FUTURE RESILIENCE OF THE UK ELECTRICITY SYSTEM

ARE WE RESILIENT TO MEET THE NEEDS OF THIS RAPIDLY CHANGING WORLD?

AN ENERGY RESEARCH PARTNERSHIP REPORT

NOVEMBER 2018

ABOUT THE ENERGY RESEARCH PARTNERSHIP

The Energy Research Partnership (ERP) is a high-level forum that brings together senior-level funders and stakeholders of energy research, development, demonstration and deployment across Government, industry and academia, plus other interested bodies. It is a partnership between public and private sector organisations providing reciprocal benefits to industry and Government members alike. Its primary purpose is to offer a consultative forum as an independent, not for profit organisation whose activities are funded by Member contributions.

By bringing together a diverse range of participants from across the sector, the ERP aims to accelerate innovation in the energy sector through enhanced dialogue and communication across industry and Government to build the public-private consensus on energy innovation.

The ERP is intended to provide high-level leadership and aims to identify recommendations to help shape future policies and regulations that benefit the UK economy and society. The ERP also supports UK trade and investment through identification of areas for export of British expertise.

On the topic of resilience, the broad spectrum within the ERP Membership, Working Group and Project Advisors (non-ERP members invited to bring specialist knowledge to the project) ensure the report represents a balanced view of the challenges that face the industry in the future and proposes recommendations that will seek to maintain and enhance system resilience going forwards.

The project scope was developed with support from Working Group Members (ERP members and Project Advisors). This report is based on information provided by each Working Group Member that set out their organisation's view on the UK electricity system resilience, and the potential future impact of the changing energy landscape. All working group members, discussed and shared findings at a workshop held at the Department for Business, Energy and Industrial Strategy on 11th June 2018. The industry views from the responses submitted and expressed at the workshop are represented in this report. This report does not represent the full views of the organisations involved in the work, nor does it represent government policy. Individual organisations may have policies and ongoing work regarding resilience which may vary from the opinions set out in this report. However, all organisations, via Energy Research Partnership governance, support the broad consensus view expressed within this report.

WORKING GROUP

ERP Members

- ABB
- Arup
- Atkins, member of SNC-Lavalin Group
- Department for Business, Energy and Industrial Strategy
- EDF Energy
- Environment Agency
- Energy Systems Catapult
- National Grid Electricity Transmission
- National Infrastructure Commission
- Welsh Government

Project Advisors

- Energy Networks Association
- Electricity North West Ltd
- Northern Power Grid
- Scottish Power Energy Networks
- UK Power Networks
- Scottish and Southern Electricity
- University of Manchester

Other ERP Members

- Bosch Thermotechnology
- University of Cambridge
- The Carbon Trust
- Committee on Climate Change
- Energy Saving Trust
- Engineering and Physical Science Research Council
- Hitachi
- Origami Energy
- Scottish Enterprise
- Department for Transport
- Turquoise International
- UK Energy Research Centre

EXECUTIVE SUMMARY

The electricity system[i] has seen significant change over the last decade with a trend towards decentralisation of generation, a rapid increase in intermittent renewable generation, and an increased electrification of other critical infrastructures and sectors. There is a growing trend of society and business becoming increasingly reliant upon new technology, broadband and communications; all requiring electrical energy and ultimately leading to an increased interdependency between sectors. Furthermore, the world is changing; from climate change inducing extreme weather events, through to an increase in malicious intent to affect networks.

The UK electricity system has enjoyed high levels of resilience historically and remains resilient today[1], providing a high degree of confidence to businesses and consumers that power will be available 24 hours a day, 7 days a week, 365 days per year. However, a reliable electricity system is not necessarily a resilient electricity system. Reliable day-to-day operation during normal circumstances is expected, however we must be able to respond to the more severe, less frequent events to ensure power supplies are maintained or restored quickly following such an event. Therefore, we consider a reasonable definition of resilience to be:

'the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events'[2].

Looking forward, we should anticipate further change to ensure that any new infrastructure is built with resilience required to meet future needs. The decarbonisation of heat and transport will introduce further complexity to the electricity system by increasing dependencies on electricity across many infrastructure sectors, and new energy vectors such as hydrogen will present new interactions and challenges. In addition to this, we should expect the rapid increase in the number of assets and different owners in the electricity system (including domestic power generation, such as roof-top solar panels) to continue.

Society's dependence upon electricity is far greater than when the current electricity system was established, and this is continuing to grow with each new technology introduced. So, in the future an external effect on the electricity system will impact a wide range of technologies dependent on power, which in turn is likely to have a much larger impact on society than in the past.

With these factors in mind, it is time to take a fresh look at how we ensure the UK has a resilient and robust electricity system in the future. The aim of this Energy Research Partnership led project is to identify and assess energy landscape changes that are likely to impact the future resilience of the electricity system and deduce the key focus areas for recommendations and proposed outcomes. The project has identified four key factors that will affect the future state of resilience in the electricity system, notably a growing economic importance of metropolitan centres, growing reliance upon technology and networks, growing complex interdependencies between networks and growing threats to network infrastructure.

[i] Electricity System is defined as the assets, businesses, services and supply chain that facilitate the transport of electricity from the point of generation to the point of consumption; and the political, societal, economic and technological environment in which they operate.

ECONOMIC IMPORTANCE OF METROPOLITAN CENTRES

- Today's society and business are gravitating towards large metropolitan centres. These centres often contain the new hi-tech, service, financial and retail industries that drive the economy today.

- The future resilience needs of these large urban centres will have to be increased in line with their economic importance, and proportion of population, if significant impacts to the economy and society are to be mitigated.

RELIANCE UPON TECHNOLOGY AND NETWORKS

- Today's society and businesses use of electricity is changing, with availability of electricity required for communication/broadband, lighting, heating/cooling, cooking, electronic payment systems and power for integrated technology.

- Further electrification of transport, the de-carbonisation of heat, and integration and automation of systems (inc. road transport) suggest a further reliance upon electricity. We should ensure our networks and systems are resilient to meet this future need.

COMPLEX INTERDEPENDENCIES BETWEEN NETWORKS

- Today's infrastructure networks depend heavily on each other - electricity and communications are a common dependency for most systems. This places them at the heart of the resilience debate.

- Complex interdependencies are expected to increase further with the fast pace of technology development and adoption of electrical powered smart devices. Electricity and Communications could become points of common failure, for multiple infrastructure networks.

THREATS TO NETWORK INFRASTRUCTURE

- Today's electricity system is under greater threat than ever, at the same time as we are more reliant on electricity. Whether these threats are from climate change, malicious cyber attacks or physical threats, they are also occuring in a time of growing international political instability.

- With more States investing heavily in cyber warfare and growing availability of information about networks available online, cyber enabled and physical threats will continue to increase, having the potential to disrupt our ever more complex and interdependent networks.

The electricity system currently undertakes extensive programmes of work to meet today's resilience requirements. To build upon the work currently being developed in the industry, through the collaboration led by the Energy Research Partnership, this report has identified a number of opportunities to further enhance future electricity system resilience to meet the growing challenges. This project has identified there is currently no common industry approach to managing resilience; further research and analysis could inform a whole-system view of a definition of resilience and strategies to manage cross sector resilience. This report has differentiated itself from other industry resilience work by strongly focusing on the future technologies and their place in a changing energy landscape. This will change the way we need to consider electricity resilience going forward, and the recommendations are suggested to build on the resilience work currently being done within the industry and Government.

The ERP expects this report to be a catalyst to initiate debate about how resilience is considered and managed within cross-sector infrastructure industry, Government and regulators.

The report's recommendations are summarised as follows, with Recommendation 1 serving as an overarching recommendation for four further recommendations:

RECOMMENDATION 1: RESILIENCE MEASURES

Investigate resilience measures which can be used cross-sector to establish acceptable levels of resilience to meet future needs.

Resilience measures can be defined in many ways, and there is currently no common methodology adopted within the electricity industry. Firm commitments are required to investigate development of a suitable measure, which could support understanding of the electricity industry's readiness and capability to meet society and business' expectations, as well as aligning with Government policy. Suitable measures, that gain support for implementation, will set clear standards for the electricity industry to achieve.

Proposed outcomes:

2020	2025	2030
Organisations across the sector to investigate applicable resilience measures, and share best practice via a regular industry and cross-sector forum.	Common cross-sector measures of resilience agreed, ensuring regulated sectors are delivering resilience levels required by society and business.	Resilience measures being refined to reflect changes in threats and learning from world-wide incidents. Continuing to demonstrate value to consumers.

RECOMMENDATION 2: ENGAGE SOCIETY AND BUSINESS

Engage a diverse set of views across society and business to establish future resilience requirements for the UK Electricity system.

With growing reliance on electricity, society and business should be engaged to understand their needs, and expectations for service provision following an exceptional event. The period society can tolerate loss of power, and the value placed on power-dependent amenities, would set the levels of resilience needed in the future. This in turn will influence Government resilience policy, balanced against constraints and National priorities.

Proposed outcomes:

2020	2025	2030
Relevant stakeholders to engage Society and Business in a meaningful way, to understand their future expectations and needs.	Understand resilience requirements for different geographical and societal needs, consulting stakeholders and setting policies.	All new infrastructure designed and constructed to meet future resilience policies. Networks meet resilience expectations of society and business.

RECOMMENDATION 3: GOVERNMENT AND POLICY

Government should work with cross-sector infrastructure parties to establish holistic resilience policies for the future.

Given the increasing interdependencies between systems, a holistic view of resilience is imperative to its management. Government needs to continue to take a lead on developing policies that enhance resilience, reflecting the future impacts of the rapidly changing world. Clear policies are required to ensure that the resilience needs of society and business are met in the right timescales. A task force comprising of senior leaders across sectors, working with Government, would be best placed to deliver the direction set in policy.

Proposed outcomes:

2020	2025	2030
Cross-sector task force, with senior industry leaders established by government to develop resilience policies.	Cross-sector government policies for resilience developed, ready for consultation and implementation.	Policy continuously reviewed to meet ongoing future needs.

RECOMMENDATION 4: REGULATION AND MARKETS

Infrastructure regulators to make resilience a central consideration of review periods. It should also stimulate markets to ensure relevant sectors provide resilience in their products and services.
Resilience should be a core topic of regulatory reviews for the electricity industry, and a strong market driver in future power-dependent sectors, such as transport. A measure would support regulatory outputs, to ensure the industry is delivering resilience levels society and business expect, whilst providing value for the consumer.

Proposed outcomes:

2020	2025	2030
Cross-sector task force identifies interdependencies and future technology impacts, supporting cross-sector regulatory consistency.	Regulatory review periods have resilience as a core defined topic across all regulated sectors, allowing Government resilience policies to be met.	Regulatory outputs and measures for resilience are demonstrating value to consumers and businesses. Market is providing resilience in non-regulated products and services.

RECOMMENDATION 5: CYBER SECURITY

Organisations to build their cyber security skills and capabilities, to address growing threats, and ensure secure network resilience during technology integration.
Cyber security should continue to be considered as a separate output in the resilience policy to physical security. The Networks and Information Systems Directive (known as the NIS Directive), being applied to the UK, ensures there is a national framework to support and promote the security of network and information systems.

Proposed outcomes:

2020	2025	2030
Electricity organisations meeting NIS directive on cyber security.	UK companies achieving robust, world leading standards in cyber security.	Robust cyber resilience ensures new technologies benefit society, through optimisation of our infrastructure networks securely.

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FIGURES

GLOSSARY

BLOCKCHAIN	A distributed digital ledger in which transactions made in cryptocurrency are recorded chronologically and publicly
CONSUMERS	An individual, or group of individuals, that purchases electricity for their own individual consumption
ELECTRICITY SYSTEM	The assets, businesses, services and supply chain that facilitate the transport of electricity from the point of generation to the point of consumption; and the political, societal, economic and technological environment in which they operate
ENERGY LANDSCAPE	The physical aspects and the societal use of, and influence, on the UK electricity system
GROSS VALUE ADDED	The increase in the value of the economy due to the production of goods and services
RESILIENCE	The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events[2].
UK BUSINESSES	An organisation, or group of organisations, that purchase electricity for their consumption within their normal operations

1.INTRODUCTION

1.1. BACKGROUND

The Great Britain and Northern Ireland electricity systems (collectively referred to as the UK electricity system for the purposes of this report) have seen significant change over the last decade, and today's highly integrated system is set to increase in complexity over the near and long term.

From a generation and supply perspective the electricity system has seen three key changes. Firstly, the traditionally linear and centralised electricity system (generation> transmission> distribution> consumption) is evolving into a decentralised and more widely integrated system, creating further interdependencies between industry sectors. Secondly, environmental and climate change factors are driving decarbonisation, bringing more intermittent renewable generation and new low carbon technologies to the mix. Finally, the threat of malicious attack, in both cyber and physical form, continues to grow in prominence.

From a demand perspective, societal dependency on electricity has grown, and is expected to continue to grow as new technologies further support our lives. Historically, road transportation, cooking and the ability to heat our homes were less dependent on electricity (e.g. in the 1950's many homes had coal fires, gas hobs and petrol cars). At this time, society also had experience of power cuts and were more accustomed to coping without power. If we contrast this to the modern home, with more controllable electric cooking appliances, gas boilers (reliant on electricity to operate), broadband routers, Electric Vehicles (EV) and many interconnected devices, it is easy to see how modern society is likely to be more impacted by supply disruptions. This is highlighted in Figure 1, which shows how the impact of power loss may change over the duration that electricity is not available.

Figure 1: Potential impacts from loss of electricity over varying outage durations

Generators, transmission and distribution network operators, and owners, undertake extensive programmes of work to ensure the electricity system is resilient to meet today's requirements.

For example, work currently in place to improve our resilience position today includes:

- Flood defences at major sites, in particular protecting sub-station to 1 in 100-year floods (i.e. 1% chance in any given year of occurring) and in some cases 1 in 1,000-year floods (ie 0.1% chance in any given year of occurring).
- Identification of single points of failure, and ensuring appropriate redundancy or protection is provided.
- Increased physical security, in accordance with guidelines for Critical National Infrastructure.
- Cyber security improvements, in line with the NIS directive[3].
- Provision of back-up power supplies to communications infrastructure, to ensure control signals can be actioned in the event of mains power failure.
- System restoration improvements, to ensure that the system can be restarted as quickly as possible.

1.2. FUTURE RESILIENCE

Looking forward, sectors such as transport, communications and heat, will become increasingly reliant upon electricity for operation. The evolution of these systems not only changes the consequences of a loss of supply event, but also changes the potential impact on society due to increased dependence on these services. Understanding the impact of a loss of supply, due to credible extreme events, is critical to develop a resilient position in the future for the UK electricity system. The Energy Research Partnership (ERP) expect the efforts industry makes to ensure resilience will continue and evolve in response to future challenges as they emerge. However, the ERP recognises that there may be low regret, long term decisions and investments that are required within the next decade in anticipation of future change. To support these, there may also be knowledge gaps that require further investment in Research and Development to optimise ensure actions benefit the whole energy system.

Overall, the Energy Research Partnership sees a need for the Energy Industry, Government, and Regulators to act now to prepare for further change presented by key future trends as outlined in this report:

- The growing economic importance of metropolitan centres, as we shift from a manufacturing to a service-based economy.
- A growing reliance upon technology and networks, as we become more dependent on electronic devices and the power that supplies them.
- More complex interdependencies between networks, as more sectors become increasingly reliant upon electricity for their operation.
- Growing threats to network infrastructure, in particular posed by climate change and cybersecurity related issues.

It is imperative that we consider these impacts now, to allow lead times for any identified solutions to be put in place. Consideration of consumers and business future dependency is a critical part of this process to identify the level of resilience that society expects and needs.

1.3. PROJECT SCOPE

The aim of this ERP led project is to identify and assess energy landscape changes that are likely to impact the future resilience of the electricity system and deduce the key focus areas for recommendations and proposed outcomes. The ERP has brought together real-life experience and the different perspectives of its members, as well as a wide range of stakeholders, collaborating across the electricity industry to explore future electricity resilience needs.

The aim of this report is to provide thought leadership on the increasing complex interconnectivity of the electricity system, and interaction with other systems. The project seeks to identify and assess energy landscape changes that are likely to impact the future resilience of the electricity system and deduce the key focus areas for future improvements This in-turn shall lead to more extensive analysis by industry, academia and Government in the short term. The project has sought to systematically gather insights from these stakeholders and use these to help inform and shape a common view. This report does not provide detailed analysis of the system, recognising that many aspects of existing system resilience are already considered in industry and Government working groups. This report has been derived following an extensive programme of workshops, working groups and reviews to provide a balanced view of future resilience needs.

In summary, the project has three key objectives:

- Review current industry definition(s) of resilience, the means of managing and metrics to quantify resilience within the UK Electricity System, and measures to improve resilience.
- Assess the impact of the changing energy landscape (including cross-sector dependencies) and external shocks, on how resilience is managed within the UK Electricity System.
- Develop an objective view of how to manage levels of resilience in the future, and what focus areas/ outcomes are required to enable the industry to adapt to the changing energy landscape, to 2030.

While the report has focussed on the electricity system to provide a focus for the work, many of the trends identified could be applicable and will have implications on the wider energy system and interdependent systems, such as transport and communications.

2. WHAT DO WE MEAN BY RESILIENCE?

RESILIENCE VS RELIABILITY

- Resilience is, 'the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events.'
- Reliability describes the daily challenges faced by system and network operators; resilience is focussed on rare or extreme events.

MITIGATION VS RESPONSE

- To prepare for events that may test the system's resilience, a balance between investments in mitigation measures and response capability is necessary.
- These in turn need to be balanced against society's expectations and requirements.

MEASURING RESILIENCE

- A common method of measuring resilience would provide a benchmark, a common industry framework for enhancing resilience and assign value to future investments to enhance resilience.
- Resilience measures can be defined in many ways and there is currently no common methodology adopted within the electricity industry. If suitable measures are identified and gain support for implementation, it will set clear standards for the electricity industry to achieve.

2.1. THE DIFFERENCE BETWEEN RESILIENCE AND RELIABILITY

For the purposes of this report, we consider a reasonable definition of resilience to be

> 'the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events'[2].

Resilience can be applied to all aspects of society, from individuals, to networks such as electricity, water, transport and oil, to governments and global organisations. This report has considered the sector interactions and interdependencies from an electricity perspective, based upon the knowledge and experience of ERP members, working group and project advisors. However, further cross-sector dependencies do exist between other sectors, that could be considered by doing similar assessments from the perspective of those other sectors. This report recommends that a cross sector task-force with senior representation working with government would be best placed to consider how a fully coordinated view of resilience can be established and managed.

Some resilience scenarios which would be considered within the UK electricity system include:

- Natural hazards and extreme weather, such as flooding or storms
- A physical malicious attack on key infrastructure
- Failure of the power and/or communication networks impacting on the operation of both systems
- Significant shortage of staff in the face of an event, to restore supply
- Power failures affecting the supply of essential services such as water or healthcare

We need to be clear that resilience is not the same as reliability. Reliability is focused on the electricity system supplying power to the end consumer and UK businesses, within normal operating conditions and credible contingencies. The differences between reliability and resilience are highlighted in Table 1[4].

RELIABILITY	RESILIENCE
High-probability, low-impact (likely to happen and impact small amounts of consumers for a short duration)	**Low-probability, high-impact** (not likely to happen, but effects are widespread locally or nationally, and potentially longer duration)
Static (the problem occurs and the situation does not evolve further following the fault)	**Short and long-term mitigation and response** (ability to build infrastructure to limit impact of an unlikely event or respond to the event quickly to reduce impact)
Evaluates the power system states (the consequences of the fault are known and the power system is stable following known understood event)	**Evaluates the power system states and transition times between states** (the problem can evolve quickly causing further faults continually changing the state of the system leading to unknown impacts)
Concerned with customer interruption time (making sure the impacts on the consumer are limited to acceptable levels)	**Concerned with customer interruption time and the infrastructure recovery time** (as the impacts are likely to be wider or unexpected, recovery of network assets can take longer and require resilience plans to be enacted)
Day-to-day challenges of running a network (making sure the system operates as expected and maintenance activities are undertaken to ensure the system is in a good operable state)	**Ability to withstand or recover rapidly from rare/extreme events** (a network is only able to respond to such events if it is prepared, delivers suitable mitigations or has response measures and assets in place to recover from the event)

Table 1: Traits of reliability and resilience in electricity systems

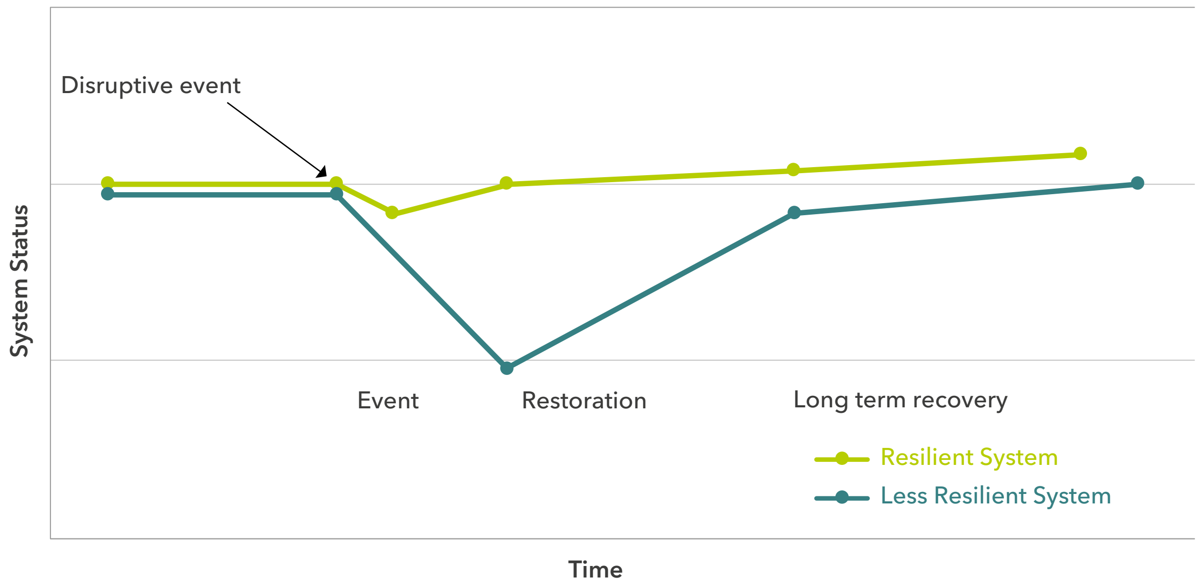


Figure 2: A resilient versus less resilient system[5]

However, the differentiation is not discrete, and not as yet explicitly considered in the operation and planning of an electricity system. An unreliable system is likely to be less resilient, as it is more vulnerable to cascade failures. However, the opposite is not necessarily true; a highly reliable system is not always highly resilient. An example would be an airport which does not normally experience snowfall, it can be highly reliable during normal conditions but if snow falls, operations are impacted or halted. Therefore, this airport has low levels of resilience to snowfall. This may not be acceptable for a large international airport, so investing in and maintaining in snow clearing equipment to mitigate this low probability event would make the airport reliable and resilient.

If an incident is not anticipated and adequately prepared for, the recovery from the event is likely to take longer than if the issue had been identified and a resilience plan put in place to deal with such an event. This is depicted in Figure 2, which compares a resilient system with a less resilient system.

More generally, several key principles typically characterise resilient systems:

- **Diversity** – ensuring diversity of generation, supply and demand management, in terms of type, size, location and timing.
- **Redundancy** – ensuring the appropriate level of backup is available and systems can continue to function with alternative supplies or networks in place to redistribute power.
- **Modularity/Temporary Response** – designing in modularity or temporary systems that can be deployed in rapid response should equipment be damaged and require a temporary solution or replacement.

2.2. RISK MANAGEMENT APPROACH TO RESILIENCE

The resilience of a system can be influenced by making enhancements to mitigate the impact of an extreme challenge on the system or by making preparations to respond to an event as it unfolds. This can be visualised using a 'bow-tie' diagram, as shown in Figure 3, which highlights the complex balance between mitigation and response.

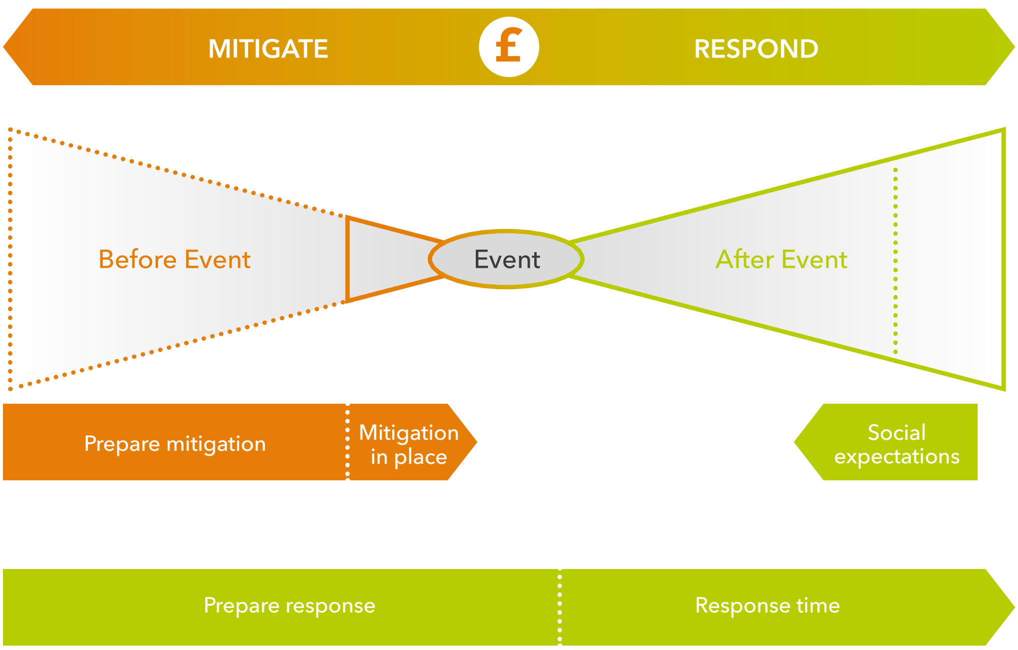


Figure 3: Bow-Tie Risk Management

With regards to whether the focus should be on mitigation or response there are three different types of extreme or rare events to consider:

1. Known-knowns: Events which can be reasonably anticipated and how they may manifest themselves

For these events, historical data can be analysed to assess the potential future impact and put in place mitigation measures as well as response measures. For example, we know where flooding is likely to occur based on environmental data, we can therefore build defences at the sites most likely to be impacted therefore mitigating the consequences of a flood.

2. Known-unknowns: Events which can be reasonably anticipated, but cannot be reasonably assessed how they may manifest themselves

For these events, it is possible to assess which mitigations to put in place, but primarily the focus will be on response. For example, cyber-attacks are a known unknown; they are a risk to the electricity system, but there are many ways to develop a cyber-attack and so may manifest in an unknown manner. Thus, an organisation will harden its cyber defences, but also spend time on response planning and preparation to enable system restoration as soon as possible should an attack breach the defences.

3. Unknown-unknowns: Events which cannot be reasonably anticipated or how they may manifest themselves

For these events, it is acknowledged that it is difficult to anticipate all scenarios which may result in a widespread supply disruption. However, even without knowing the exact cause for a potential power loss, it is possible to assess the potential impact. Therefore, it is more likely for investment to be focussed on response activities rather than mitigation. However, it should be noted that the mitigation activities for known events, can also enhance resilience against unknown-unknown events, for example having strategic assets or temporary solutions available for deployment.

The bow-tie diagram in Figure 3 demonstrates the economic balance to achieve the appropriate mitigation and response actions, for an associated event; known-known, known-unknown or unknown-unknown events. This is a difficult balance as to mitigate against every possible event would be very expensive and time consuming, indicated by the left-hand side of the bow-tie. Mitigation like flood defences are sensible, however it takes time to implement mitigations so preparation time along with the cost must be considered.

Where mitigation is financially excessive to the risk, response measures may represent the most economical solution represented by the right-hand side of the bow-tie. However, response measures, for example temporary flood defences for low probability events, take time and money to develop and take time to deploy. Once in place a temporary solution can be deployed anywhere on the network where a low probability event has occurred rather than protecting every site and can be done at lower cost.

It is a collaboration between government, markets and networks, on behalf of society, that develop the plans for rare and extreme events and take the most appropriate actions in the most economically efficient manner. To achieve this balance, costs and benefits of different options for mitigation or response actions are evaluated, to align with society's expectations and requirements for the return of power supplies following an incident.

2.3. MEASURING RESILIENCE

This report does not seek to propose a methodology for a resilience measure, as this is best done as a separate exercise led by organisations within the sector. This report seeks to set out why a resilience measure would be beneficial and provide insight in to existing measures that could support the development of an industry wide measure.

Resilience measures can be defined in many ways and there is currently no common methodology adopted within the electricity industry. It is acknowledged that reliability measures have often been applied to measure resilience within the industry to-date. However, these may not be the most appropriate metrics, as these evaluate average events, which are managed within business as usual activities, whereas resilience concerns itself with extreme and rare events. The primary benefit of measuring resilience of the electricity system is that it would enable objective targets defining levels of resilience against which we can identify gaps and propose solutions for consideration by regulators and stakeholders. Furthermore, it could also provide a common language to discuss how the changing energy landscape may affect the levels of resilience, and to agree how the different mitigation and response strategies could benefit the level of resilience available.

It is widely acknowledged that different metrics are required to quantify reliability and resilience. The traditional and widely used reliability metrics, such as Expected Energy Not Served (EENS) and Loss of Load Expectation (LOLE) are not considered appropriate for measuring resilience. The traditional reliability metrics focus on the average event; on the contrary, resilience is concerned with severe and rare events, which cannot be modelled by the expected average impact of frequent events.

This project identified a range of possible approaches to measure resilience as summarised in Figure 4; these suggestions were presented by the project working group. However, the purpose was not to debate and agree one approach. Some approaches adopted by industry to-date are discussed further in Appendix A. These methods focus on evaluating the events in the tail of the probability distribution; high impact, low probability events, which resilience focusses on. It is important to recognise that some approaches are attribute based assessments (e.g. Cities Resilience Index in Appendix A2), which require a review of system properties that contribute to resilience while other approaches are outcome-based assessments (e.g. Trapezoid method in Appendix A1) which typically need a defined scenario to test the system against.

The wide variations in the suggestions lays the foundations for further investigation of the proposals with the aim of developing measures in the future. The ERP considers that developing a common methodology for a resilience measure would be beneficial to all industries.

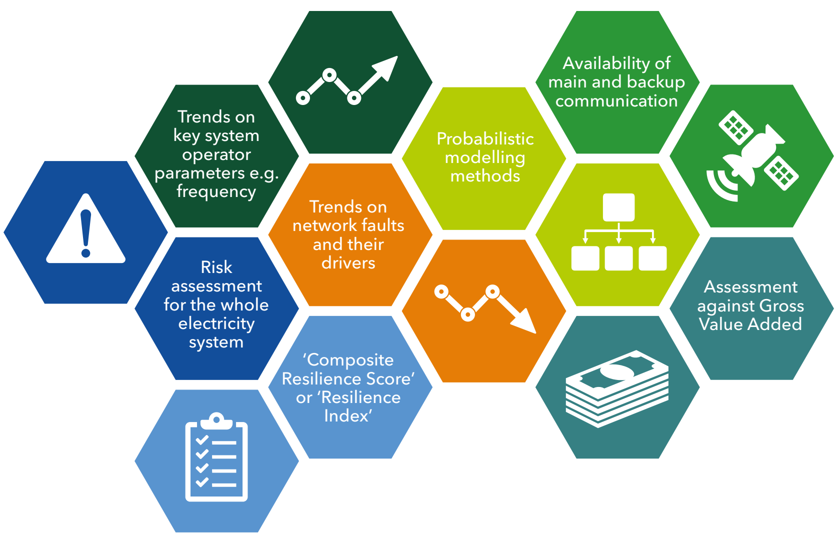


Figure 4: Possible approaches to measuring resilience

3. ECONOMIC IMPORTANCE OF METROPOLITAN CENTRES

A SYSTEM DESIGNED FOR HEAVY INDUSTRY

Historically the backbone of our power system was developed to support an economy dominated by heavy industry

THE MODERN ECONOMY

The UK economy is dominated by the high-tech industry and services sector, with the most Gross Value Added concentrated in metropolitan centres

POWER DEMANDS IN CITIES

With the shift to a service based economy and the population gravitating towards metropolitan centres, there is a need to review the future electricity needs for the growing cities alongside a review of the electricity system feeding those cities.

3.1. A SYSTEM DESIGNED FOR HEAVY INDUSTRY

Historically the electricity system has been developed as a linear system (generation> transmission> distribution> consumption). The electricity system was built around domestic consumers and heavy industry following the industrial revolution, where the largest areas of demand at the time were industrial users, and critical contributors towards the UK economy. However, as technology has evolved, so has the UK economy.

Heavy industry is no longer the UK's greatest contributor towards the economy[6]. This is highlighted in Figure 5 which demonstrates the change in economic output within the UK between 1970 and 2010, by industry. Manufacturing delivers approximately a third of its proportion of economic output in 2010 compared to 1970, whereas the business services and finance sector has more than doubled its relative economic contribution.

The world has become more connected through the development of broadband networks and electronic devices, enabling business services, such as finance and data centres, to be located anywhere in the world. The UK economy will continue to evolve on the back of new levels of connectivity.

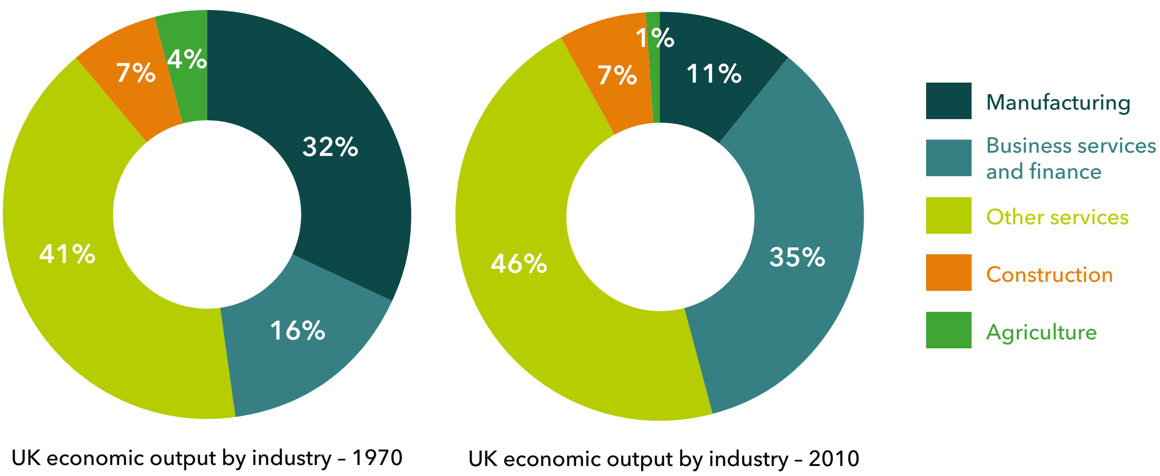


Figure 5: Changing UK economic output by industry from 1970 to 2010[7]

3.2. THE MODERN ECONOMY

Over the last two decades, the UK's economy has seen a large expansion of the services and high-tech sectors, which includes[6]:

- Transport, storage and Oil (Scotland),
- Business services and finance,
- High-Tech communications, software and advanced technology Industries,
- Government and other services,
- Distribution, and hospitality.

A map of the Gross Value Added (GVA), by region within the UK, demonstrates that the largest areas of GVA are predominantly within cities, which are focussed on supporting the service sector and high-tech industries (see Figure 6).

Figure 6 clearly shows the concentration in output around Greater London and the surrounding commuter belts stretching along the Thames Valley, with further pockets through Oxfordshire, Cambridgeshire, the West Midlands, Greater Manchester, Cheshire, Leeds, Glasgow and Edinburgh in particular. The concentration in eastern Scotland shows the large influence of the offshore oil industry in this area.

When GVA is considered alone it is clear that the combined authorities of Greater London dominate the UK economy, contributing a total of £408B in gross value added; almost a quarter of the £1,748B for the entire UK. Furthermore, over one third of Greater London's economic output is concentrated in just two local authorities; Camden and City of London and Westminster[8]. The London urban example is becoming more relevant in other large cities across Wales, Scotland and England, where movements to urban centres are driving the British economy.

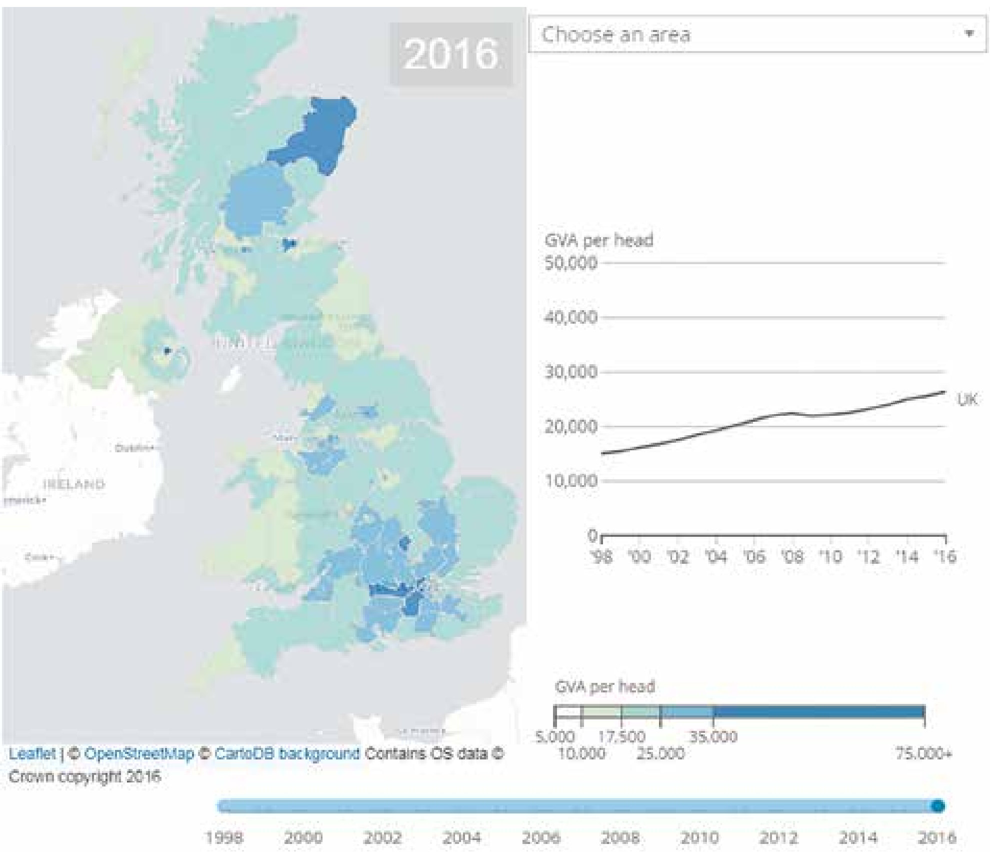


Figure 6: Gross value added by UK-2016[8]

3.3. POWER DEMANDS IN CITIES

There is a potential correlation with the focus of British industry changing, and where the British population live and work. This is changing daily travel patterns, with the average person in Great Britain now commuting 29 minutes to their place of work[9]. As the British economy, has moved towards metropolitan centres, so has the British population, as shown in Figure 7. There has been a significant increase in the urban population, over the past 50 years, which is anticipated to continue. As the population in these metropolitan centres increases, so does the electricity demand in these locations, through electricity use for domestic properties, transportation, and businesses. Consideration should be given to whether infrastructure is designed to meet the future geographical changes in electricity demand, and how this may impact on city resilience (see Case Study 1).

We especially need to think about how these urban centres will be affected by power outages and if their reliance on electricity and technology for business, transport and homes is different from more remote, and arguably, more fuel resilient rural communities. Cities are more adversely affected by power shortages as train and road network signals failing quickly could cause gridlock or pumps supplying water to large buildings fail, for example. Whereas in rural and small towns there are likely to be lower traffic volumes, more manageable levels of road signals and water supplies may remain operational longer without pumps. This may lead the industry to consider the need for different levels of resilience for different locations, dependent on the impact on and welfare of the public in that particular location.

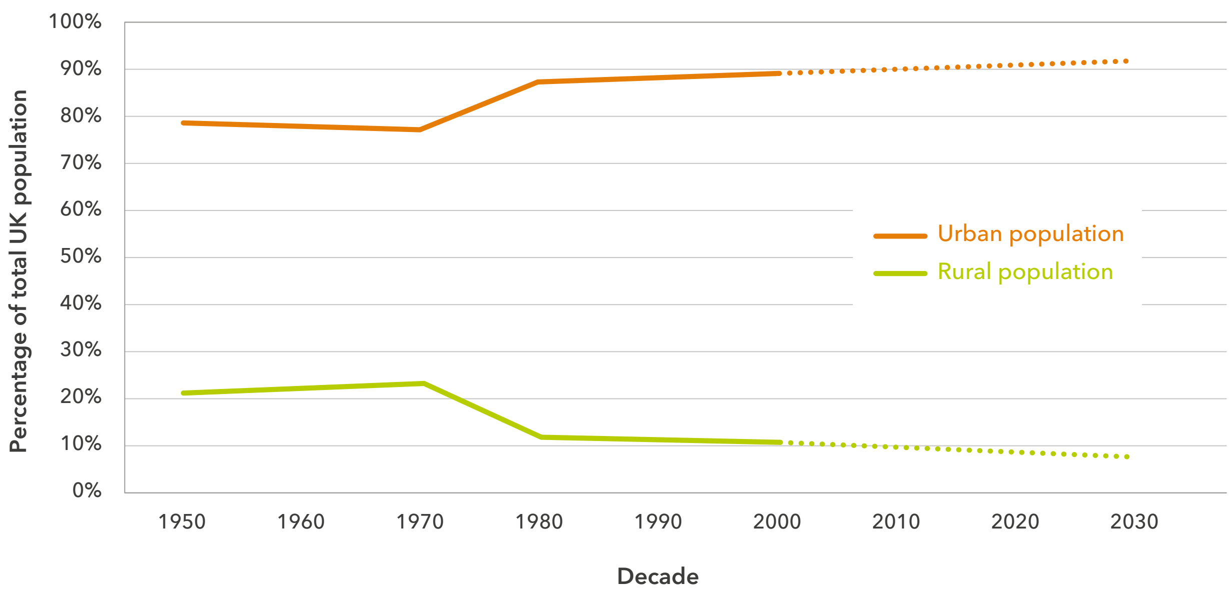


Figure 7: Trend in UK urban/rural population 1950 – 2030 (predictions from 2005 data)[10]

CASE STUDY 1: 2003 SOUTH LONDON AND EAST BIRMINGHAM BLACKOUTS

In the early evening of 28 August 2003, electricity supplies to 476,000 consumers in South London were involuntarily interrupted. Just over a week later, electricity supplies to 220,000 consumers to the East of Birmingham were also involuntarily interrupted (including the west coast main rail line, hospitals, major shopping centres, and Birmingham International Airport). In both of these events power supplies were restored to all customers within an hour. However, there were significant disruptions to normal activities, particularly transport systems.

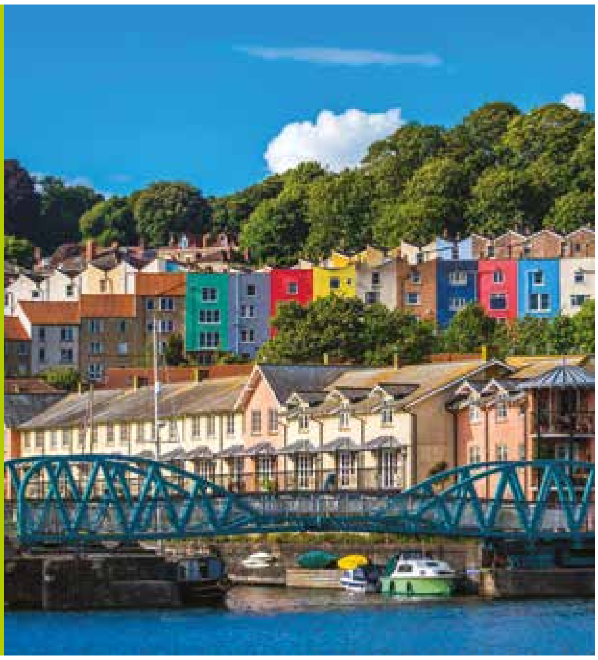
Such unplanned involuntary events directly impact customers and also have wider impacts on the operation of local infrastructure and services. Some consumers' standby arrangements (hospitals, airports etc.) minimised the impacts whereas for others (e.g. London Underground) the short interruption of supply led to extended disruption of services. There were lower levels of disruption to infrastructure in Birmingham, than that experienced in London, and reflects, in part, the measures adopted by customers, such as Birmingham International Airport, to mitigate the (small) risk of supply interruption[11].

The National Infrastructure Assessment also notes the growth of cities, recognising them as the engines of the economy, and in 2018 recommended additional funding for major cities to support economic growth[12]. However, the infrastructure and set-up of the UK electricity system has not changed significantly to adapt for the change in the focus within our economy.

A review of the future electricity needs for the growing cities should be done side-by-side with a review of the electricity system feeding those cities, determining if it can meet their future electricity needs. Appropriate representatives of society and business, should be engaged by the electricity industry to understand the future electricity demands and aspirations for these cities. An example of this in action can be seen in Bristol, UK, which recently participated in a review under the global, '100 resilient cities' programme (see Case Study 2).

CASE STUDY 2: 100 RESILIENT CITIES – BRISTOL

100 Resilient Cities, pioneered by the Rockefeller Foundation, is dedicated to helping cities around the world become more resilient to the physical, social and economic challenges that are a growing part of the 21st Century. '100 Resilient Cities' supports the adoption and incorporation of a view of resilience that includes shocks and stresses. Bristol is one of the 100 Resilient Cities, that has assessed its resilience as a city for 2050. Energy supply was identified as a focus area for Bristol, as a basic need, and the Bristol City Council have since developed an energy framework to ensure a continual energy supply is provided in an uncertain future.[13]



4. RELIANCE ON TECHNOLOGY AND NETWORKS

RELIANCE UPON TECHNOLOGY

Modern technology is increasingly integrated into our lives. Whether it be with tablets and smartphones, or connected devices, our dependence is likely to increase further. Other changes in technology include electric vehicles and decarbonisation of heat.

RELIANCE UPON ELECTRICITY

While generally technology has become more energy efficient, the number of devices and systems that rely upon electricity has increased exponentially over the last 70 years.

INCREASED IMPACT OF FAILURE

As society now relies on technology for going about their day-to-day lives, their tolerance to loss of power reduces, and their expectations rise as to an appropriate response and recovery time following an incident.

4.1. RELIANCE UPON TECHNOLOGY

From a societal perspective, we have seen technology advance significantly in recent years, making powerful electronic devices and new technologies relatively affordable, and therefore widely available. This is reflected in the quick societal uptake of new technologies available in the market, such as with smartphones/tablets.

Many people now rely on technology to go about their daily business, from ordering shopping on-line to managing their home heating from their phone. Younger generations are adapting to technology quicker and have no experience of life without these devices, further compounding the effect of dependency and lack of experience of managing without the technology, when power is lost. Many homes no longer have a battery-operated radio, as phones and the internet are used to consume news and information people require. However, in the event of a loss of power these devices cease to operate, and it can be hard for people to remain informed. It is imperative that we recognise this growing reliance and vulnerability to manage in exceptional circumstances, this should help inform policies to make society more resilient to such events.

The connected nature of our devices, through the technological revolution and development of broadband and communication networks, means that individuals have become used to being able to access any information on the internet within a matter of seconds. In the present day, individuals have more than 1,000,000 times the processing power in their pockets than some of the original supercomputers from the 1950s[14]. Moreover, electronic devices have become widely available within the market, with most members of society having a smartphone, with the average European now upgrading their smartphone every 22 months[15]. Businesses and households now rely upon a wide range of electronic devices and the industry is seeing a growth in home automation equipment such as remotely controlled thermostats, fridges, freezers and home management systems.

Rural communities presently may be acclimatised to poor broadband and phone signal. However, the National Infrastructure Commission's ambition is to deliver full fibre connections across the country, connecting all homes and businesses by 2033[12]. Therefore, in the future, even the most remote domestic consumer or business will have the same access to broadband, and perceptions on its availability could be more aligned within rural and urban environments. The increased reliance on technology means that if there was an incident which affected many of the electronic devices in the UK, society would struggle to operate as efficiently as normal.

Business and industry are also set to change, with technology being critical to most organisations' business operations. This is set to increase further with greater adoption of sensors, connected devices and the broader Internet of Things. With these there will be a proliferation of data which will bring new opportunities to deliver greater insights from recurring trends, for example using artificial intelligence and machine learning algorithms. From a resilience perspective, this poses an opportunity and threat; it has the potential to allow enhanced system visibility and optimisation but also presents an increased reliance upon technology that could pose a potential weakness.

4.2. RELIANCE UPON ELECTRICITY

As technological advancements, have become ingrained in UK society on-the-whole, individuals now have a greater dependence on electricity than ever before, as highlighted in Figure 8. In the 1950s, in a power cut domestic consumers had candles for light, gas hobs for cooking, letters were a more common form of communication, and businesses used typewriters, rather than computers.

Figure 8 highlights how more and more devices in our lives are becoming more dependent on electricity; all indications suggest that this will increase further in the coming decades. For example, research and development trends indicate that there will be more automation equipment released in the future, such as autonomous home management systems, autonomous vehicles and widespread deployment of smart technologies[16 17]. These will further change the structure of the electricity system, and even change the way the electricity market operates, with artificial intelligence and machine learning used to optimise system demand.

As the population continues to grow, and as individuals become more reliant on electricity, then future electricity demand has the potential to increase, albeit partially offset by energy efficiency measures. As society becomes more dependent on technology and the techno-dexterous population ages, the expectation is that the tolerance for loss of power will be reduced, which should be considered when reviewing the electricity system resilience.
As we all start to move to decarbonised technologies such as electric vehicles and electric heat pumps, electricity dependence will further penetrate our lives. With these vehicles potentially operating autonomously on roads with optimised traffic flows, power failures would further disrupt the highly efficient world we are seeking to build[18]. If we do not enable a resilient network at the same time as building these new technologies, we will fail to deliver a robust future for the next generation.

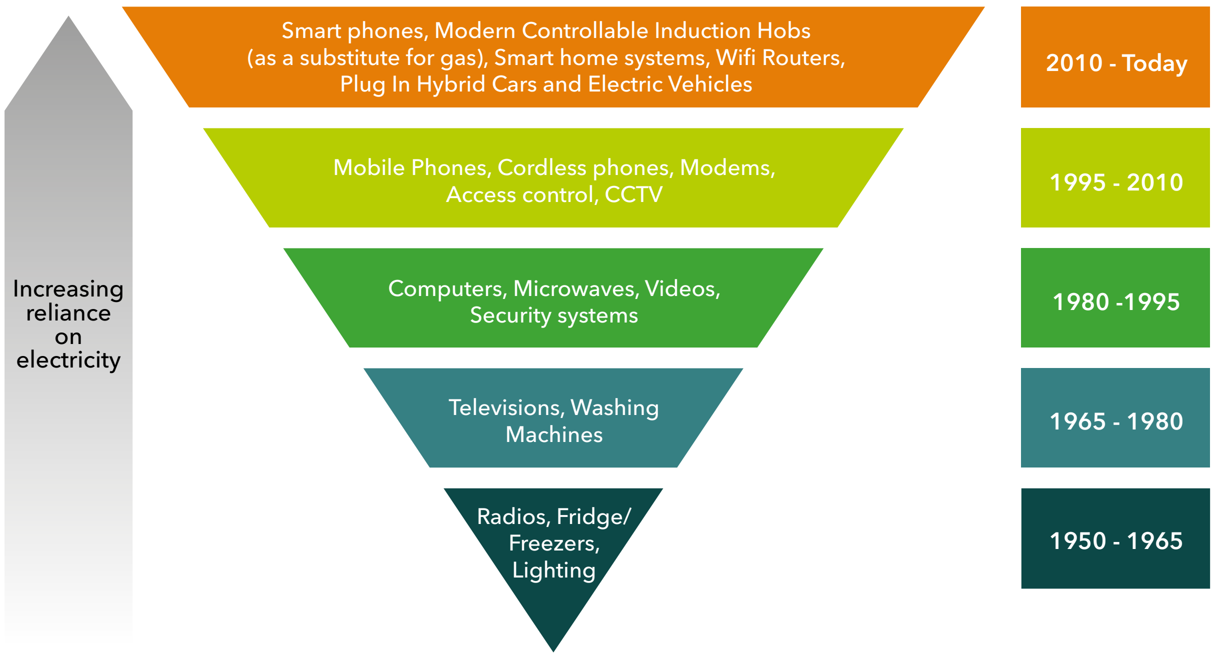


Figure 8: The increasing reliance upon electricity over the last 70 years

4.3. INCREASED IMPACT OF FAILURE

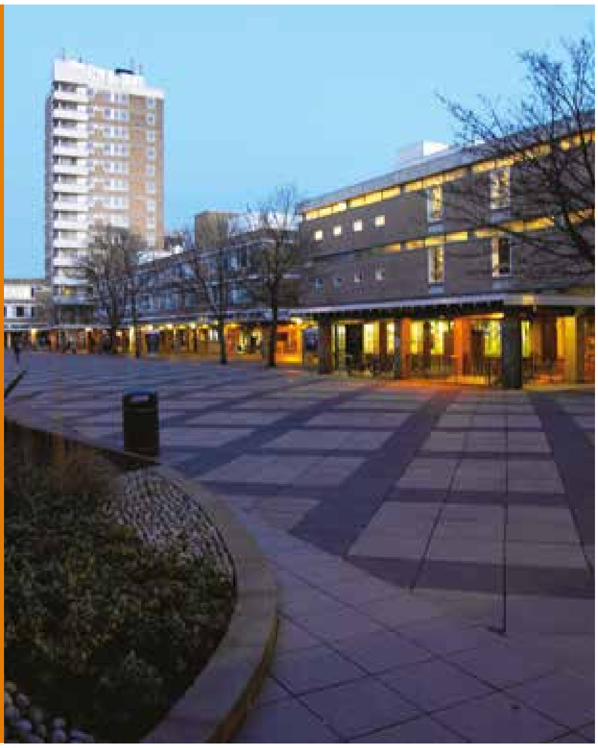
All these types of technology are dependent on electricity to operate. Those that contain rechargeable batteries require electricity to charge, and their battery life may last a few hours to a couple of days, until they need to recharge. Those which operate without rechargeable batteries, may require a constant electricity supply. On the other hand, all modern-day devices mentioned require broadband network services to operate as designed. If there is a power loss in the broadband network or power loss to individual routers, modern society as we know it will struggle to operate, impacting both individuals and businesses. As society relies on these devices for going about their day-to-day lives, their tolerance to loss of power reduces and their expectations rise as to an appropriate response and recovery time following an incident. The perception is that society and business do not have full visibility of the implications of a power cut, due to the interconnected nature and complexity between sectors. The impact of loss of power on modern life was highlighted in December 2015, when Storm Desmond caused flooding in the Lancaster area and the resulting failure of a key electricity substation[19] (see Case Study 3).

An organisation without a vested interest should be encouraged to engage with society and business, or appropriate representatives to understand their expectations. This should include preparedness and response to power cuts and how long they can tolerate being without certain amenities that are dependent on power, such as broadband, water and heating. This should include thinking about how the future changes in technologies and decarbonisation agenda will affect societies ability to cope during power outages. As our society becomes ever more optimised, efficient and technology-focused, the level of resilience required is likely to increase over time.

Engaging with society and business should continue to be carried out by the industry, as gathering understanding of society and business needs over future time horizons should inform Government on the direction and timescales that they should set the electricity industry. This will in turn allow for Regulators to endorse incentives and mechanisms to drive the right behaviour from the electricity industry, to meet society and UK businesses expectations regarding electricity resilience going forward.

CASE STUDY 3: LANCASTER, DECEMBER 2015

Modern day society's reliance upon electricity was exposed across the city of Lancaster following floods in December 2015. With limited experience of living without electricity, both domestic and international students were faced with several challenges. While candles would normally be relied upon to provide lighting in such a situation, these were banned in the campus accommodation due to the associated fire risk. With much of the university communication to students operating via email, delivering instructions to the 7,000 students living on campus became challenging, with some messages becoming corrupted through word of mouth. The university decided to close and send students home a week early for their Christmas break, due to the anticipated prolonged power outage.



5. COMPLEX INTERDEPENDENCIES BETWEEN NETWORKS

CRITICAL LINKAGE OF SYSTEMS

- The wider energy system, and the services enabled by it, are heavily interconnected with electricity and communications.
- Historically systems were less dependent on each other, but with rapid technological development the boundaries between systems are increasingly blurred.

GROWING INTERDEPENDENCIES

- Communications and electricity networks are already interdependent with each other. As systems become smarter, the cyclical dependency between communications and electricity is only set to increase.
- With electrification of vehicles, the interdependency between transport and electricity is also set to rapidly change, particularly with forthcoming automation and optimisation of road transport networks.

NEW SYSTEMS EMERGING

- New systems are emerging, which are dependent on electricity, for example to decarbonise heat options include adoption of heat pumps powered by electricity or new hydrogen fired systems, which could be generated through electrolysis.
- Financial payments systems are rapidly changing and increasingly dependent on power and communications, with mobile money and cryptocurrencies becoming more common.

5.1. A CRITICAL LINKAGE OF SYSTEMS

The electricity system is a key part of the wider energy system that includes the provision of fuels, all of which support key services such as telecommunications, water supply and transportation (Figure 9). All these systems have dependencies on each other and in the future, are expected to be increasingly interconnected, as illustrated in Figure 10 (reproduced with permission from Arup).

For modern infrastructure, communications, 4G and high-speed broadband have played an increasing role in managing the whole electricity system, and growing interdependencies between systems. This has enabled a faster response to meeting changing demands, bringing significant benefits to improve the reliability of the electricity system daily. However, it also increases vulnerabilities in the electricity system, from a resilience perspective, through reliance upon active and increasingly intelligent, rather than passive or manual, systems.

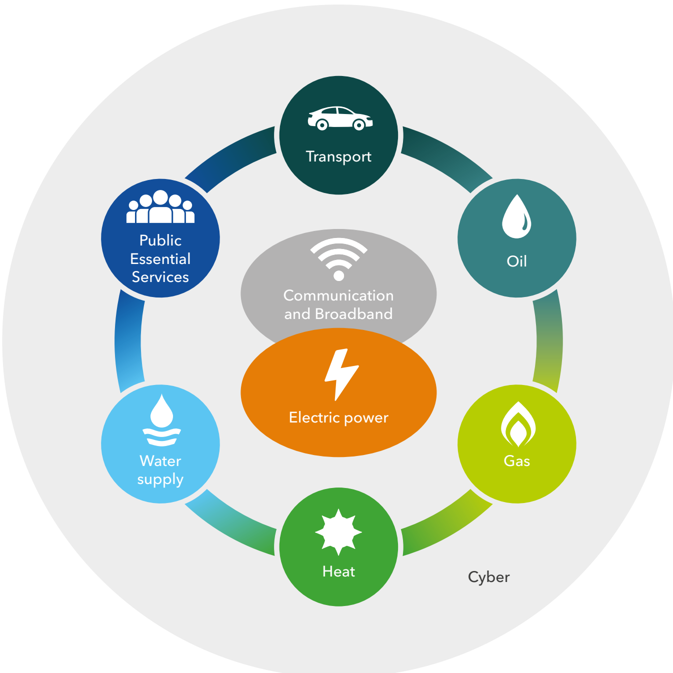


Figure 9: Key systems dependent on electricity

There are currently many interdependencies between different networks and sectors. This report has focused from an electricity system perspective and other sectors may have a different perspective on their reliance upon other systems.

However, with technological advancements and the speed at which new technology is utilised in networks, electrical power-dependent devices and systems will become more embedded in different sectors:

- Clean water supply; electricity is required for the filtration, treatment, pumping and pressurisation process, for the water industry.
- Security and access systems; that provide access control across modern buildings and broader supervision of our cities and roads.
- Communications Networks; there is a cyclical relationship between electricity and the communications and broadband networks, where the communications and broadband networks require an electricity supply to operate. However, many electricity network operations depend on communications and broadband networks for normal operation, highlighting the co-dependency of the networks. There are a diverse number of communication networks, with special secure networks provided for control systems, providing some resilience through diversity.
- Financial and payments systems rely on electricity and communications/broadband to function normally. As our use of cash and cheques declines, particularly as we move to smartphone payment systems, this dependency will only increase further. As an extreme example of where the future may take us, cryptocurrencies such as Bitcoin and Ethereum are entirely dependent on power and communications systems for their operation. The hardware failures at VISA, in June 2018, highlighted the impact of a relatively short duration event on our ability to complete financial transactions (See Case Study 4).
- Provision, and production processes, of other fuels such as natural gas and even petrol/diesel at the pump rely on electricity for their delivery to the consumer.
- Trade and Economy; many contributors towards the UK trade and economy, have an element of dependency on electricity. Industry and manufacturing plants require electricity for machine operations. Retail and supermarkets depend on electricity for refrigerating produce, financial transactions, security, access, lighting and heating. Rail networks require electricity for signalling and points across the entire network, as well as powering a significant number of trains across the network.

The electricity system is made up of a number of different components such as generation, transmission and distribution. Therefore, to determine and assure a resilient position all components need to be resilient. A holistic approach is required to review the impact of the changing energy landscape on the resilience of the UK's electricity system. This report recommends that an overarching task-force is developed, with sufficient breadth, vision, authority and impetus to direct a far-reaching assessment into this increasingly complex area. A cross sector task-force with senior representation working with Government should be best placed to consider how a fully coordinated view of resilience can be established and managed. This in turn should inform a resilience policy which reflects the best interests of society and business. There are a number of different ways this policy could be developed. One method, may be to look at the required service level in a sector, for example water supply or rail network, where an assessment of holistic interdependencies can be undertaken. However, as this report's scope has been limited to the electricity system, the ERP has not suggested solutions to the holistic system issue at this stage.

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Such a system will be heavily dependent on electrical powered technologies, telecommunications, broadband and 4G/5G networks

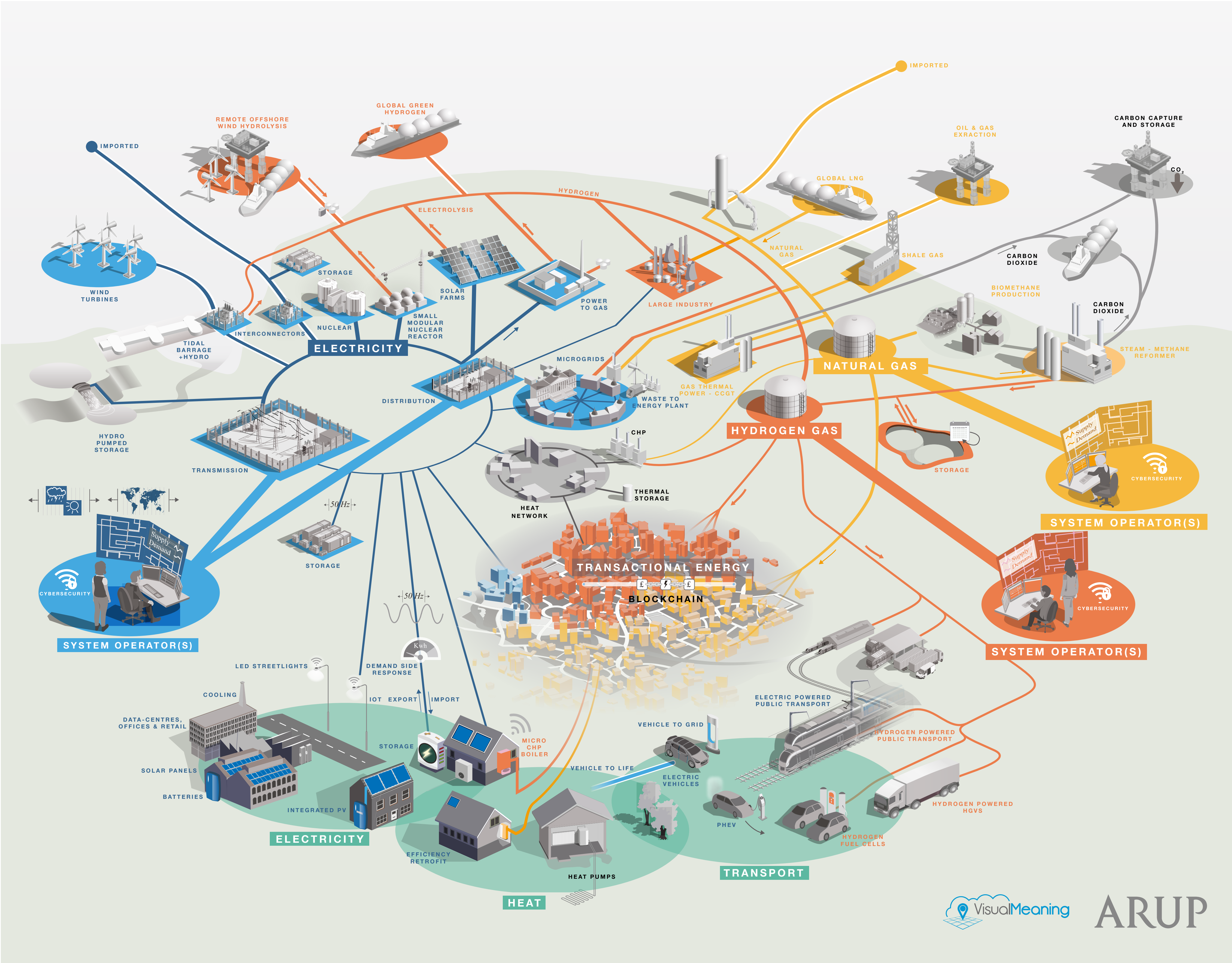


Figure 10: Layers of interdependencies between sectors – 2035

This diagram indicates one potential future energy system and the complex interactions within it. As highlighted in the report, such a future system will be highly dependent on electricity, communications and technology for its operation.

CASE STUDY 4: VISA PAYMENTS SYSTEM FAILURE

On Friday 1st June 2018, a hardware failure meant Visa struggled to process payments across the UK and Europe around 2.30pm and 10pm, meaning many businesses were unable to take card payments. In some cases, cardholders found multiple transactions were processed when they tried to make one payment, or customers were forced to use alternative payment systems. Visa stated the outage was not due to a hack but resulted from a problem with its back-end processing system and worked with its banks to try and cancel pending transactions as quickly as possible.[20] Globally, VISA handled on average $28B of transactions per day in 2017, which highlights the potential impact to consumers of these system failures.

In this scenario, customers could pay with cash. However, if the electricity system was unavailable, ATMs would not operate to access cash. In the case that individuals have a supply of cash ahead of a power cut, shops may not be able to accept it if they cannot operate their electronic tills. In the future, with a reduction in ATMs available[21], an increase in electronic forms of payment such as contactless, Google and Apple Pay, as well as developments in Artificial Intelligence to ease the process of payment transactions; the impact of losing power supplies to payment systems will become even greater.

5.2. GROWING INTERDEPENDENCIES BETWEEN SYSTEMS

We are already living in a complex world, with many interdependencies across infrastructure sectors, and to some degree they all rely on electricity. As technology continues to develop, we expect to see the interactions between sectors increase, adding to the complex interactions between different systems. To meet these future complexities the right infrastructure and systems should be developed to ensure that the UK electricity system continues to be resilient in this ever more changing and complex world. Significant uncertainty exists about how current trends will shape the future; the answers to many questions remain uncertain, some examples of these questions are included in Figure 11.

The electricity system depends on the broadband communications networks for day-to-day operations, however there are a diverse range of communications networks that support this activity. As more future technologies are developed and integrated into the energy system, they are also dependent on the broadband networks, which are also dependent on the electricity system. Therefore, there is a cyclical dependency between electricity and communications with each dependant on the other, where the societal impact for loss of either network increases. Loss of the communications and broadband networks would make operating the electricity system more difficult day-to-day and even more so during response to an extreme event. Due to the continuing and growing cyclical relationship between the electricity system and the communications/broadband networks, the resilience of both systems should be reviewed and considered in conjunction with each other.

Given these growing complexities, an understanding of the impact of the interdependencies between all networks is paramount, to ensure that the UK electricity system manages the appropriate resilience levels in the future. Government and industry are investigating improvement activities for cross sector interdependencies based on the current configuration of networks. In addition to this work, this report recommends a focus on the possible future interdependencies across sectors is required to have a complete understanding of the social impacts of a power cut, both local and regional. Understanding the social impacts of a power cut, and the value that individuals place on amenities dependent on power, such as water supply or integrity of the transport network, can inform the resilience requirements, detailed in Government policy, that the electricity system should meet.

In developing a resilience policy, consideration should be given to the breadth of the topic to cover the range of interdependencies between sectors. This report has been developed from the perspective of the electricity system. However, reviewing the interdependencies from the perspective of different sectors, such as water, rail, transport and communications, may reveal further or different interdependencies than identified in this report. Furthermore, the ERP recognises a range of possible futures could manifest in the energy landscape; Government policy needs to be functional to remain applicable to a range of possible futures.

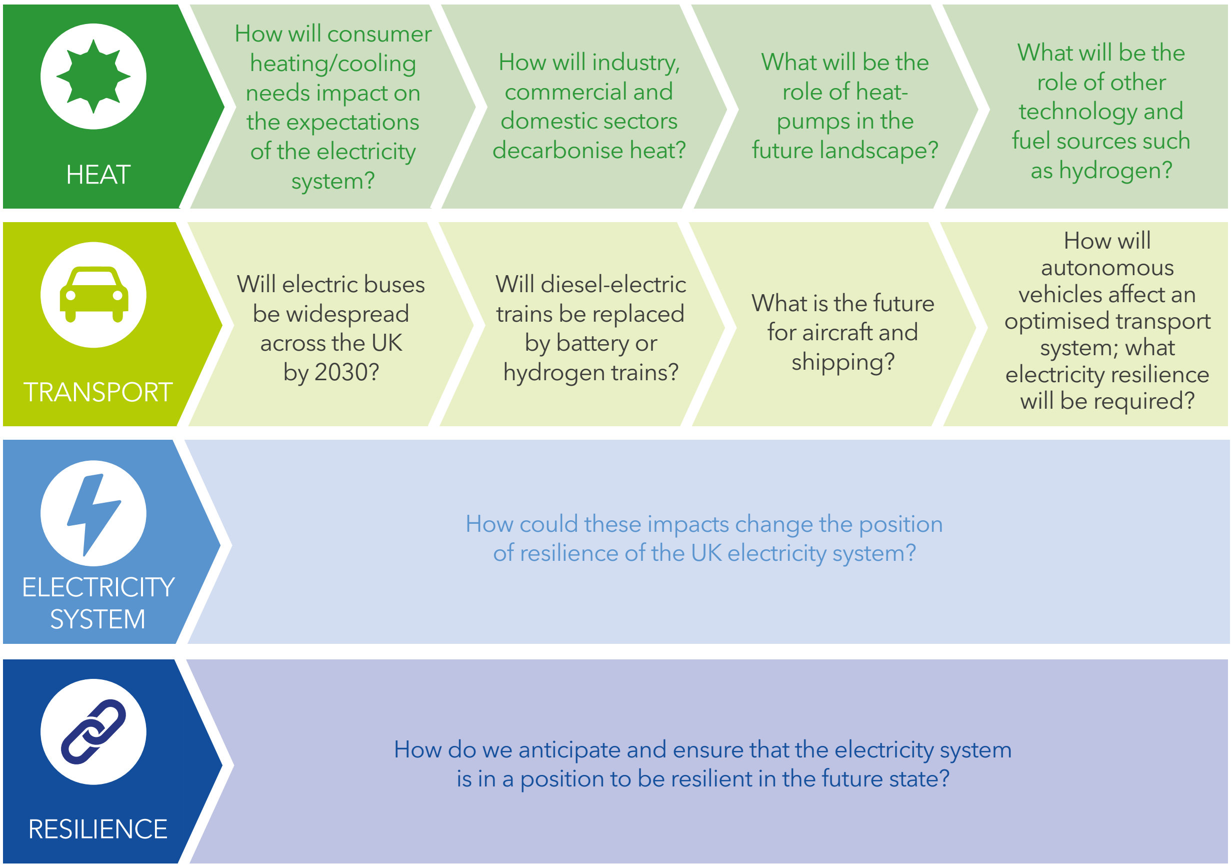


Figure 11: Uncertainty posed in different sectors (non-exhaustive)

5.3. NEW SYSTEMS EMERGING

To meet the UK's emissions targets, further decarbonisation of many sectors, such as transportation, heating and electricity generation is required. The electricity system is facilitating connection of low carbon generation sources and electricity is seen as a prime source of energy for decarbonising heat and transport[12 22]. New technology will also change the way we interact with the electricity market, with smart technologies available to control demand of devices in homes and businesses, using artificial intelligence and machine learning to help drive down costs to consumers. Smart Technologies and decarbonisation in turn increases dependency on its electricity in all conditions, including unexpected significant events. One example of the many possible future energy systems in 2035 is sketched out in Figure 10[23] and highlights the anticipated interdependencies that may occur in such a system.

In the heating sector, there are a range of alternative fuels being trialled, to facilitate the reduction in the sector's carbon footprint. Hydrogen is being researched as an alternative fuel to natural gas, where the National Infrastructure Assessment recommends that a community scale trial is conducted by 2021. Hydrogen can be produced either by electrolysis of water, or steam reformation of methane combined with carbon capture and storage. The process of electrolysis is dependent on electricity. If electrolysis proves to be a viable production method for hydrogen to facilitate the conversion of heating systems from natural gas to hydrogen, this would increase the electricity demand significantly. To enable this the electricity system would have to adapt to incorporate this technology at the right locations and ensure resilient supplies.

Electrical heat pumps are also being considered as a solution to decarbonise heating for communities, individual homes, offices and industry[24]. It is likely that in the future, there will be a combination of different heat technologies to decarbonise the sector[22]. However, whichever technology prevails, the implication is that there will be a larger demand on the electricity system as a consequence. Electricity, from generation, transmission to distribution will become of greater importance, in the large-scale demand development/production processes, as well as the delivery and technology for the heating sector.

In transportation, we are seeing electric vehicles becoming more embedded within society with the increased adoption of electric cars and buses in the UK, as highlighted by the recent publication of "The Road to Zero" and the "National Infrastructure Assessment".

'We will continue to bring down the cost of purchasing and owning ultra-low emission vehicles through grants and other incentives.'[18]

'Electric vehicles are easier to drive, quieter and less polluting than conventional cars and will soon have the same range and be cheaper to buy and maintain. Once this happens, their take up could increase rapidly. Given their benefits for the environment, this is something government should encourage. A key way to do this is by ensuring that charging an electric vehicle is as easy as refilling a conventional vehicle, or even easier.'[12]

All indications are that the growth of electric vehicles will accelerate over the coming years as the cost of the technology reaches parity with conventional vehicles. It is also important that electrical charging capability is available and convenient to all in society, enabling both short and long-distance journeys in the most reliable and resilient ways possible to match conventional vehicle fuelling capabilities. To support this, the electricity industry is facilitating the anticipated increase in electric vehicle uptake by developing charging solutions to meet all of society's needs. A key aim is to tackle range anxiety; a driver's concern that the battery will run out of power before the destination or a suitable charging point is reached. The network would ensure that 95% of drivers in England and Wales will be within 50 miles of a charging station, with the capacity to charge a car in 5-12 minutes[25 26]. The solutions also allow a range of options for private vehicles and fleet vehicles to charge at homes, destinations or en-route to provide a charging networks fit for the future.

All solutions are looking at deploying complex technology to manage supply and demand of electricity at peak times, smoothing supply through lower demand periods. These technologies themselves shall introduce complexity and must be resilient to supply interruptions, both from a local or wide scale event. The importance of electrical vehicle supply needs to be considered, especially if essential services also adopt the technology in the future. It is also important to ensure that any technology is designed such that it does not hinder the restoration of supplies following any loss of supply event.

Road networks are also likely to be impacted by new technology deployment, especially considering the optimisation of traffic and public transport flows around our major cities. Autonomous vehicles and city-wide vehicle flow control are all technologies on the horizon, which will need to be deployed in a resilient way. Such technologies will be heavily electrical power technology and communications dependent. Such an optimised transport network will require increased resilience to ensure we can manage the additional journeys people are expected to make, ensuring we drive the UK economy forward. Transport for London (TFL), for example expect an additional

5 million additional trips a day to be made by public transport in London by 2041, with similar projections for many cities across the UK[27].

The decarbonisation of transport is also going to affect rail, aviation and shipping in the near future with developments in these areas moving forward apace. All the changes to the way we travel for business and leisure, with the ambitious and understandable objective to do so carbon free, need to be understood holistically. If we consider resilience and these future technologies at the same time as we deploy them, it will be cheaper in the long run for society and business while maintaining a functioning society and delivering the carbon free objectives to limit climate change effects, even in the most severe events.

A resilience policy and framework should reflect the cross-sector interdependencies, to enable full evaluation of the potential risk in managing utilities and wider social services such as transport. The policy should be sufficiently broad to encompass the electricity sector, and all interacting cross-sectors. This report does not advocate a single future scenario but recommends a holistic resilience approach applies to a range of possible future scenarios. This must remain applicable such that each individual organisation can develop their own resilience policy, compliant with the broad Government resilience policy, and any resulting regulatory obligations. Given the cross-sector interdependencies, this will require co-ordination between different regulators such as Ofgem, Ofwat and Ofcom, along with Government transportation departments.

6. GROWING THREATS TO NETWORK INFRASTRUCTURE

THREATS TO NETWORKS

- Natural hazards, system failures, new technologies, cyber, geopolitical and human are identified threats to the electricity system, with noticeable catalysts being climate change, world political instabilities and increased reliance by society on technology.
- Looking forward, a number of emerging trends will increase the risk these threats pose.
- Technology introduced to reduce the carbon footprint of other sectors, increases the complexity of the electricity system, such as with electric vehicles and heating.

CYBER SECURITY

- Smart technologies and artificial intelligence uptake will increase the reliance on technology in the electricity system.
- This is changing the digital security landscape, with Internet of Things raising new vulnerabilities for the electricity system to consider.
- Cyber security threats are increasing; not only individual malicious intent to affect the electricity system, but also state sponsored attacks.

CLIMATE CHANGE

- Climate change is already increasing the intensity, frequency and variability of extreme weather events, particularly flooding and extremes of temperature.
- Alternative fuel sources for generating electricity such as solar, wind and tidal introduce a reliance on the climate to meet our electricity demand.

6.1. THREATS TO NETWORKS

Broad system changes are taking place that will change the way the electricity system can respond to extreme events; there are a number of potential challenges that are likely to influence system resilience. These have been broadly grouped into four categories as shown in Figure 12.

In an ever-growing, more technology based and complex world, there are many potential trends anticipated to occur in conjunction with one another, across these four groups. These require careful management, to ensure the UK electricity system remains resilient, given these potential threats. Each group of threats is discussed in more detail in the following sections.

TECHNOLOGY

- Growing reliance on technology and smart systems
- Telecommunications failures
- State-sponsored and individual malicious intent to affect networks
- Rapid rate of change of technology
- Maintaining standards in a global and diverse supply chain

ELECTRICITY SYSTEM

- Growing dependency on electricity
- Complexity in managing electricity system
- Changing generation mix; affecting system inertia and redundancy
- Electrification of transport and heat
- TSO-DSO co-ordination
- Adverse impacts from decentralisation
- Regulatory models for managing resilience levels, to drive the right behaviour

GEOPOLITICAL AND HUMAN

- Resource capability, and knowledge
- Malicious Attacks: Physical and Cyber
- Resource availability: Industrial action and flu pandemic
- Population growth
- Worldwide Political instability and State intervention
- Fuel availability
- Societal expectations of electricity system
- Visibility of complex interdependencies between sectors

NATURAL HAZARDS

- Flooding
- Severe weather, including; Wind, Snow, Temperature and Drought
- Space weather (solar storms)
- Volcanic eruptions
- Poor air quality
- Earthquakes
- Wild fire
- Urban heat effect

Figure 12: Summary of potential threats to network resilience

6.2 TECHNOLOGY

KEY TAKEAWAYS

- Greater adoption of smart technologies, with greater reliance on technology more generally, puts ever increasing pressure to assess and identify potential vulnerabilities before implementation.
- The digital security landscape has changed significantly, and expected to continue at an accelerated pace. This has led to the emergence of industrial control systems' internet usage; alongside the broader use of the internet for consumer goods and systems.
- Cyber security threats are increasing with the growing availability of information, and more connected devices. These not only come from individuals with malicious intent to affect the electricity system, but also state sponsored attacks.

As society, has become more dependent on technology for daily life, so too has our electricity system to meet consumers' needs. With new technology, there are possible unseen vulnerabilities that need to be identified and addressed prior to implementation. However, this is increasingly challenging as technology progresses at a rate faster than the industry can sometimes put appropriate mitigations and response activities in place. With greater integration of smart technologies, such as smart charging or smart homes, the number of potential vulnerabilities is expected to increase exponentially.

Over recent decades there has been a shift in behaviour, where most people rely upon new technological devices, but few people know the details of how these devices operate or know what to do when they fail. Consumers expect devices to work and be secure, however, the production process behind a piece of technology is very different to that of other technologies, such as a car. With a car, the manufacturer is liable for any serious faults, even after the initial warranty period. However, the same liability does not necessarily exist for software. For consumers to remain secure, both the manufacturer and the consumer must be willing to actively update and maintain their devices, follow good cyber practice in selecting the software to install and check permissions granted to access devices. The increase in the use of electronic devices, in industry and for personal use, presents new threats. For example, unmonitored permission checks could mean a malicious individual(s) gains access to a device. Devices connected and communicating to each other, means that a malicious attack from one compromised device would likely have a much larger impact, affecting many devices. In summary, our society is highly-dependent on devices that require manual intervention to ensure their security, which makes society more susceptible to cyber-attack risks.

In the past, digital security was limited to information assurance, information technology and more recently industrial control systems. Looking forward, the emergence of the industrial control systems' use of the internet, along with the broader internet use is set to change the security landscape further (Figure 13).

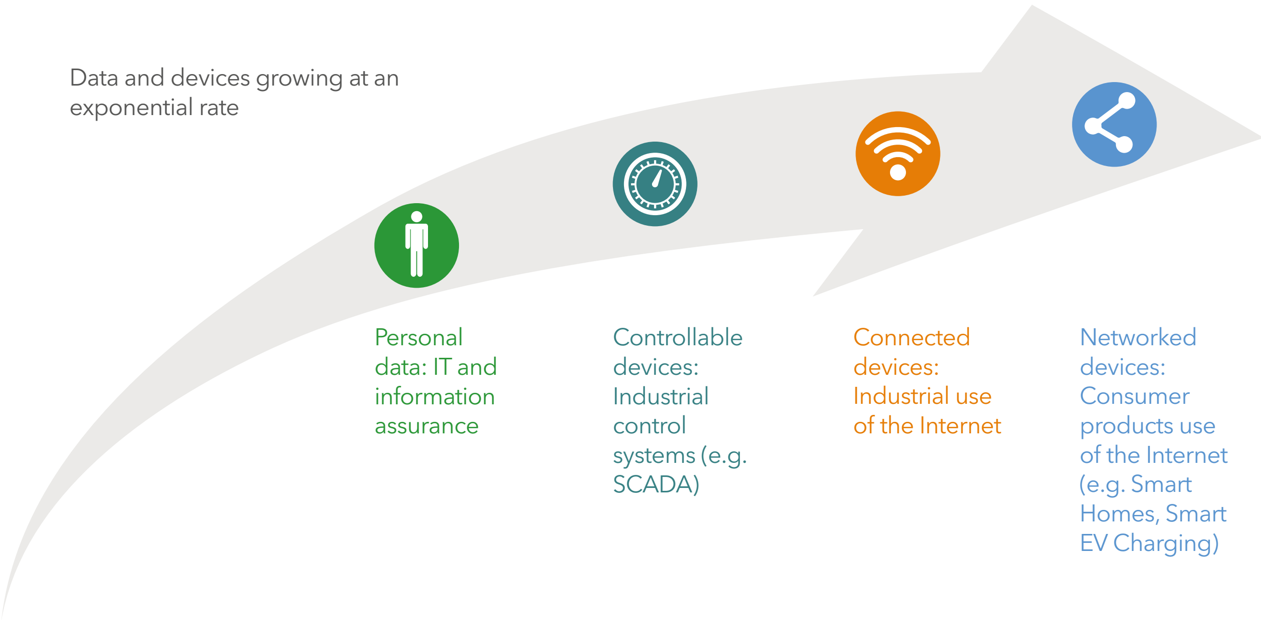


Figure 13: The changing digital security landscape[28]

While these systems will undoubtedly improve electricity system optimisation and help integrate further new technologies into the energy system, appropriate mitigations and response strategies need to be in place to ensure they can positively enhance system resilience.

The occurrence of cyber-attacks is on the increase in conjunction with their level of complexity and sophistication. For example, in May 2017, the UK National Health Service was severely compromised by the WannaCry Ransomware attack, and prior to that the Ukrainian electricity system was struck by two successive attacks in December 2015 and a year later in December 2016 (see Case Study 5). These attacks highlight the potential for individual malicious intent to affect critical national infrastructure, but also the potential for involvement from state-sponsored organisations.

Full understanding of vulnerabilities and impacts of a cyber-attack should be assessed to enable effective recovery from such an event and ensure that the UK electricity system is resilient against a cyber-attack. Government considers cyber risks as a high priority issue and is continuously seeking to address the threat, due to the importance of technology contributions to UK society. One eighth of the UK's Gross Domestic Product (GDP) comes from the digital economy, and UK digital industries grew two and a half times more quickly than the economy overall between 2003 and 2013. Moreover, UK businesses rely on cyber security to keep our digital economy safe. Also, individuals within the UK have the highest percentage of individual internet usage of any G7 economy. The future trend is that the likelihood of a malicious cyber-attack will increase, due to an increase in availability of information in the public domain, which could highlight vulnerabilities in different technologies. The scale of our dependence on technology means that all aspects of UK society can be affected by cyber-attacks; our prosperity, key infrastructure, places of work and our homes can all be affected by cyber-attacks[29].

The risks and importance of cyber security should continue to be promoted by Government, in a similar manner to how physical security has been promoted in the past. A policy should provide guidance or obligations on both manufacturers of electronic products/smart devices and users of those products. This should add extra flexibility and agility into the system to help our response to events, and ensuring the devices enhance rather than detract from electricity system resilience. However, if we do not manage new technology appropriately, it has the potential to have a significant negative impact on our resilience position.

Due to the dependency of the electricity system on communications/broadband networks, reinforcing and having redundancy in these networks will increase the operability of the electricity system during a partial or total loss of the communication network. Due to the nature of cyber-attacks, they have a characteristic of being 'known-unknown' events. This is because new vulnerabilities in hardware and software are being identified by hackers all the time. Therefore, new cyber-attacks across society are considered likely, but the form the attack can be unknown. The focus in managing these events, should be balanced by mitigating with strong security and software updates, whilst also putting in place response procedures to minimise the impact of such an event and to restore networks as quickly as possible.

On the other hand, technology provides many solutions to the other challenges that we face and is an enabler to managing the potential scenarios that may manifest, such as the electrification of the heat and transport networks. Consideration should be given to reinforcing, for resilience purposes, electricity systems and communications networks, for hi-tech smart systems, such as transport solutions. This is important, by recognising the role of new smart systems in making infrastructure and networks operate more efficiently and deliver more capacity for society and business.

CASE STUDY 5: UKRAINE CYBER ATTACKS

On 23rd December 2015, Ukrainian media reported a cyber-attack had left half the homes and 1.4 million people in the Ivano-Frankivsk region without electricity. Although services were restored within a few hours, this was largely due to manual intervention rather than by recovering compromised automation systems. Slovakian security firm ESET later reported that the initial incident was not isolated, and that multiple electricity companies had been affected simultaneously. Reuters also reported similar malware was found in Kiev's Boryspil airport, on IT networks which included air traffic control.

The most recent campaign is reported to have commenced on 6th December 2016, continuing through to 20th December 2016. Vsevolod Kovalchuk, a director at the Ukrainian national energy company Ukrenergo, told Reuters that the 200-megawatt interruption was equivalent to approximately a fifth of Kiev's night time energy consumption, and that the scale of the interruption was very rare.

The automation was shut down in the Pivnichna power transmission substation located north of Kiev. The remote terminal units (RTUs) opened circuit breakers, causing a power outage that lasted for 75 minutes. Power was restored manually, with full restoration early the following morning. Power loss was reported in northern Kiev and on the eastern bank of the Dnieper River and the surrounding area.

The Ukrenergo director described 'external influences' affecting workstations and SCADA (supervisory control and data acquisition) servers, and anomalies with transmission network data. Although investigations are ongoing, in the meantime researchers have confirmed significant similarities to the power outage a year earlier. This includes phishing attacks, with malware embedded in Microsoft document macros, and traces of Black Energy 3 malware used in the attacks targeting Ukraine Government organisations.

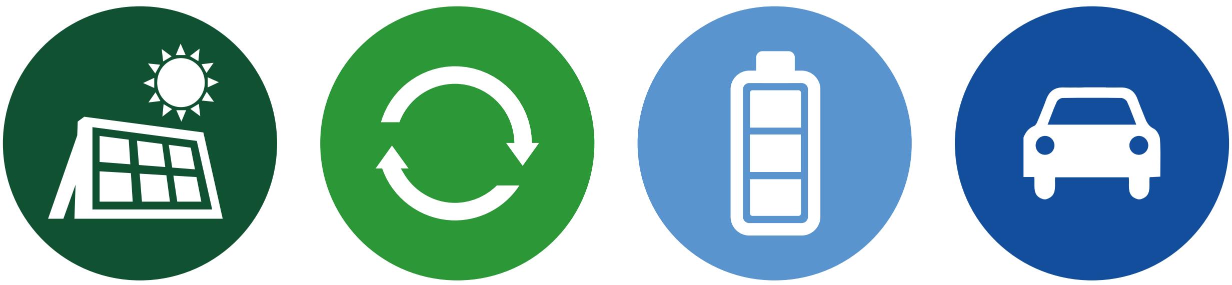
Ukrainian media and security researchers have also reported further cyber-attacks including distributed denial of service (DDoS) attacks on the Defence Ministry, government sites, financial sector, railways, ports and electrical power transmission.

6.3. ELECTRICITY SYSTEM

KEY TAKEAWAYS

- Improvements to renewable generation technologies are changing the generation mix which requires the system to operate differently to how it was originally designed. System inertia, the role of bulk storage and the integration of local (embedded) generation all require careful management to maintain resilience into the future.
- The decarbonisation of heat and transport is likely to place an increased reliance upon electricity whilst also contributing to rapid variations in demand profile, both on a local and national level. Distribution and transmission networks will have to manage these changes, which are likely to involve new smart devices managing demand on the consumers' behalf.
- Post-event response strategies will also need to factor in the expected changing consumer behaviour, together with heat pump and electric vehicle requirements immediately after a power cut.
- Technological development of our cities; such as utilising automation and optimisation of transport and sophisticated service management of water resources could demand different levels of resilience to that in the past.

As the interdependencies and introduction of technologies change, we need to adapt our electricity system to maintain the required level of resilience expectation and required by society. These changes need to consider the potential difference in resilience requirements, corresponding to the impact caused by loss of electrical power. This can vary between locations and vulnerabilities of society to the loss electrical supply and the speed of restoration following an event. Technological developments, particularly in very densely populated cities where significant optimisation of services has taken place, is likely to lead to greater vulnerability of loss of supply and should lead to consideration of a change in resilience requirements. Consideration of how we protect the most vulnerable in society is also important to ensure a resilient electricity system protects society. The four areas below discuss significant changes impacting our electricity system.



CHANGING GENERATION

SYSTEM INERTIA

ENERGY STORAGE

DECARBONISATION

CHANGING GENERATION

While the UK economy has changed, the electricity system has also evolved due to technological advancements. Alternative and renewable sources of electricity generation, alongside new electricity storage solutions, are enabling the UK to decarbonise the electricity sector in line with the Government's 2050 target of reducing the UK's greenhouse gas emissions by 80%[30]. The development of wind turbines, solar generation in particular have unlocked the capability for renewable energy to be a viable option for electricity generation in the UK. With the aid of Government incentives, solar and wind generation are now widespread across the UK, but due to their installation at many levels within the energy system; transmission, distribution, business and even domestic[31], it can be difficult to understand the full picture of the renewable generation profile. Looking forward, further cost reductions in key technologies such as solar, wind turbines and batteries are forecast, following experience or 'learning' curves which have been observed over recent decades[32]. These trends, driven by global supply chains, have the potential to increase the amount of embedded generation seen on the UK network, further decentralising the power systems and adding to the complexity of balancing the electricity network.

The fairly recent technological developments highlighted above have changed the way electricity flows in the UK network, from the traditional linear model of generation to point of consumption, to a non-linear, integrated model, with power flowing in-between components as shown in Figure 14. The flows around the network add to the complexities of the system and have benefits and drawbacks to system resilience. Greater diversity in generation will help increase resilience, but as highlighted the lack of visibility and complex technology systems, with cyber vulnerabilities can adversely affect resilience.

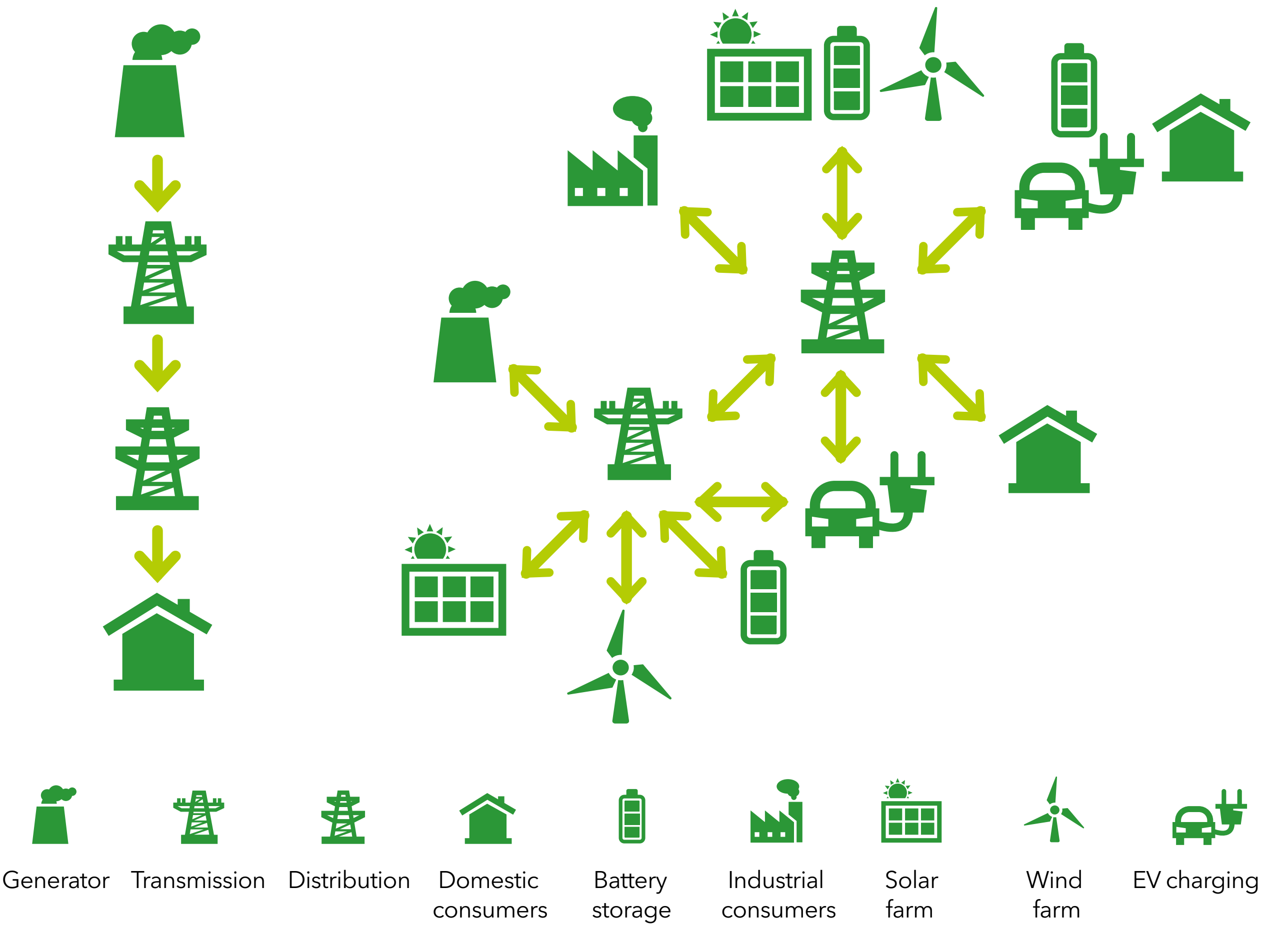


Figure 14: Traditional Linear Electricity System Structure and Current Non-Linear, Integrated Structure

The increasing number of smaller scale generators connecting to the system has been a trend highlighted in industry data published annually, as highlighted in Figure 15. By sorting all the generators above 1MW in order of size and cumulatively summing their contribution to the overall generation portfolio, it can be seen that from 2004 through to 2015 there has been a progressive increase in the number of generators providing the bulk of our power. Further analysis of the data highlights that while in 2004, less than 70 generators provided 85% of total capacity, in 2015 this number had increased to more than 450. With the introduction of more renewable energy, these technologies are climate dependent. These technologies can introduce their own resilience issues; for example, winter blocking anti-cyclones across the UK are characterised, by light winds, cold days and nights, formation of fog and short days. In such conditions output from wind and solar can be significantly reduced so it is important that a resilient system retains significant generation and interconnection sources to cover such periods. The balance of generation is important along with the ability to utilise as much renewable generation as possible when it is available.

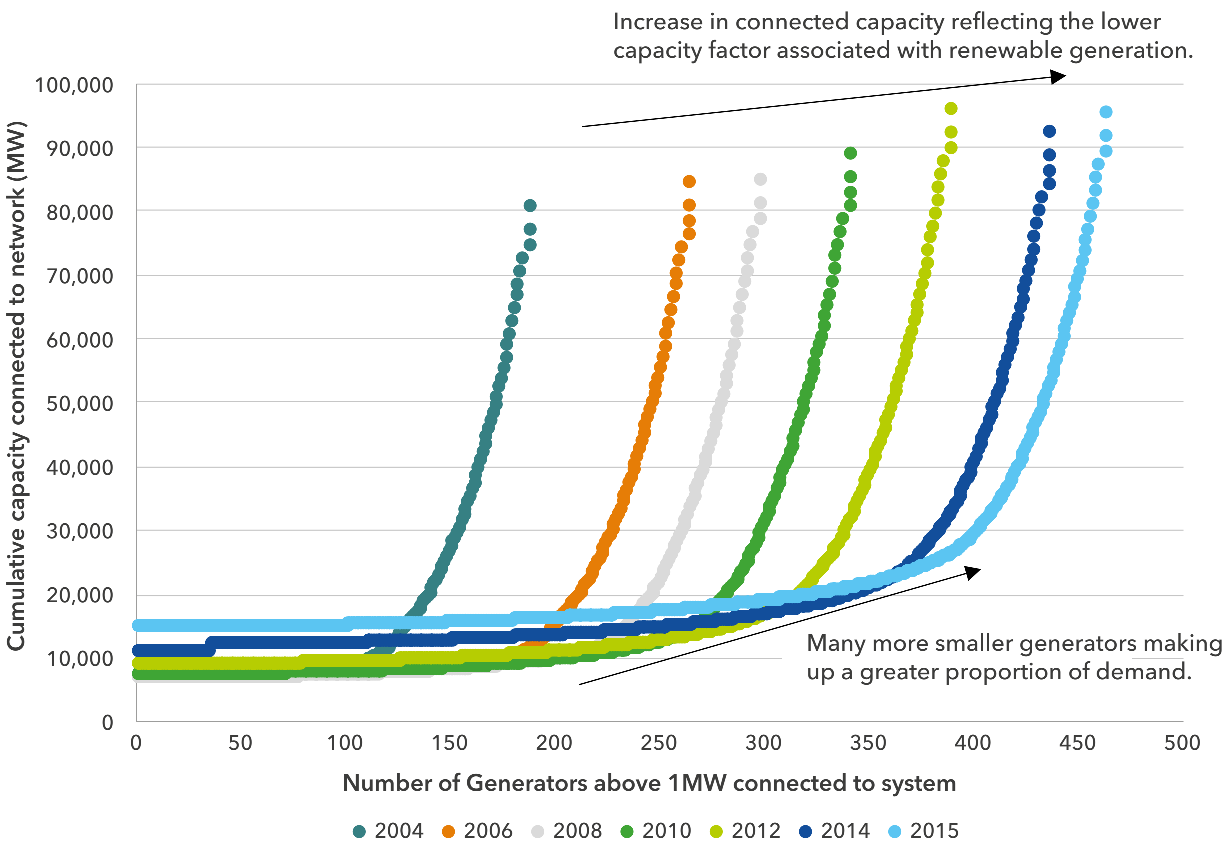


Figure 15: The changing nature of supply in terms of number of generators and cumulative capacity[33]

Note: The vertical axis offset accounts for renewable and CHP generation not listed in the DUKES Table 5.10. It is since 2010 that this figure has begun to increase significantly.

EFFECT ON SYSTEM INERTIA

For an electricity system to function when a fault occurs, inertia in the system is required. When a fault occurs on the system the electrical power is lost but the generation power from steam, wind or the sun is still entering the system. Without inertia, the generation very quickly accelerates due to its inputs and becomes out of balance with the electrical energy leading to system instability. In the past, inertia was provided by large generators which had a very large rotating mass and ensured that any fault did not cause system instability. With the closure of many of these large generators the inertia of the electricity system as a whole is falling. This introduces the possibility that significant faults on the system will have a bigger impact than they did in the past.

As the generation mix diversifies further and more small, renewable sources of generation replace existing power stations, new solutions to provide additional system inertia need to be identified. We need to do this to maintain a reliable and resilient system under extreme events; during restoration of a power system in particular, a strong inertia is important. Potential solutions to resolving the problem are likely to involve new technologies or deployment of large rotating masses to strengthen the system.

CHANGING ENERGY STORAGE NEEDS

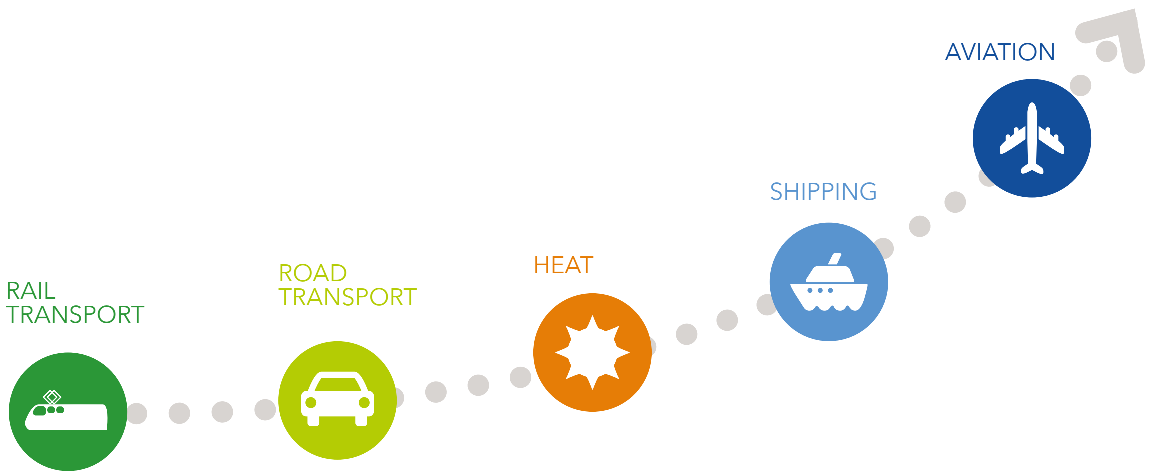
From a redundancy perspective, each of the existing energy vectors currently has some storage; natural gas for heat, liquid fuels for transport and gas and coal for electricity. These inherently provide significant bulk storage and therefore have some resilience to supply shocks. However, these back up fuel stores will reduce as we transition to a low carbon future and we continue to utilise more renewable and intermittent forms of generation. Due to thermal losses and inefficiencies, much of energy stored in fossil fuels is wasted, but nonetheless as we move to renewable generation the need for bulk electrical storage to maintain power resilience will increase.

Battery technology has rapidly improved over the past five years and continues to evolve, contributing to the UK meeting its greenhouse gas emissions targets. Batteries have been utilised in decarbonising the transport sector where we have seen the uptake of Electric Vehicles (EVs) and Hybrids increase by almost 2000% in the past five years[34]. In addition, battery storage has become more wide-spread with announcements of large network battery storage solutions both at distribution and transmission levels, as well as the development and availability of domestic battery storage[35]. Applications of battery solutions are now growing in size with the ability to provide many services to the electricity system, economies of scale are driving ever bigger installations and capabilities in the market. With the increased penetration of solar and wind generation, there will be a greater need for alternative standby generation, interconnection to Europe and/or large scale longer duration solutions to provide storage to assist in maintaining acceptable levels of resilience during weather conditions adverse to renewable generation.

DECARBONISATION OF OTHER SECTORS

A key future trend is the decarbonisation of other sectors such as heat and transport, where the evidence to-date suggests that electrification will be a major contributor to their decarbonisation[36]. In transport, we have seen an uptake in EVs, which is anticipated to increase with the UK Government's announcement of the ban on new diesel and petrol car sales from 2040. Provision of charging for EVs including long distance travel with convenient charging times is a challenge a resilient electricity system must meet. More broadly, the transport sector is likely to evolve with the wider adoption of electric buses, increased automation, further electrification of the railway network, and perhaps electrification solutions supporting shipping and aviation both directly and indirectly[37]. The introduction of new technology can prove to be a disruptor to the operation of the electricity system, presenting an alteration in power flows on networks, and a challenge that the networks were not originally designed for. Further electrification of sectors increases the level of uncertainty when predicting the future of the electricity system, making it more difficult for network owners and operators to manage and invest in the system infrastructure. It is important for consumers that we consider the right level of resilience as we deliver new infrastructure systems, to avoid retrospectively trying to provide resilience at a potentially higher cost.

Decarbonising the heat sector points towards further electrification, with the uptake of heat pumps, centralised heating networks, and the testing of hydrogen as an alternative fuel to liquefied natural gas. With proposals to ban gas boilers for new build housing after 2022, legislation may drive different consumer behaviours[38]. As summer temperatures potentially increase and consumers seek greater levels of comfort, there may be a greater requirement for domestic cooling, alongside winter heating adding to the increase in electrical demand. This poses a further consideration for demand forecasting and capacity required within our transmission and distribution electrical networks.



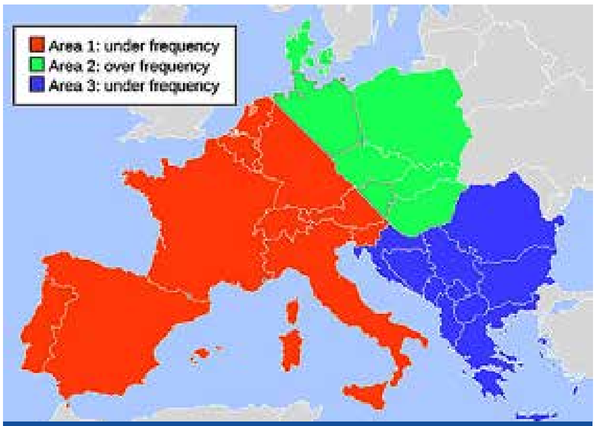
FUTURE ROLES

The future electricity system is very different to the original electricity system design, where technological advancements have altered how power flows around the electricity system. The Future Energy Scenarios, produced by National Grid Electricity System Operator, highlight the levels of uncertainty for the future for the electricity system. The four scenarios evaluate the speed of decarbonisation and decentralisation, with a variety of results such as the majority of cars being EVs by 2033 in two scenarios, and by 2040 in the other two. Whilst the Future Energy Scenarios are only one view of the future, they highlight that it is difficult to accurately assess what the electricity system will look like in fifteen years' time, due to the fast-changing energy landscape with increasing levels of uncertainty with time[39].

The role of a Distribution System Operator(s) (DSO) alongside the GB Electricity Transmission System Operator (TSO), has been proposed in response to recent decentralisation of the system, which is forecast to continue over the next two decades. Research has shown that some system flexibility and ancillary services could potentially come from lower voltage distribution networks in the future, to support transmission led services, particularly where groups of distribution users can provide reserve services to account for network fluctuations. Both transmission and distribution solutions have positives and negatives in providing the right level of resilience. Therefore, for a small island fully interconnected system like Great Britain, the ability to maintain system frequency of 50Hz across the whole system shall require a balance of solutions across transmission and distribution.

The European System Disturbance in November 2006 (Case Study 6) identified a number of main causes and critical factors that contributed to a cascade tripping across a significant part of the European power grid. Of relevance to the evolving roles of the TSO and DSO, insufficient coordination between TSOs helped initiate the event, with the system restoration hampered by a lack of coordinated action between TSOs and DSOs when reconnecting distributed generation (mainly wind and combined heat and power generators). When planning for the transition to a DSO model in the UK, it is vital to ensure good coordination and visibility of operations to all operators is made in order to maintain system resilience, for our fully interconnected electricity system.

A future whole system approach should bridge energy vectors, such as electricity, gas and hydrogen, through a collaboration of approaches to system security across different networks and operators. This approach will enable a balance of different networks reliability, management of system inertia, capacity issues between energy types, meeting CO2 reduction and air quality targets, along with power and fuel quality. This approach will also increase our understanding and preparedness levels for concepts like blockchain, cross energy reserves, grid management and islanded networks.



CASE STUDY 6: 2006 EUROPEAN SYSTEM DISTURBANCE[40]

On the evening of 4th November 2006, there were significant East-West power flows as a result of international power trade and the obligatory exchange of wind feed-in inside Germany. These flows were interrupted due to the tripping of several high-voltage lines, which started in Northern Germany and split the Union for the Coordination of the Transmission of Electricity (UCTE) grid into three separate areas (West, North-East and South-East) with significant power imbalances in each area.

The power imbalance in the Western area induced a severe frequency drop that caused an interruption of supply for more than 15 million European households. The event was not caused by some extraordinary climatic conditions or technical failures, but instead was triggered by causes in the E.ON Netz control area. The very rapid splitting of the interconnected system could not be stopped once the cascade tripping of the lines had started.

Due to the good performance of countermeasures activated at UCTE level in the individual control areas, a Europe-wide black-out was avoided and together the TSOs were able to re-establish a normal situation in all European countries in less than two hours.

6.4. GEOPOLITICAL AND HUMAN

KEY TAKEAWAYS

- Retaining and training people with the right skills is a key element to ensuring a resilient system – by ensuring power supplies are restored as quickly as possible following an outage, as highlighted in the Ukraine cyber-attacks (see Case Study 5) or by consumers adapting during power cuts.
- Government policy can strongly influence future direction of regulation and markets, particularly in relation to transport, heat and communications networks. The role of the electricity system and its resilience to support other systems should be recognised.
- Maintaining the capability to respond to events is vital to ensure resilience, and consideration needs to be given to the potential for reductions in capability that may arise from an aging workforce or widespread sickness, such as flu pandemic.

People play a key part in operating, maintaining and using the electricity system. Retaining and training people with the right skills is key to delivering a resilient system alongside the plant and processes being in place to manage large events. It is the staff within the electricity network owners and operators who will be carrying out the emergency response plans. Society and business will drive the increase in electricity consumption and will have ever increasing expectations of the electricity system. It is also people that are behind malicious attacks, whether that be physical attacks on infrastructure or attacks within the cyberspace. Geopolitical instability is a large driver behind both cyber and physical disruption, with some states actively planning and implementing a disruptive role worldwide.

The political direction can have a large influence on society's uptake of technology, with Government setting ambitions targets for low carbon technology especially. Few had predicted the rapid increase in uptake of solar panels and installation of wind farms. However, the Government incentives for installation facilitated and encouraged this uptake[41 42]. We expect the announcements regarding no new diesel/petrol cars to be manufactured after 2040 to increase the uptake of EVs, as highlighted in the Government's 'The Road to Zero' document[18]. To enable the uptake in EVs there is a need to deploy the right resilient electricity infrastructure to enable people to utilise their electric vehicles as they do their conventional vehicles today, enabling both short and long-distance journeys, providing the consumer the freedom to travel they value today. Future policies and legislation accompanying decarbonisation should influence the direction the markets take in transport, heat and broadband networks.

International politics also influence the state of play for the energy system in the UK, for example, where we have dependencies on imported supplies of gas, oil and electricity. The political climate in a supplier country, as well as the UK's relationship with that state may determine the UK's access to imported resources. This could have an impact on our generators which use fuels such as gas, as well as our heating, transport fuel and cooking supplies. Moving forward to a world where we decarbonise our fuel sources, society may increase the electricity demand to fill the gap from carbon-based fuels, by greater use of electric stoves and electric heaters, instead of domestic appliances dependent on fuels such as gas. It is anticipated that many high impact political events will occur over the next few years, with some states seeking to strengthen influence and others facing political uncertainty, leading to a highly unpredictable political landscape.

INTERNATIONAL RELATIONSHIPS

SUDDEN POPULATION INCREASE

STATE MALICIOUS ATTACK

The political stability of other nations can have an indirect impact on the UK and our resources. There has been great unpredictability of recent international politics, as highlighted in big data analysis of press articles and financial analysis by Blackrock Investment Institute, which demonstrates how quickly the pace of the political landscape can change. Figure 16 shows how political change can drive risk, which in turn affect markets and people's willingness to invest. This can lead to volatility, uncertainty and can drive crisis in financial markets which can compound electricity outage events if systems are not resilient. This can lead to larger financial and reputational damage being done to an economy, also presenting further issues for society.

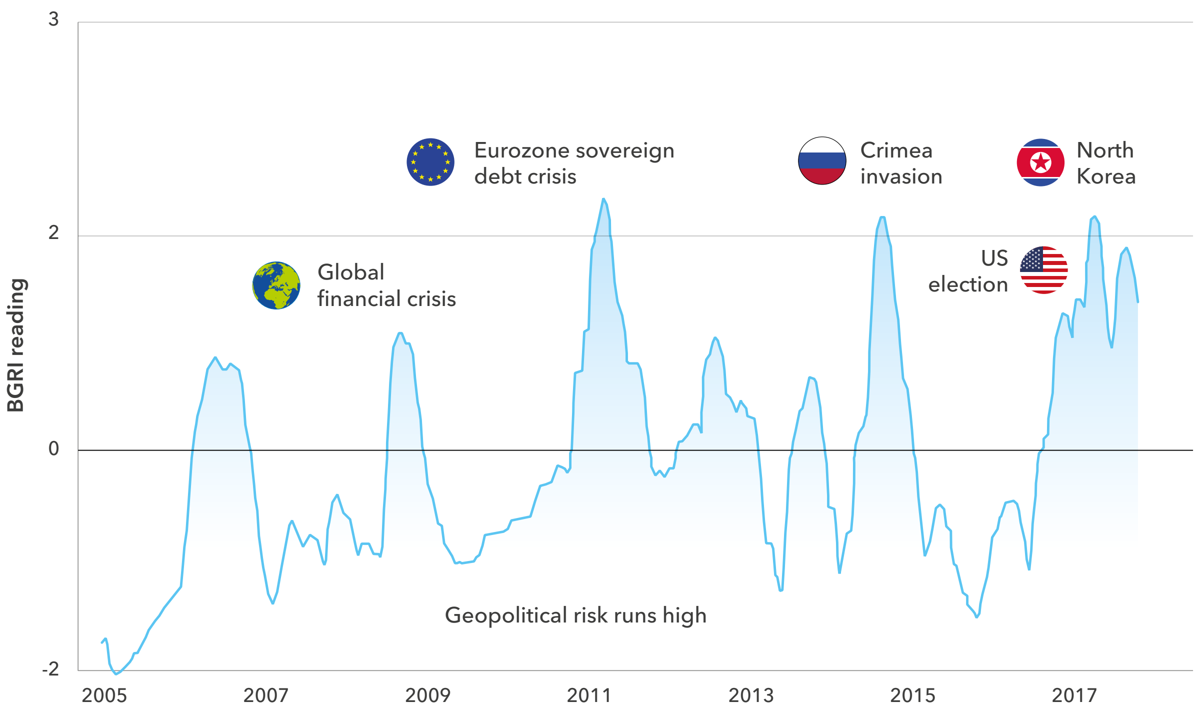


Figure 16: Ups and downs – Blackrock Global Risk Indicator (BGRI) 2005–2017[43]

Organisations within the UK electricity industry can maintain normal operations even with some resource unavailability. However, major incidents, such as a flu pandemic, can result in many staff being unavailable, which can pose a risk to delivering electricity supplies, organisations have contingency plans to mitigate this risk, however staff levels need to be sufficient to maintain resilience in the industry.

Along with mitigation of extreme risks, careful consideration is required to ensure the future capability of staff; through training, development and appropriate exercises, is undertaken to maintain organisational resilience. Furthermore, for an emergency response plan to be implemented, the right resources need to be deployed in a timely manner and to the correct locations to take the remedial actions required. This may prove difficult in the event of a power cut, with petrol pumps no longer working or with low-charge on EVs. Therefore, making provision for utilities to have access to reserve fuel supplies is important, whether it be for backup generators or electrical storage to provide power for petrol/diesel pumps or to quickly charge batteries of essential electric vehicles.

6.5. NATURAL HAZARDS

KEY TAKEAWAYS

- Climate change is already increasing the intensity, frequency and variability of extreme weather events, particularly flooding and extremes of temperature. Climate change also increases the risk of localised and difficult to forecast extreme events.
- This is set to increase further as we continue to produce more green house gases from increased human activity. Hence the need for government to strongly intervene with its decarbonisation agenda.
- There is the risk that 'ambient' conditions shift away from historical averages, and thus break design assumptions. This may reduce capacity on the network as higher tempratures affect the rating of electrical equipment, especially in normally cooler seasons of the year.

Natural hazards and extreme weather events are some of the well-understood potential external effects on the electricity system. The natural hazards and extreme weather challenges identified as a reasonable threat to occur within the next five years are regularly reviewed by the UK Government[29].

The natural hazards that a country may anticipate will vary geographically, depending on the local climate, historical weather events and projected weather forecast. Natural hazards can pose real and significant threats both at a local distribution level, but also at national levels, as highlighted by events in Puerto Rico in 2017 (see Case Study 7).

CASE STUDY 7: PUERTO RICO, HURRICANE MARIA, SEPTEMBER 2017

On 20th September 2017, Hurricane Maria swept across Puerto Rico, causing unprecedented damage and considerable loss of life. The storm caused significant damage to the electrical transmission and distribution network and resulted in a blackout lasting over 9 months. No electricity meant that water pumps and sewage systems couldn't function. Taps wouldn't work, so people turned to natural sources of water. In some parts of Puerto Rico, rivers and streams became contaminated. And without electricity, people couldn't operate medical devices like dialysis machines or refrigerate critical medicines such as insulin.

Climate change is identified as not only a challenge in the future that may affect risks associated with some natural hazards, but also an emerging phenomenon, with experts already observing changes in the UK's climate[44].

- **Temperature over land**. Average temperatures have risen by around 1°C over the last century with most of this rise occurring since 1970. There has also been a trend towards warmer winters and hotter summers, with eight of the hottest years on record all occurring after 2002. This temperature increase is exacerbated in cities where the urban heat island effect can lead to higher temperatures and longer periods for the thermal cooling of surrounding buildings and roads to take effect.
- **Sea levels**. Sea levels around the UK's coast are rising by around 3 mm a year, approximately double the long-term trend with notable acceleration since 1990.
- **Rainfall**. There is evidence of changing rainfall patterns, in particular there has been a significant upward trend in annual rainfall over Scotland, to a level more than 10% above the average during the early decades of the 20th century. Heavy rainfall during winter is increasing and contribute to increases in winter run-off and high river flows, such as the UK saw over the winter of 2015/16.

It is anticipated that climate change will increase the intensity, frequency and variability of extreme weather events, particularly flooding and extremes of temperature. The Adaptation Sub-Committee of the Committee on Climate Change highlighted six thematic risks for the UK. Of these six risks, the top two priorities were flooding and risks associated with coastal changes and risks to health, well-being and productivity from high temperatures. While all electricity systems are designed for a degree of protection from storms or flooding, resilience considers extreme and rare events where there may be a breach of current flood protection in place, or a severe storm where wind speed may reach unprecedented levels. Mitigations currently put in place by electricity networks include permanent flood defences at identified vulnerable sites, and temporary defences to deploy to less vulnerable sites should the need arise.

Figure 17: Key climate change risks to the electricity system

The Engineering and Physical Sciences Research Council, a UK Government agency for funding research and training in engineering and physical sciences, has provided a grant to investigate the adaptation and resilience of the UK energy system to climate change. The models that have been developed combine climate change forecasts with information about the UK electricity networks. The computer simulations predict the likely extent of disruption that adverse conditions could cause to power supplies in the future, looking out to 2080. The outputs to-date suggest that frequency of events may rise, but not necessarily the severity[45].

The largest difficulty identified for managing resilience levels, to natural hazards and extreme weather events, is the potential for ambient conditions to shift away from historical averages. This changes the way weather events can be modelled and reduces our ability to reliably predict the impact and likelihood of extreme weather events and natural hazards. Increased temperatures can affect the rating of electrical equipment leading to a reduction in capacity; this can be significant especially if winter temperatures rise significantly when generally higher electricity system demands are seen. Additionally, a heatwave can stress other systems, such as the water system and cooling systems, which can have an indirect impact on the electricity system as highlighted by the 2018 European Heatwave (Case Study 8).

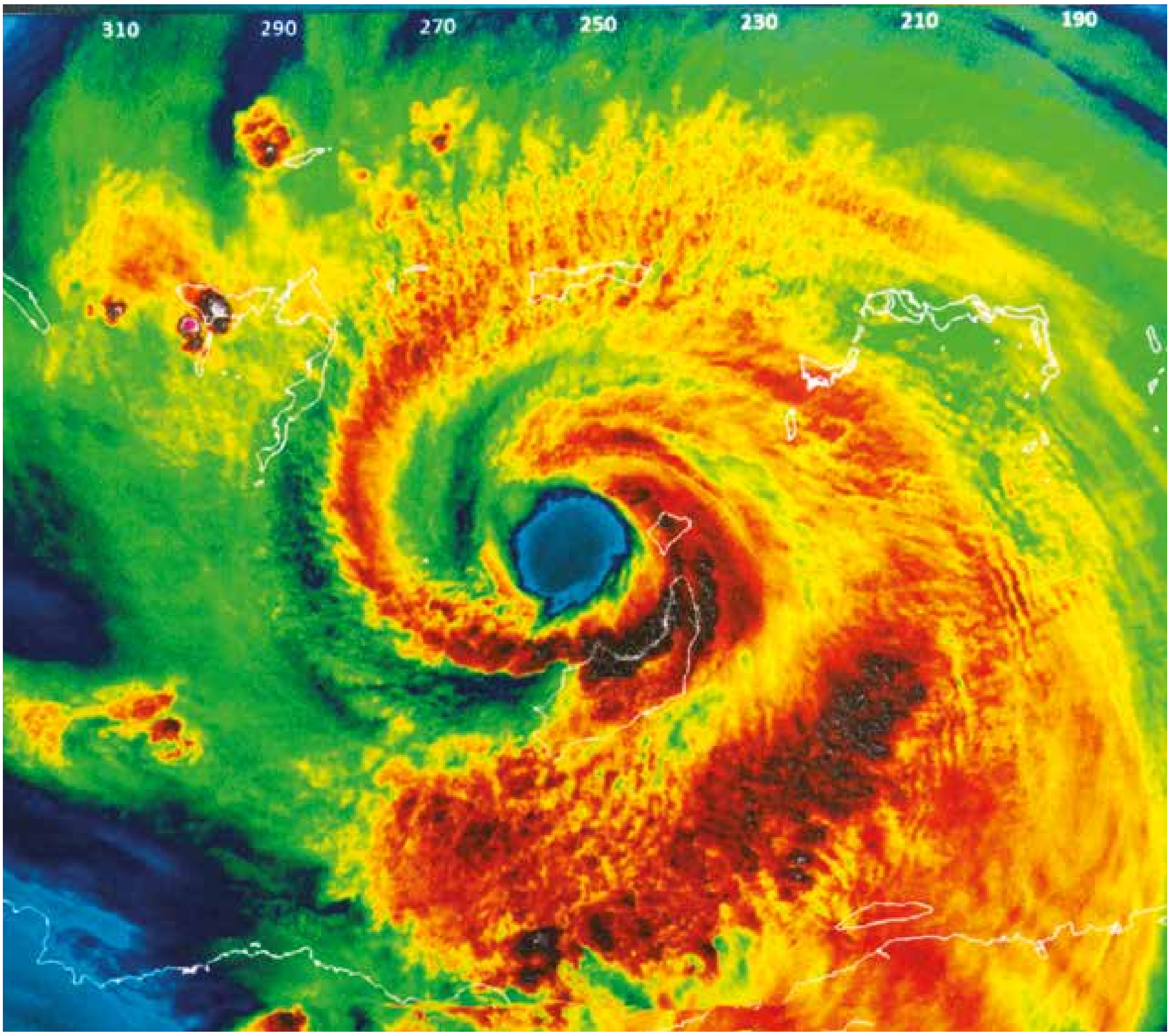
CASE STUDY 8: EUROPEAN HEATWAVE 2018

On 23rd June 2018, the UK was announced to officially be in a heatwave. In July, the UK reached a record-breaking temperature of 37°C. As a result, the UK experienced a drought, where some areas had threats of hose pipe bans, due to the additional stress put on the water supply system. There were huge spikes in demand for water at morning and evening peak times, meaning that water companies were pumping billions more litres of water into the system, which was being consumed almost as fast as it was supplied[46]. The act of pumping water through the system relies on electric pumps and electricity within the treatment of the water supply, thus increasing overall electricity demand.

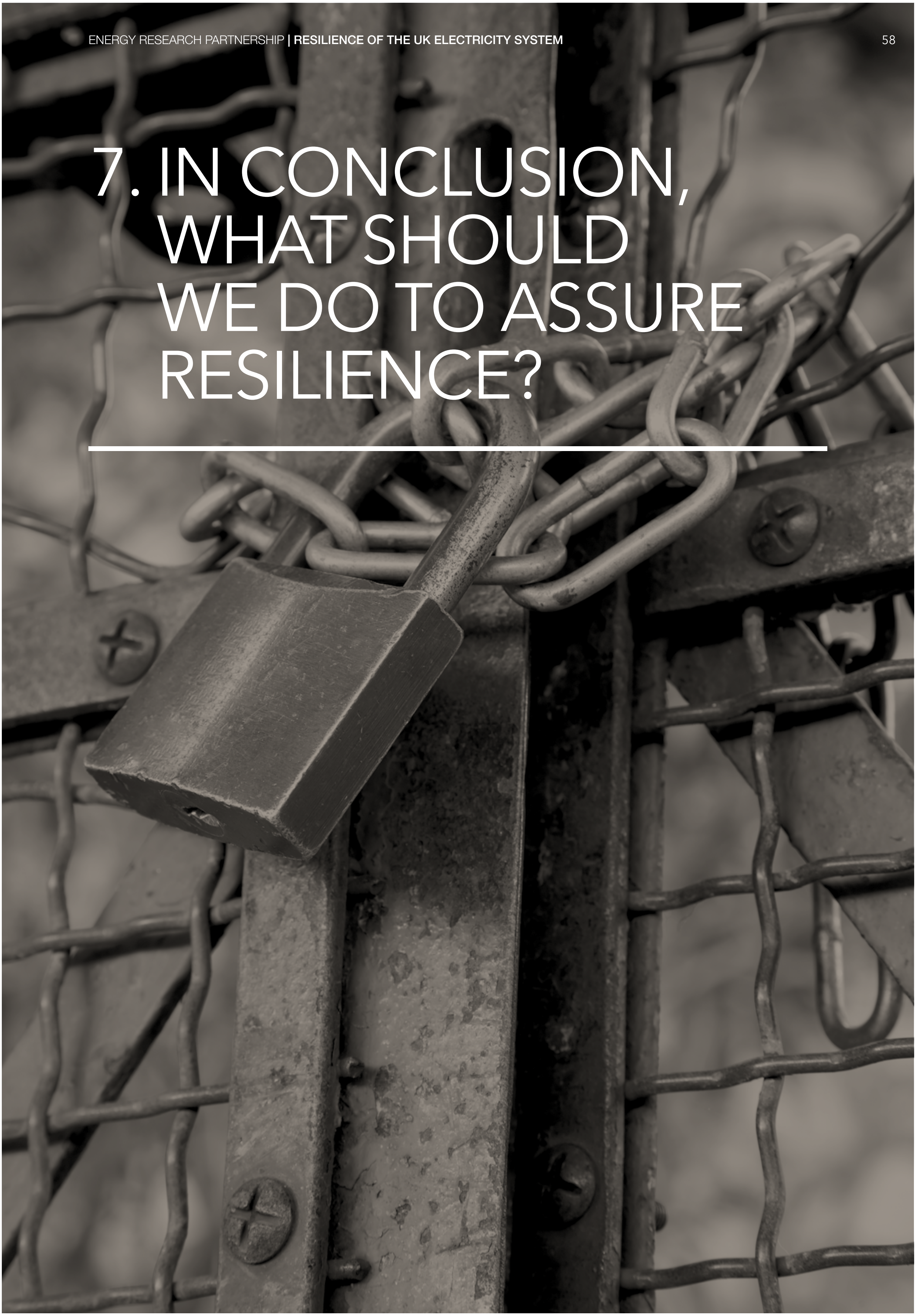
Additionally, as the temperature increases, the role of air conditioning, refrigeration and cooling for data centres rises. In the last week of June, the UK temperature rose by 3.3°C, which related to an increase in 860MW electricity demand, for cooling and increased water treatment (equivalent to an additional 2.5 million households)[47].

What we term as High Impact Low Probability (HILP) events, not only considers events related to natural hazards and extreme weather of short period[s], but also how electrical faults during such events would have a large-scale impact. An event of duration longer than a few hours- stretching beyond a day during droughts and long periods of high temperatures would have a bigger impact than normal[48]. Also, the longer the duration of extreme temperatures and water unavailability, the greater the impact on generation and network resilience due to water being used for steam and cooling, and hence on overall UK electricity system resilience.

Climate change impacts resilience of the electricity system in three ways; more extreme weather; more decentralised low carbon technologies to mitigate the effects and more complex technologies to manage system demand. There is the element of increased severity and frequency of extreme weather events such as drought, storms and flooding, which can affect networks. Also, as temperatures are increasing globally, there are international incentives to reduce greenhouse gas emissions, to reduce the effects of climate change. Reducing greenhouse gases causes us to evaluate how we operate today, what we use that is carbon intensive and develop innovative solutions, which use significantly less carbon. This has brought new technology to society such as electric cars, domestic solar panels and carbon capture and storage, all of which introduces new complexities and further interdependencies between sectors. Climate change management requires a dual assessment of the impact of severe weather events on resilience and the integration of technology into the operation of electricity networks, which assists in the delivery of climate change targets.

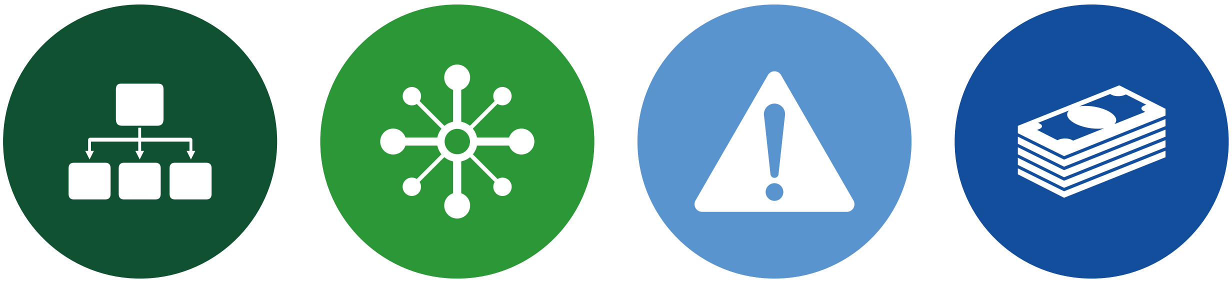


7. IN CONCLUSION, WHAT SHOULD WE DO TO ASSURE RESILIENCE?



7.1. CONCLUSIONS

This ERP report has benefitted from a significant level of industry engagement – an indication of the importance of electricity system resilience and its future development. The project has identified four key factors that are expected to affect the resilience of the electricity system in the future:



RELIANCE UPON TECHNOLOGY AND NETWORKS

COMPLEX INTERDEPENDENCIES BETWEEN NETWORKS

THREATS TO NETWORK INFRASTRUCTURE

ECONOMIC IMPORTANCE OF METROPOLITAN CENTRES

The project has focussed on the electricity system, however these factors are likely to be applicable to the wider energy sector and potentially other sectors, such as transport and communications. This project has identified there is currently no common industry approach to managing resilience; further research and analysis could inform a whole-system view of a definition of resilience and strategies to manage cross sector resilience.

This report identifies that electricity use has changed significantly since the majority of the current electricity infrastructure was put in place. This trend is anticipated to continue with further electrification of sectors such as transport and heat, leading to a greater reliance upon electricity in the future. It is expected that for a given power disruption today, the impact on society and business will be higher for a similar event in the future.

With further reliance on technology and networks, the interdependencies between sectors will increase, with most sectors having a level of dependency on communications and electricity. A holistic approach to managing resilience across sectors will offer greater visibility of the state of resilience and enable system wide solutions to be prescribed.

A key driver for change in the electricity system is the recognition of the variation in threats to future network infrastructure. The electricity system needs to be physically resilient to severe weather patterns attributable to climate change. At the same time, it must be resilient and adaptable to the new technologies that are being employed to decarbonise the electricity system, which are leading to a more decentralised topology. The increase in deploying new and smarter technologies reflects the need for future resilience to maintain a focus on cyber security.

The UK population and economic activity is concentrating in metropolitan centres, which in turn increases the criticality of future electricity requirements at these centres. Moreover, large urban centres are likely to see further optimisation of transport systems and services through deployment of automation and technology, which in turn is likely to see increased requirements for resilience in these locations[49].

7.2 RECOMMENDATIONS

In response to these key drivers for change, one overarching recommendation is made as a key enabler to four further recommendations to assure resilience in the future:

RECOMMENDATION 1: RESILIENCE MEASURES

Investigate resilience measures which can be used cross-sector to establish acceptable levels of resilience to meet future needs.

Agreeing a single common definition of resilience is possible, however developing a single resilience measure that is applicable to all elements of the electricity system represents different challenges. Clear government policy, which reflects the needs of society and business, is a key requirement ahead of the definition of a measure(s). The measure(s) should reflect the level of resilience being achieved, by meeting the policies, and highlight any shortfalls which need to be addressed.

- Leading measures of resilience should be investigated that can be interpreted and applied across the electricity sector.
- A common resilience measure(s) should be developed but should be sufficiently broad to apply to all organisations in the electricity system; it should be applicable to the assets, businesses, services and supply chain that facilitate the transport of electricity from point of generation to point of consumption. Ideally this measure(s) should also be equally applicable to other infrastructure sectors, recognising interdependencies across sectors.
- If a common view is agreed across the electricity industry, resilience measures could support understanding of the industries readiness and capability to meet society and business' expectations and should align with Government policy. Such measures would set clear standards for the electricity industry to achieve resilience levels that are in the best interests of the national economy and demonstrate value to electricity consumers.
- A dedicated working group, cross-sector forum, or individual organisations, should seek to derive methods and share best practice, with the aim of agreeing a suitable measure of resilience. In the absence of a measure, Government and regulators should continue to set guidance driving cross-sector collaboration, to deliver future resilience needs.

RECOMMENDATION 2: ENGAGE SOCIETY AND BUSINESS

Engage a diverse set of views across society and business to establish future resilience requirements for the UK Electricity System.

Given society and business' growing reliance on electricity, it is important to understand how this impacts the period society can tolerate loss of power, following an exceptional event in the future. Society and business' power needs and expectations should be a consideration in setting policies and the mitigation/response required in the future. The following actions are proposed:

- Appropriate representatives of the public, such as Local Authorities, Government and Citizen's Advice Bureau, should be engaged to accurately reflect on society's needs and expectations. These representatives could also provide insight on how society will use power in the future.
- Government policy should reflect business requirements and future aspirations for power use. Appropriate representatives of business, such as Confederation of British Industry (CBI) or Government departments, should be engaged to reflect business requirements and future aspirations.
- Evaluation of society and business expectations should include the value they place upon amenities, including energy, heat, transport, broadband/communication networks.

RECOMMENDATION 3: GOVERNMENT AND POLICY

Government to work with cross-sector infrastructure parties to establish holistic resilience policies for the future.

Given the increasing complexity and interdependency between systems, a whole system view of resilience is developed and managed. Government needs to continue to take a lead to produce policies for resilience, ensuring we have a resilient electricity system to meet the future needs. Clear future direction and policy is required to ensure the resilience needs are met in the right timescales, in-line with the Government's decarbonisation and climate change policies, which are driving the change in electricity demand and reliance [18] [30]. It is acknowledged that a range of possible future scenarios could manifest in the energy landscape; approaches adopted should be applicable to a range of possible futures and avoid unnecessary expense to consumers and business.

This ERP report has considered resilience from an electricity system perspective, and cross-sector dependencies apparent to the electricity sector. The following actions are proposed:

- An over-arching policy should be developed, incorporating all elements of resilience that the electricity system faces, recognising that different elements will be applicable to different electricity system components. This policy needs to be broad enough to encompass the whole electricity system, as well as its cross-sector interdependent counterparties. However, it must provide sufficient direction allowing for the electricity sector and sectors dependent on power, to make it applicable to their organisational resilience plans. The ERP recognises that the production of a resilience policy and its impacts needs to be weighed against the competing agenda for Government's time and resource.
- Government resilience policies should account for cross-sector interdependencies; this should set the direction and approach for regulation (e.g. Ofgem, Ofwat and Ofcom), as well as setting standards for non-regulated markets. In the future, it may be more beneficial to evaluate resilience by specific services, that reach across multiple sectors, rather than individual sectors. Government should reflect society and business' view; protecting the interests of society and considering expectations of businesses.
- A taskforce of senior cross-sector leaders, working with Government should be formed to consult on this policy. This should build upon the Green Finance Taskforce's recommendation to, "establish a national resilience unit to coordinate and champion climate resilience and ensure Government investment is 'future proofed' to climate change,"[50] recognising the wider future trends identified in this report. The taskforce should also align with other industry work, such as by the National Infrastructure Commission, to further understand cross-sector resilience, National Risk Assessment Process[51] and National Infrastructure Forum[52]. A task force that brings together the perspectives of other sectors with Government, may highlight further and/or different cross-sector interdependencies to provide a more holistic view of resilience.

RECOMMENDATION 4: REGULATION AND MARKETS

Infrastructure regulators should make resilience a central consideration of review periods. It should also stimulate markets to ensure relevant sectors provide resilience in their products and services.

In order to translate Government policy into applicable and meaningful industry drivers, resilience needs to be a distinct core topic of regulatory reviews for the electricity industry, which is distinguished from existing reliability measures. It should also be a strong market driver for those within the sector, which are not directly regulated entities. The following actions are proposed:

- A set of measure(s), as proposed in Recommendation 1, should support resilience outputs, as part of regulatory reviews, to ensure that the industry is delivering resilience levels society and business expect, and in line with the direction set in Government policy.
- Markets dependent on UK sectors such as heat, transport, and the wider energy sector, should take the direction set by Government in a resilience policy, to maintain the levels of resilience of the UK electricity system. This will enable a more flexible, and agile network that meets the nation's future needs.
- Some elements of resilience are covered by some regulatory reviews and price control periods for networks. However, in the long term, a more holistic view of resilience that is applicable to potential future challenges facing the electricity system is recommended.
- Cross-sector dependencies in delivery of 'services' and geographical specific requirements should be considered. Whilst this does not necessarily mean that additional or different measures for resilience would be required in these areas, degrees of application would need to be considered in any regulatory or market drivers.
- Given the complexities already existing with interactions, and interdependencies between different sectors, regulatory resilience frameworks should enable the delivery of solutions for resilience across sectors. The respective regulators (e.g. Ofgem, Ofwat, Ofcom) will require cross-collaboration to ensure that Government policy meets the need of all sectors and their interdependencies.
- A regulatory resilience mechanism (such as through incentives/allowances) could provide an organisation a level of autonomy, and be factored into organisational decision-making, driving cross-collaboration where it is economically beneficial to the consumer.

RECOMMENDATION 5: CYBER SECURITY

Organisations should build their cyber security skills and capabilities to address growing threats and ensure secure network resilience during technology integration.

Cyber security is a present and evolving threat to any industry that uses communications and technology-based solutions. The more dependent our electricity system becomes on these solutions; the greater the impact of a cyber-attack on electricity assets, affecting interdependent sectors and potentially causing widespread disruption to UK society and businesses. Conversely, an increase in new technologies being utilised within the electricity system, can also contribute to increase a level of resilience, with the potential to allow enhanced visibility and optimisation of the electricity system. From the electricity sector perspective, cyber is therefore a key focus area. The following actions are proposed:

- This work has focussed on cyber security from an electricity perspective, and therefore it is suggested that other sectors could review their own dependencies, to draw appropriate conclusions for their sector.
- From an electricity perspective, the focus and importance provided to cyber security across the electricity industry should continue.

The UK is implementing the EU directive on the security of Networks and Information Systems (known as the NIS Directive), which came into force on 10 May 2018[53]. The NIS Directive aims to raise levels of the overall security and resilience of network and information systems across the EU by ensuring member states have in place a national framework to support and promote the security of network and information systems. This includes a National Cyber Security Strategy, a Computer Security Incident Response Team (CSIRT), a Single Point of Contact (SPOC) and a NIS competent authority[3].

The electricity industry has been identified as an essential service under this directive and The Secretary of State for Business, Energy and Industrial Strategy (England and Wales and Scotland) and the Gas and Electricity Markets Authority have been designated as the appropriate competent authorities and are responsible for the oversight and enforcement of the NIS Regulations within their sector[54].

The National Cyber Security Centre (NCSC) will undertake the role of Technical Authority providing guidance to both the competent authorities and the operators of essential services. They have developed a set of principles that, collectively, describes good cyber security for operators of essential services.

The NIS directive demonstrates one possible approach to managing an emerging threat across sectors. Recommendations 2,3,4 highlight some challenges in developing a common agreed approach to managing resilience. The NIS directive could be used as a point of reference in developing an approach to future resilience management that applies to a range of organisations and sectors.

Figure 18 presents outline timescales for a set of proposed outcomes derived from the five recommendations in this report, which should be delivered to ensure we achieve the right level of resilience to benefit UK society and business.

DRIVERS

- RELIANCE UPON TECHNOLOGY AND NETWORKS
- COMPLEX INTERDEPENDENCIES BETWEEN NETWORKS
- THREATS TO NETWORK INFRASTRUCTURE
- ECONOMIC IMPORTANCE OF METROPOLITAN CENTRES

RECOMMENDATIONS

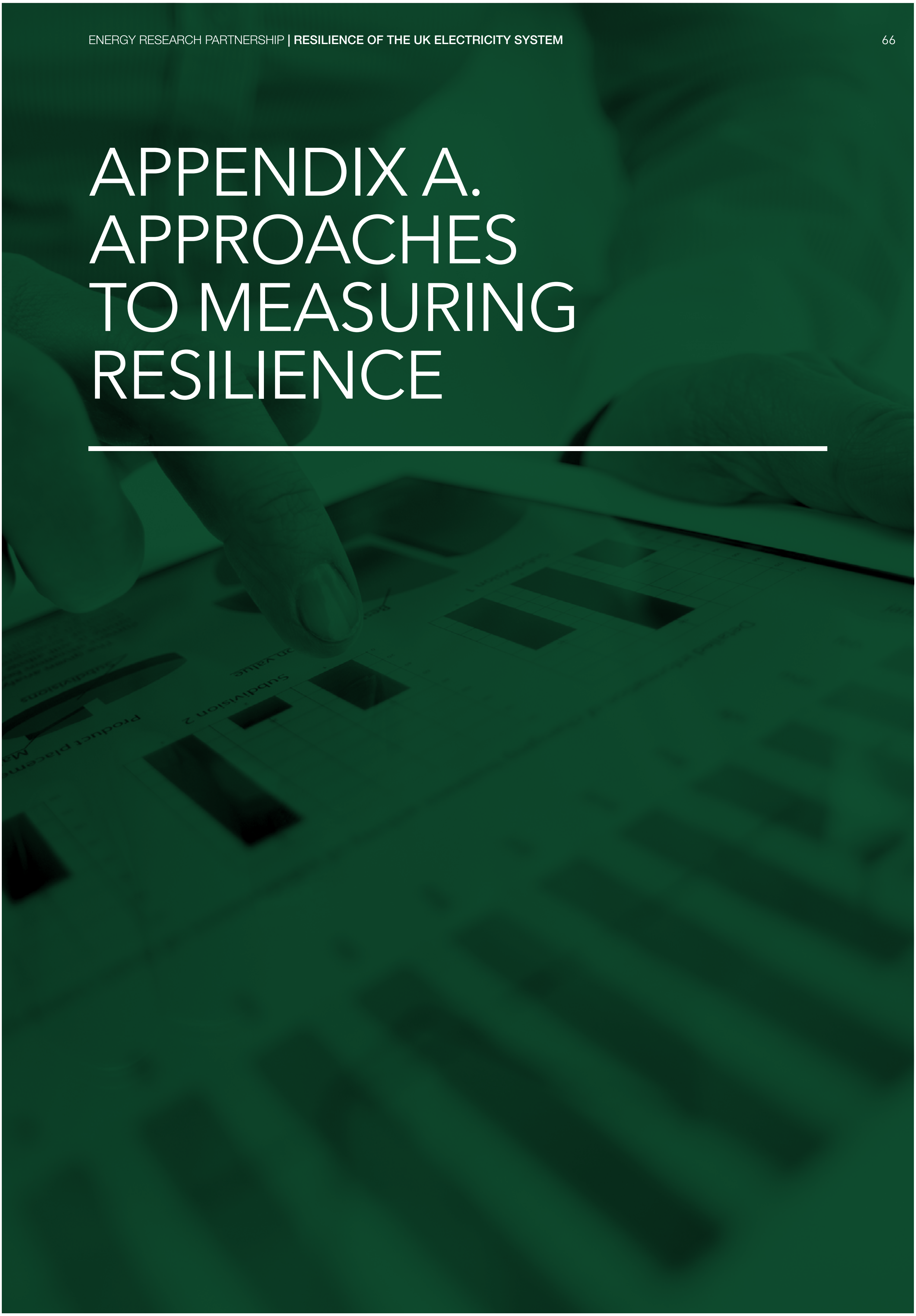
- RESILIENCE MEASURES
- ENGAGE SOCIETY AND BUSINESS
- GOVERNMENT AND POLICY
- REGULATION AND MARKETS
- CYBER SECURITY

OUTCOMES

2020	Organisations across the sector to investigate applicable resilience measures and share best practice via a regular industry and cross-sector forum.	Relevant stakeholders to engage Society and Business in a meaningful way, to understand their future expectations and needs.	Cross-sector task force, with senior industry leaders established, by government to develop resilience policies.	Cross-sector task force identifies interdependencies and future technology impacts, supporting cross-sector regulatory consistency.	Electricity organisations meeting NIS directive on cyber security.
2025	Common cross-sector measures of resilience agreed, ensuring regulated sectors are delivering resilience levels required by society and business.	Understand resilience requirements for different geographical and societal needs, consulting stakeholders and setting policies.	Cross-sector government policies for resilience developed, ready for consultation and implementation.	Regulatory review periods have resilience as a core defined topic across all regulated sectors, allowing Government resilience policies to be met.	UK companies achieving robust world leading standards in cyber security.
2030	Resilience measures being refined to reflect changes in threats and learning from world-wide incidents. Continuing to demonstrate value to consumers.	All new infrastructure and systems designed and constructed to meet future resilience policies. Networks meet resilience expectations of society and business.	Policy continuously reviewed to meet ongoing future needs.	Regulatory outputs and measures for resilience are demonstrating value to consumers and businesses. Market is providing resilience in non-regulated products and services.	Robust cyber resilience ensures new technologies benefit society, through secure optimisation of our infrastructure networks.

Figure 18: Proposed set of outcomes

APPENDIX A. APPROACHES TO MEASURING RESILIENCE



A.1. THE TRAPEZOID METHOD

The Trapezoid Method, developed by the University of Manchester, aims to capture the response of a critical infrastructure (including electricity systems) when exposed to an extreme event, that fall in the tail of the probability distribution of the impact of the event, and not on the expected, average impact. It is based on a risk-based approach, such as using Value at Risk and Conditional Value at Risk. Further, it is also captures the temporal impact of the event and models the temporal behaviour of the system during and after the event. The Trapezoid Method can be seen in Figure 19, such that it represents the behaviour/response of the system during and following the event.

The resilience metric system of Table 2 has been specifically designed to quantify the resilience trapezoid of Figure 19 and has been efficiently applied to model the spatiotemporal impact of windstorms on the GB transmission network, as well as evaluate the contribution of different adaptation strategies. This metric system can be effectively complemented by the area metric, which measures the area of the trapezoid providing an indication of the overall system resilience and enables a comparison of the Figure 19 efficiency of different resilience enhancement strategies (both infrastructure hardening and smart grid solutions)[55 56].

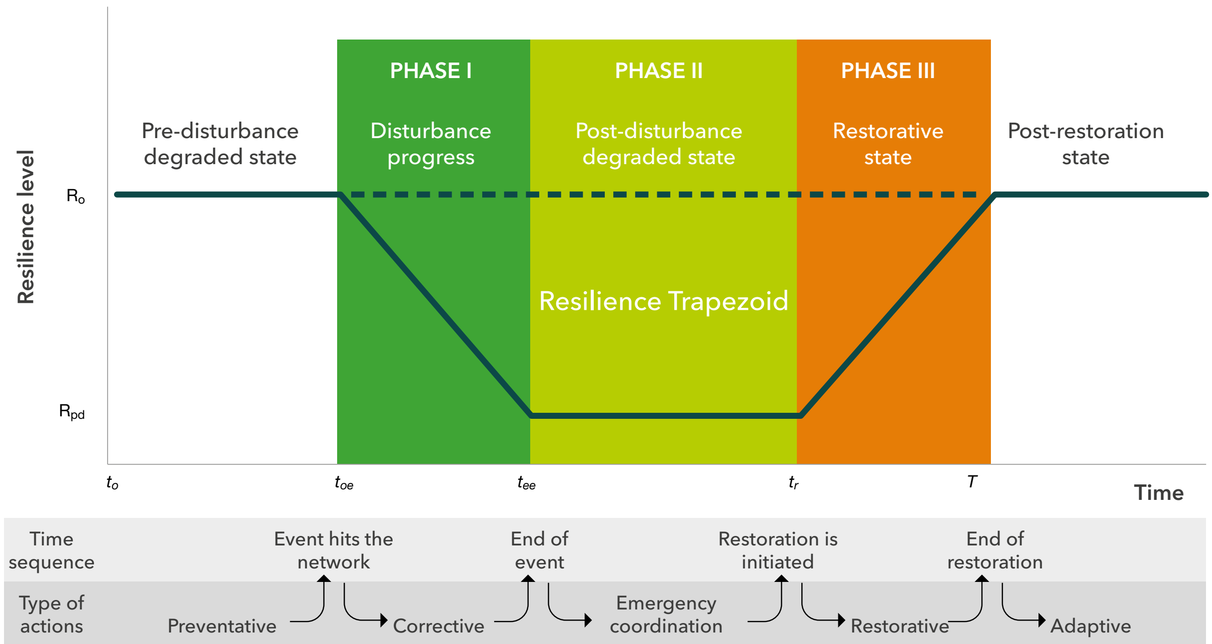


Figure 19: The Resilience Trapezoid Associated with an Event

PHASE	STATE	RESILIENCE METRIC	SYMBOL
I	Disturbance progress	How *fast* resilience drops? How *low* resilience drops?	Φ Λ
II	Post-disturbance degraded	How *extensive* is the post-disturbance degraded state?	Ε
III	Restorative	How *promptly* does the network recover?	Π

Table 2: The ΦΛΕΠ resilience metric system associated with the resilience trapezoid

A.2. CITY RESILIENCE INDEX

The Rockefeller Foundation, in conjunction with Arup, developed a City Resilience Index, which can be applied to cities internationally.

This evaluates cities across four dimensions[57]:

- Leadership and Strategy
- Infrastructure and Environment
- Economy and Society
- Health and Well-Being

The electricity industry falls into the Infrastructure and Environment dimension, as part of the critical national infrastructure that supplies cities and supports society.

It is possible to minimise the City Resilience Index criteria, to apply a measure applicable to the electricity system using the following indicators[57]:

- Flexible infrastructure: critical services are support by diverse and robust infrastructure
- Retained spare capacity: Resourcefulness and flexibility of key resources reduces demand on critical infrastructure
- Diligent maintenance and continuity: Robust monitoring, maintenance and renewal of essential utility infrastructure with effective contingency planning
- Adequate continuity for critical assets and services: Resourceful, reflective and flexible continuity plans to maintain utility services to critical assets during emergency situations

This index has been applied to 100 cities internationally, allowing cities to identify areas that require improvements, and develop plans to improve or maintain levels of city resilience (see case study 6). Despite the complexities in measuring resilience, it has been successfully implemented in other sectors, providing hope for success in developing a resilience measure in the electricity industry.

A.3. BOW-TIE APPROACH

An approach that is currently used within industry applies to evaluating how prepared an organisation or industry is referencing the bow-tie risk model, shown in Figure 20. This evaluates whether there are proactive mitigation activities in place, ahead of a particular event, or reactive response activities for post-event. It is possible to count, and place a weighting, on the mitigation or response activities in place to determine a level of preparedness in the face of an incident. As a risk-based assessment method, this approach does have some limitations as it doesn't capture the speed of recovery or potential for adaptation.

Often the resilience problem comes down to the bow-tie risk management approach: can you put mitigation in place ahead of an event, to reduce the likelihood or size of impact of the event? Or can you put a response in place, after the event, to reduce the size of the impact?

Often there is a balance with cost as to how much mitigation or response is to be put in place. The more mitigation ahead of the event, including preparation of mitigations, the more likely that the solution will involve a larger committed cost. However, with less mitigation the likelihood is that more response activities will be required, and time to prepare and test for the recovery scenarios. The less preparation for response activities, the likelihood that the response activities can accumulate to a large sum. So, it is key to get the balance right between mitigation and response activities, for the most economical and efficient solution for the event faced. Further, and in line with the resilience definition adopted in this report, the adaptation of the electricity system (as a key resilience feature) is critical in order to amend and improve the operation and planning of the electricity system to be better prepared to future (maybe unforeseen) events. In addition, it is important to get the balance right between what society expects, what the electricity system can provide and the total social benefit for the resilience solution.

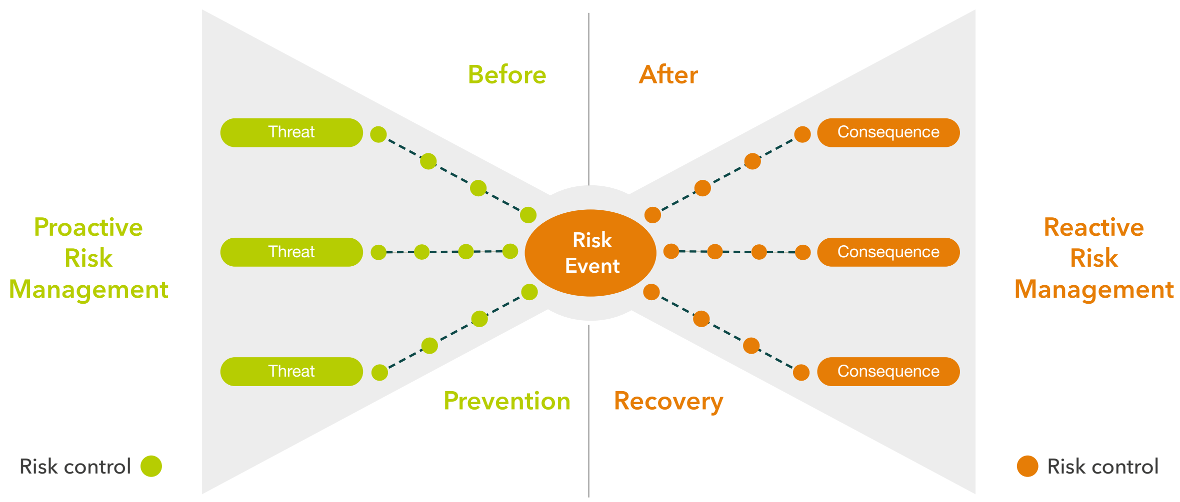


Figure 20: Bow-Tie Risk Model

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