind conditions[6]. The frequency and duration of customer disconnections were used as resilience indices of the test system for quantifying the influence of wind. The simulation results show that the test system is robust to the expected range of wind conditions as expected from a well-designed and operated system, but it is less resilient (i.e. significantly higher frequency and duration of customer disconnection) to unforeseeable severe wind conditions. This tool is currently being applied to a model of the UK's transmission network, which will provide insights on the level of resilience of the system to severe weather conditions and also quantify the effects of resilience enhancement measures.

2. What measures are being taken to improve the resilience of the UK's electricity system until 2020? Will this be sufficient to 'keep the lights on'?

There are several hardening measures for improving the resilience of UK's electricity infrastructure to extreme weather events, which refer to structural and topology measures such as undergrounding distribution and transmission lines, upgrading poles and structures with stronger, more robust materials and building new transmission facilities. However, the considerable uncertainty associated with projections of future extreme wind speeds (and in general extremes of weather) leaves serious uncertainty in the estimation of the extent of these measures required to meet possible increased hazard. Whilst it is very unlikely that the future wind and icing regimes in the UK will be as hazardous as those in other parts of the world (such as North America or Scandinavia), there are plausible suggestions that the frequency of occurrence of wind speeds capable of disrupting distribution networks may increase, as has been observed in recent years (e.g. winter of 2013/2014).

Hence, the question arises as to whether it is worth investing in assets to withstand a small number of more severe high impact events, whilst considering that even with such investment the infrastructure may not be able to cope with the most extreme events anyway, or it may be better and more cost effective to invest in operational, "smart" measures, such as demand response and automated wide-area protection schemes for protecting the integrity of the entire infrastructure or strategic parts of it. Recent advances in seasonal weather forecasting might even enable improved preparation and planning for such events. We aim to answer this question through our modelling in the near future.

In the short to medium term, increasing the penetration of variable renewable energy sources could impact on the ability of the system to deliver the current levels of reliability of supply, especially if electrification of heating and electric vehicle penetration increases. This is also to be

[6]M. Panteli and P. Mancarella, "Evaluating the impact of weather on the resilience of critical power infrastructure", IEEE Systems Journal, Under Review.

seen in the light of our recent studies that indicate that traditional analytical approaches to estimate the adequacy of a hybrid renewable-conventional generation portfolio might provide different results relative to more detailed time-series based simulation approaches[7].

3. **How are the costs and benefits of investing in electricity resilience assessed and how are decisions made?**

   Reliability standards and extents of redundancy at different levels of the system have traditionally been set on the basis of an underpinning cost benefit analysis that would take into account the occurrence of foreseeable events. The underlying assumption was that extreme events would be so rare that they could basically be neglected. This approach justifies the current level of security the system is operated with. However, a wealth of research, mostly prompted by extreme weather events in the US, is emerging in the power system community, sufficiently so as to trigger some rethinking of this approach. In fact, the so far low-probability extreme weather events might become more frequent due to climate change, and in addition their impact is so high that measures have to be taken to mitigate the risk of supply introduced by such events. Ongoing RESNET work is using a systematic cost-benefit analysis to weigh the benefits gained from applying several resilience enhancement measures (in terms of reducing the frequency and severity of weather-related loss-of-supply events) against the cost of these measures. This should help future decisions be more informed on the most suitable and economically justifiable measures.

4. **What steps need to be taken by 2020 to ensure that the UK's electricity system is resilient, affordable and on a trajectory to decarbonisation in the following decade? How effective will the Government's current policies be in achieving this?**

   Our research indicates that more studies are needed to quantify the level of security of supply that a hybrid renewable-conventional generation system might deliver, as well as that reliance on alternative technologies such as demand response and storage to deliver system capacity might be less effective than believed[8]. In addition, improved climate model projections of extreme winds are necessary to assess and hence ensure resilience to weather related electricity outages.

   RESNET research makes clear that even the UK's domestic mitigation commitments (i.e. around the 80% target) will, during the 2030s, require a grid that can deliver twice as much energy as that of today. However, for the UK to meet its international commitments on climate change (i.e. to make its fair contribution to *"stay below a 2°C rise"* and in keeping with the latest IPCC carbon budgets), the scale of electrification necessary is far beyond anything yet countenanced. Even with a rapid and major improvement in energy efficiency, the 2°C

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[7] Y. Zhou, P. Mancarella, and J. Mutale, "Generation Adequacy in Wind Rich Power Systems: Comparison of Analytical and Simulation Approaches," International Conference on Probabilistic Methods Applied to Power Systems, July 2014.
[8] Y. Zhou, P. Mancarella, and J. Mutale, "Contribution of Demand Response and Electrical Energy Storage to Adequacy of Supply," IEEE Transactions on Power Systems, Under Review

commitment will likely require a zero-low carbon grid delivering three or more times the energy per year than does today national grid.

5. **Will the next six years provide any insights which will help inform future decisions on investment in electricity infrastructure?**

   Developments in technology, such as energy storage and microgrids, as well as findings from research projects like RESNET, will support the decision-making on the most suitable and economic solutions for improving the resilience of the electricity infrastructure in the near future. This is discussed in more detail throughout this response.

Medium term (to 2030)

6. **What will affect the resilience of the UK's electricity infrastructure in the 2020s? Will new risks to resilience emerge? How will factors such as intermittency and localised generation of electricity affect resilience?**

   To meet the requirements of the UK's domestic climate change targets there is likely to be a substantial shift to electricity as an energy vector through electrification of heating and road transport. Not only will this place substantial new loads on the grid, but there will also be an associated impact on societal resilience, i.e., people's ability to go about their everyday tasks, as their means of energy service provision becomes less diverse. Moreover, potential higher temperatures during summer will lead to higher use of air-conditioning by the house holders and businesses, which will introduce a significant new load during summer months. Probably from the late 2020s, this might introduce new challenges on the system, as the power plant fleet will have to operate at higher average utilization throughout the year, which depends however on the future demand profile.

   From an operational perspective, work carried out in RESNET shows that changes to the weather conditions experienced by components of electrical networks such as overhead lines and transformers may lead to different extents of de-rating[9]. This will in turn affect their operational reliability and power transfer capability, and in turn the reliability of the electrical network. De-rating of components will also amplify the challenges in accommodating large amounts of renewables, which requires the full utilization of the existing transmission network and possibly the building of new transmission facilities. This aspect is increasingly important as DECC[10] estimates that around a fifth of generation capacity available in 2011 will be retired by the end of this decade and expected to be replaced with renewables. In addition, increasing constraints arising at the transmission level could further reduce the capability to securely and economically

[9]X. Hu and I. Cotton, "Impact of climate change on overhead lines operated using dynamic rating in a smart gird," International Conference on Innovative Smart Grid Technologies (ISGT EUROPE), October 2013
[10]DECC, "Electricity Market Reform: policy overview", November 2012

maintain the current level of electricity supply. The possible increase in the frequency and severity of extreme weather events makes the picture even more challenging.

As previously noted, in the short to medium term, increasing penetration of intermittent renewable energy sources (localised or not) could impact on the ability of the system to deliver sufficient capacity at peak times so as to maintain the current level of reliability of supply, especially if electrification of heating is undergone. Further challenges are related to operational balancing and reserve requirements, as well as voltage issues particularly for generation embedded in the lower voltage levels. However, localised generation connected to the distribution level could, accompanied by advanced protection and control strategies and possibly improved energy storage capabilities, enable the operation of autonomous islands (i.e. microgrids) during electrical emergencies (and in particular the ones associated to weather events), which could help increase the resilience of the electricity network. Ongoing work in the RESNET project will try to address this latter aspect in more detail.

7. What does modelling tell us about how to achieve resilient, affordable and low carbon electricity infrastructure by 2030? How reliable are current models and what information is needed to improve models?

How future power supply and demand will evolve post 2030 is uncertain, as current mitigation policy could lead to various different low carbon systems. Our research suggests flexibility and extensibility of the grid usage is essential for improving resilience. Flexibility includes curtailment and/or shifting of the demand, together with operational schemes that would be applied following an electrical contingency. Extensibility includes techniques to integrate new technologies/systems, possibly demonstrated on trial projects, to the grid along with storage and distributed generation.

In addition, modelling the impact of severe weather events on the UK transmission network will help inform on the most appropriate and cost effective measures for achieving a resilient UK electricity infrastructure. These do not only refer to infrastructure interventions, but also (and probably most importantly) to the operational emergency measures. Understanding the most significant changes anticipated of the climate will contribute to improved scenarios used in our modelling, which in turn will help provide better and more accurate suggestions for the resilience of the UK network in the future.

8. What steps need to be taken to ensure that the UK's electricity system is resilient as well as competitively priced and decarbonised by 2030? How effective would current policies be in achieving this?

The actual steps depend fundamentally on what role electricity is to play in helping the UK meet either its domestic 80% by 2050 decarbonisation agenda or its much more stringent international commitments around *"staying below 2°C"*. These very different framings of the UK's climate change commitments (80% & weak carbon budgets or 2°C and tight IPCC-based budgets) were discussed briefly in response to Q4; for a more detailed explanation see[11].

As it stands, current UK policies fall far short of delivering on either the strong (2°C) or weak (80%) framings of climate change. Consequently, whatever the final choice, the electricity supply system, as well as the transmission and distribution networks, require a massive programme of decarbonisation and expansion. Until such challenges are recognised and a quantitatively coherent analysis of the necessary responses developed, any assessment of the resilience of a grid of unknown size and fed by an unspecified portfolio of generators, will inevitably be very coarse. From an analytical perspective, the RESNET project overcomes this by postulating a small suite of alternative decarbonisation scenarios, assessing the resilience of these and drawing conclusions on the basis of this analysis. Once completed, lessons can be learned and implications for the UK's incrementally changing grid inferred; however provisional findings clearly demonstrate that current policies will not deliver a resilient and decarbonised electricity system.

9. Is the technology for achieving this market ready? How are further developments in science and technology expected to help reduce the cost of maintaining resilience, whilst addressing greenhouse gas emissions? Are there any game changing technologies which could have a revolutionary impact on electricity infrastructure and its resilience?

Energy storage will play a key role in the future for improving network resilience. It is currently a quite expensive solution, which prevents its wide application in the electricity network. However, the developments in technology will help reduce its cost, which will enable the use of energy storage for enhancing resilience. Storing energy locally will help deal with the challenges of distributed generation and will also contribute to balancing microgrids, which will be an effective measure for coping with electrical emergencies on the transmission network.

10. Is UK industry in a position to lead in any, or all, technology areas, driving economic growth? Should the UK favour particular technology approaches to maintaining a resilient low carbon energy system?

We need to look wider than technology, and take a more holistic view of resilience and how buildings and their environment may impact on electricity demand, including future demand for cooling. The size of the decarbonised electricity network required to meet future electricity demand, including electrification of services such as heat and transport, has implications for the resilience of the network, and a knock-on effect on social resilience.

[11] K. Anderson, A. Bows, and S. Mander, "From long-term targets to cumulative emission pathways; reframing the climate policy debate", Energy Policy, 36, pp. 3714-3722. 2008

11. **Are effective measures in place to enable Government and industry to learn from the outputs of current research and development and demonstration projects?**

    The project is supported by National Grid, which gives us the opportunity to get an industrial perspective of the important issues we are facing. In addition, we believe that better support by and communication with the relevant governmental bodies would help us improve our modelling and make it more applicable to issues and challenges that they may be aware of and that may be of urgent interest.

12. **Is the current regulatory and policy context in the UK enabling? Will a market-led approach be sufficient to deliver resilience or is greater coordination required and what form would this take?**

    The time-scales that high-impact low-probability weather events occur over are significantly different to the sorts of time-scales that markets are good at responding in. While the current transmission network is relatively resilient, this was mainly developed by the government sector, and while market led industries can consider longer time-scales, the large uncertainty over some key future extreme weather events (such as wind) may prevent them from doing this.

4. Conclusions

The UK's electricity infrastructure can be considered resilient to the current climate conditions, but is very unlikely to be resilient to the future challenges imposed by climate change, especially when changes to both the generation and patterns of consumption necessary to deliver a decarbonised energy sector are considered. Uncertainty in future climate projections makes it difficult to quantify changes in resilience due to extreme weather; however, preliminary work in the RESNET project shows that extra reliance on the electricity sector is in itself a cause for concern if the current system remains unchanged. Therefore, measures have to be taken to both hardening the network and improving its operation through advanced, "smart" solutions. Such changes will help build a UK electricity infrastructure that is resilient to future challenges and sudden shocks.

The RESNET project and accompanying expertise offers useful insights on the development of a decarbonised and resilient electricity system, but, as it stands, there remains no evident political commitment or planned route to such a future. If such commitment was forthcoming, expertise of those engaged in RESNET could certainly help guide policymakers and industry in detailing a resilient electricity system commensurate with either the UK's domestic (80%) carbon target or its more stringent (2°C) international commitment.