Resilience of the Future Energy System: Impacts of Energy Disruptions on Society

UKERC Working Paper

Dr Emily Cox (Cardiff University)

January 2021

Introduction to UKERC

The UK Energy Research Centre (UKERC) carries out world-class, interdisciplinary research into sustainable future energy systems.

It is a focal point of UK energy research and a gateway between the UK and the international energy research communities.

Our whole systems research informs UK policy development and research strategy.

UKERC is funded by the UK Research and Innovation, Energy Programme.

Contents

1. Summary

The resilience of the UK energy system is changing. New technologies, including those vital for meeting the UK's decarbonisation objectives, are being introduced at a rapid pace; new information technology is changing the way in which systems operate; and patterns of energy demand are changing. New risks are also emerging, including the potential increase in occurrence or severity of extreme weather events due to climate change, and the possibility of a damaging cyber-attack. Our growing dependence on energy, particularly electricity, means that more than ever we need to plan for disruptions and be prepared for them. This means increasing the resilience of systems and society: preventing disruptions from occurring, but also containing and recovering from the disruptions which do occur. What happens *during* the disruption is important: we need to understand how individuals, communities, businesses, and economies experience the event, how they act, and what measures can be taken to reduce the overall impacts. This report reviews the literature on the societal impacts associated with a lengthy, widespread disruption to energy supply, particularly electricity supply.

A review of the academic and grey literature was carried out between September 2019 and March 2020, finding a total of 104 papers on the societal impacts of energy disruptions, focusing on electricity disruptions. This literature was from a wide range of disciplines, and broadly fell into five categories: impacts on households and individuals; impacts on health and vulnerable people; economic impacts; critical infrastructures; and measuring and defining 'resilience'. These are addressed in separate sections of this report.

1.1 Main findings

There is a medium-size body of existing work on the impacts of outages on individuals and households. Much of this comes from the USA, where the electrical grid experiences frequent and sometimes severe outages, and northern latitudes such as Scandinavia and Canada which experience severe winter weather. A large number of publications appear following major events, particularly the 2003 New York blackout. Many of the findings from these studies can be extended to the UK; however, high dependency on gas for space heating in the UK means that the gas sector requires special attention, with many people unaware that their gas boiler and heating system rely on electricity. Case studies of previous events find that disruptions often create societal cohesion: people tend to cooperate and perform altruistic acts, and panic is unlikely. In this respect, academic case studies using observational and interview methods differ from media reports, which tend to be more pessimistic. However, the response depends on the historical context, because disruptions can magnify existing vulnerabilities and tensions. In cases where the societal context at the time was one of poverty, inequality, cuts to public services,

corruption or racial tension, then disruptions have been associated with disorder, violence and crime.

The literature overwhelmingly finds that impacts can be reduced via good communication and preparedness. Unplanned outages are difficult to prepare for, but the existence of good community amenities helps to mitigate the impacts of disruption. Many adverse health impacts could be avoided via better community provision, particularly by diverting non-emergency problems away from the hospital. Communication is key for reducing both anxiety and strain on public services: people's first need in a crisis is to know why it is happening, how long it is expected to last, and to be able to check that loved ones are safe. As communication shifts to mobile phones and internet, and away from copper phone lines and analogue radios, communication during an outage may become more problematic, yet the review found little information on the likely extent of availability of mobile phones and internet in the event of a prolonged outage.

An important factor in understanding societal impacts is the behaviour of interlinked infrastructures. There is a small body of literature on 'Infrastructure Failure Interdependencies' (IFIs), which sits almost entirely separately to the literature on impacts to individuals and households. Systems are becoming more tightly coupled, and IFIs could render the impacts non-linear, for instance if there are 'tipping points' when key sectors (e.g. telecommunications) run out of backup power and cease to operate. Case studies can help us to understand where these interdependencies lie, but are often incomplete, because the outage has been relatively short in duration or has been relatively localised, allowing supplies to be brought in from outside the affected area. There are gaps in understanding of IFIs for a long, widespread disruption in the UK, although there are significant methodological complications, including a lack of publicly available data. We know that water, gas, and communications have major two-way interdependencies – in other words, they may not be able to operate due to a loss of power (at least, not after a period of time, when their backup provisions run out), and this in turn could rebound onto the electricity system, causing further problems. Other sectors appear to be relatively understudied in the literature, particularly regarding shortages of labour and skills, which could be caused by disruption to transport systems, healthcare and education.

1.2 Areas for future work

This report identified the following key gaps in our understanding of the societal impacts of energy disruptions:

- The societal impacts of disruptions which are both *lengthy* and *widespread*; these are extremely rare, but the risk may be increasing in future.
- The likely impact of changes to the system over the next decade, particularly in terms of increasing reliance on information technology, changing user

expectations, decentralised and distributed energy generation, and decarbonisation objectives.

- Differences between urban and rural populations; in particular, the potential impacts on urban households is poorly understood.
- The difference between older and younger generations: older people may be more vulnerable to health problems and isolation, but also might have more experience of outages and be better prepared. Young urban populations may be more socially isolated and more dependent on electric devices.
- The lived experience of vulnerable people and fuel poor during an outage. Those experiencing fuel poverty have lower energy usage, and therefore may be less dependent on electricity; they may also be more used to dealing with a lack of power, for instance because of bill payment failure or deliberate disconnection. However, they may also experience compounding vulnerabilities such as physical and mental health difficulties and the presence of very old or very young members of the household.
- Infrastructure interdependencies in the UK, particularly in the case of a lengthy and widespread disruption, and whether there are ‘tipping points’ at which critical infrastructures cease to operate.
- The impact of a hydrogen transition on the resilience of the energy system, and the resilience of hydrogen-fuelled heating and transport infrastructures.

2. Introduction

The UK energy system is set to undergo considerable changes over the coming years. The UK has set a target for ‘net zero’ carbon dioxide emissions by 2050, legislated within the Climate Change Act, which means that every sector must be almost entirely decarbonised. Electricity in particular must decarbonise further and faster, to make up for more difficult-to-decarbonise sectors such as agriculture, and to enable the low-carbon electrification of heating and transport (Committee on Climate Change, 2019). Increasing penetrations of renewable energy sources will completely change the way electricity systems are run, with intermittency requiring increased flexibility of demand, and a more decentralised system as large fossil plants reach the end of their lifetimes (Evans and Pearce, 2019). Heating supply will have to change dramatically to meet the net zero goal, as natural gas must be phased out and replaced with either electric heating or hydrogen, which in turn could increase demand for electricity and put more strain on electricity systems at peak times. Energy demand is also changing, not least due to the rapid growth and penetration of ever-more sophisticated information and communication technologies, which will enable new energy practices, new working patterns, and new models of economic activity. These technologies create opportunities for smart, flexible management of energy supply and demand, but they also create challenges and risks, as businesses, households, and energy systems alike become increasingly reliant on technologies powered by electricity (Energy Research Partnership, 2018).

At present, large disruptions to energy supplies are rare in Western Europe. The majority of incidents affect only a small area (for instance, due to storms or flooding), or occur only for a short duration (for instance due to technical faults or human error). However, the combination of changes to the energy system, combined with stressors such as extreme weather caused by climate change, may bring new risks of disruptions to energy supplies, particularly electricity supplies (Bialek, 2020). Unanticipated shocks to energy supplies will likely never be completely avoidable; the nature of complex systems is that accidents will occur, and that these will often result from an unexpected combination of factors which is challenging to predict or avoid (Perrow, 1999). The growth of renewables and distributed generation have also led to a significant amount of new equipment and controls being added to the system in a very short space of time, causing some unknown interactions, and such a pace of change is likely to increase in the coming decades due to the decarbonisation imperative (Bialek, 2020). The National Research Council (2012) argue that electricity systems are now so complex and tightly coupled that there is no way of completely avoiding big outages, yet our dependence on electricity means that more than ever, we need to plan for these outages and be prepared for them.

Thus, in addition to making systems as reliable as reasonably possible, it is important to improve the *resilience* of a system – and of the society within which it operates – to shocks and stresses. Definitions of ‘resilience’ are numerous, and this in itself is a complex area of literature, covered in more detail in section 4.5 of this report. As a starting point, this report uses a definition from Bell (2019; Bell et al., 2020): resilience is the ability to prevent, contain, and recover from a disturbance to an end service, in this case the supply of energy to end users. In other words, planning for disruptions requires not only learning how to prevent them, but also how to contain the disruption so that it does not significantly impact the end user, and if necessary how to recover from it quickly and effectively, whilst minimising the impacts on those who are affected. This means that we also need to understand what happens *during* the disruption: how individuals, communities, businesses, and economies experience the event, how they act, and what measures can be taken to reduce the overall impacts to end users. There may also be trade-offs between efficiency and resilience; for example, ensuring that every sector has backup capability to continue operating during an outage will be extremely expensive, and often seen as economically sub-optimal when large disruptions occur very rarely.

This research sits within the UKERC project 'Resilience of the future energy system'. The overarching research question of the project is as follows: "How might risks to the energy system change in the future, and what will be the societal impacts associated with a lengthy, widespread disruption to energy supply?" This working paper focuses on the second half of this question: what are the impacts on energy system users? This part of the project will proceed alongside an engineering component assessing the main hazards and potential benefits to the changing energy system. The two parts will come together to determine what could be done to reduce the risks, and what societal and engineering interventions could be implemented to reduce the impacts to society. The purpose of this working paper is to identify the main topics which may be relevant to answering this question, to summarise the existing literature, and to identify knowledge gaps which the remainder of this project could help to fill.

'Disruption' is defined as a disturbance or problem which interrupts the supply of energy. In electricity terms, the focus is on complete loss of supply for a period of time, also termed an outage or blackout; this report does not consider drops in voltage magnitude or quality, known as 'brown outs', as these generally cause little impact for citizens. Use of the broader term 'disruption' means it is possible to include loss of other energy supplies (gas, diesel, hydrogen etc.), as well as interlinked critical infrastructures (see section 4.4), and the broader context surrounding the event. In this project, we are particularly interested in lengthy, widespread disruptions to energy supply, which have not been experienced in the UK in recent decades, but which might become more likely as the characteristics of the energy system change. 'Lengthy' is used here to mean a loss of supply lasting at least 24 hours, although this report considers a range of durations, with some interesting case studies lasting only an hour or so, and others lasting for several weeks. We are mainly interested in disruptions which affect a large area, for example a whole region of the UK. Again, this report considers a diversity of cases, and many case studies are based on fairly localised disruptions, but it is important to consider what may happen if supplies cannot be easily brought in from a nearby unaffected area.

It is also important to emphasise that this project focuses on *unplanned* disruptions, the most common of which are caused by extreme weather and by unexpected technical failure. There is a large literature on planned interruptions to energy supply, for example where rolling blackouts have been implemented to deal with a severe supply shortage (e.g. following the Fukushima disaster in Japan). However, previous work (RAEng, 2013) demonstrates that the societal impacts of these two types of outages are very different, and therefore difficult to consider side-by-side, because one of the most important factors in reducing impacts is communication and preparedness (see also C2ES, 2018; Heidenstrøm and Kvarnlöf, 2018; Rubin and Rogers, 2019). Planned outages generally allow citizens and businesses some time to prepare and to implement coping measures such as heating up water and shifting business operations to a different time. Planned outages are not insignificant, and can have severe economic consequences, but are outside the scope of this study.

3. Methods

A systematic review of the academic and grey literatures was carried out between September 2019 and March 2020, using the databases Google Scholar, Web of Knowledge, Scopus, and Google.co.uk. From the Google and Google scholar searches, only the first five pages of results were used, since the search terms often returned several hundred thousand hits, and after the first five pages they tended to become increasingly irrelevant. The Google.co.uk searches were appended with 'pdf' to return documents rather than web pages. No chronological boundary was set on the searches, yet the use of online sources only and search engine optimisation means that there will be a bias toward more recent studies. No geographical terms were used, yet as this is a UK study, papers with relevance to the UK context were prioritised when deciding what to read and what to include in this report. In particular, the large bodies of literature on energy access and electricity security in developing country contexts was not included.

The search was carried out using the terms shown in Table 1. The terms in the four columns were searched in all possible combinations. Search terms were determined according to the research question to identify the impacts of power outages on society. The terms in column 1 were selected to represent different ways of referring to power outages; in particular, different terms are often used in different countries. The search terms in column 2 were selected to identify a range of possible societal impacts: on society (soci*), communities, politics and political institutions, and the economy. Impacts on critical infrastructure sectors were identified early on as being an important area for research, therefore the term 'sector' was added as a blanket term to identify risks to a wide range of non-energy sectors. The search terms in column 4 were included on the basis of suggestions from a UKERC Theme meeting in October 2019, where it was suggested that gas, heating and hydrogen all represent important topics in terms of societal impacts, particularly as the UK is highly reliant on gas for space heating in winter.

Table 1: Search terms

Term 1	**Term 2**	**Term 3**	**Term 4**
Blackout	Soci*	Impact	[blank]
“Electricity shortfall”	Politic*	[blank]	Gas
Electricity AND resilience	Economic		Heat
“Power cut”	Communit*		Hydrogen
“Power outage”	Sector		

It is worth noting that the inclusion of the search terms in column 1 will have inevitably led to a focus on electricity system disturbances, regardless of whether any of the terms in column 4 are also included. There is good reason to believe that electricity disruptions will have a greater impact than gas disruptions, mainly due to the shorter timescales over which an electricity disruption occurs and because of the larger number of sectors which depend on electricity for their core operations (as discussed in section 4.4 on ‘critical infrastructure’). However, this means that important literatures on gas disruptions may have been missed using this search strategy; furthermore, this review does not provide evidence of a lack of literature on the impacts of losing gas supply. Another omission of note is the lack of oil or petroleum-related search terms, as some of the literature notes the dependency on petrol and diesel for transport and for backup generation.

Search terms such as ‘disruption’, ‘interruption’ and ‘disturbance’ were not included. This was to bound the study in terms of power outages only; including these terms would have opened up to a much broader range of disruptions, some of which may be relevant to this project, but would have made the review unmanageable with the available resources. Future work focusing on a range of types of disruption would be valuable, particularly as the recent Covid-19 situation has improved our understanding of societal responses to disruption, and behavioural responses may be similar in many ways (Cox, 2020). That said, this report highlights some unique dynamics of energy disruptions, particularly the extremely short timeframes over which an unplanned outage can occur, and the dependency of a number of critical infrastructure sectors on electricity.

The initial searches generated a large number of papers. The Web of Knowledge searches returned 2,255 results in total (without the inclusion of the narrower ‘impact’), although many of these will be duplicates. The Google Scholar and Google.co.uk searches generally returned results in the tens of thousands: for example, the search “blackout AND hydrogen AND soci*”, which only returned 15 papers on Web of Knowledge, generated 10,300 hits on Google Scholar, therefore only the first five pages were reviewed. Of the initial search results, many were irrelevant. For example, the search returned hundreds of papers on the impacts of alcohol-induced blackouts, where heavy drinkers cannot recall anything from the night before. As another example, there is a very large body of literature on nuclear plant operation and safety during a blackout scenario, because decades of research has gone into safety improvements to ensure that this would not lead to a nuclear accident; these were also omitted, as nuclear engineering is not the focus of the research question. It is quite common for papers focusing on technical questions – for instance, a new design for a nuclear reactor – to include a brief mention of societal impacts as part of the justification for the broader relevance of the paper. Therefore, papers which did not have societal dimensions as their focus were omitted from the final corpus. Of course, this is not to say that technical papers do not ever contain relevant insights; however, the number of papers returned by the initial searches meant that reading these in their entirety would have been unfeasible. Papers focusing solely on the *causes* of power outages were omitted, because they are not relevant to the research question which focuses on *impacts*, although papers which cover both topics were included. From reading the abstracts, introductions and conclusions of the remaining papers, the decision was made not to review in detail the large body of literature on measuring the economic impacts of outages. Economic impacts do comprise an important aspect of societal impacts; however, it became clear from the resulting papers that this body of literature is extremely large and outside the scope of a project which does not have economics as its main focus. This report does include a section on economic valuation of outages (section 4.3), focusing on recent UK studies which update the valuation review carried out in RAEng (2013); however, a thorough review of the econometric literature on the valuation of outages was not in scope.

The final corpus of relevant papers numbered 104, comprising 80 from the initial search, and 24 identified using snowballing from the reference lists of relevant papers. The papers are mainly from disciplines relating to the search terms, notably sociology, psychology, economics and engineering, but also span disciplines including history, health and medicine, communications, risk management, policy studies, architecture, and science and technology studies. Approximately 70% are academic (journal papers, conference papers and books); the remaining 30% comprise grey literature including policy papers, Select Committee reports, and reports by think tanks and NGOs. The vast majority of papers were published in the last 20 years, and around 50% in the last 5 years, reflecting the online bias mentioned previously. Spikes in the number of publications occur surrounding major events, most notably the New York blackout of 2003, which generated a number of relevant publications from 2003-2005. The search was also kept up-to-date using web alerts of the terms in column 1, in Scopus and Web of Knowledge, meaning that it was possible to include some more recent publications in this report.

The aim of the study was to scope literature relating to the core research question, therefore this account will not be exhaustive. In particular, the scoping study was restricted by resource constraints, and it was conducted by just one researcher working for four hours per week; therefore bias may have been introduced by not having another researcher to conduct blinded double-extraction.

4. Scoping review of existing literature

The main areas of literature identified by the review can be ordered into the following overlapping categories:

1) the impacts of outages on individuals and communities;
2) impacts on health and on vulnerable people;
3) economic impacts;
4) the impacts of outages on critical infrastructures and essential services;
5) papers on measuring, defining or building ‘resilience’ to outages and/or their impacts.

Much of the literature on the societal impacts of outages focuses on individuals and communities, therefore the first section is the largest. However, all the other topics are also crucial for determining societal impacts of unplanned disruptions, either because they create the basis for determining the impacts that society experiences (for example, in the case of critical infrastructures), or because they explore means of mitigating or minimising the societal impacts (particularly in the case of resilience).

4.1 Impacts on households and individuals

As this is a substantial body of literature, this report divides this topic into three: sociological accounts, historical analyses, and survey studies. All of these are fundamentally interconnected and overlapping; however, in general, sociological studies tend to look in detail at one or two major disruptions, whereas historical accounts tend to look across multiple events, although this distinction is not absolute. Some papers attempt to make predictions about the impacts of future or hypothetical disruptions, which are also covered in this section.

4.1.1 Sociological accounts

In an important paper for this review, Rubin and Rogers (2019) conduct a full review of existing knowledge on public responses during a power outage, revealing a total of 47 studies on the topic. The paper highlights seven key messages from the literature:

1) Preparing the public should reduce the impact of an outage
2) Vulnerable groups will need targeted help to prepare
3) Health communications are needed

4) Loss of communication infrastructure is likely to be a major stressor
5) Panic is unlikely
6) Acts of altruism will (probably) outweigh acts of criminality
7) Public information needs will focus on 'what has happened' and 'when will power be restored'.

The detailed findings of the review under each of these headings are all covered in the literature discussed in this section. The review thus shows that relatively good knowledge exists about 'what households do during an electricity outage', and thus provides a solid basis from which to determine gaps in the literature which this project could aim to cover. The authors identify a number of gaps, summarised in the concluding section of this report.

Several studies look at the impacts of unplanned energy disruptions on household energy practices, using Social Practice Theory (SPT) as a theoretical framework. These studies generally rely on interviews with individuals and households affected by an outage in the past. Ghanem et al. (2016) interviewed Welsh households affected by winter storms in 2014, and found that during disruptions, the 'linkages' between materials, competences and meanings are broken, and therefore practices are modified and new linkages made (see also Heidenstrøm and Kvarnlöf, 2018; Wethal, 2020). For example, people adapt their cooking practices, using makeshift cooking appliances and adapting by preparing simple meals; during this process, people accept new meanings for achieving comfort, and gain new knowledge about how to cope. Many papers demonstrate that the way in which households perceive outages can be decisive for their ability to feel comfortable during them. Participants expressed resilience in terms of 'making do' or 'making the most of it'. Generally, these SPT accounts find high degrees of community cohesion, and they identify the importance of informal networks of support when formal networks (e.g. government agencies or emergency services) become unavailable. However, emotions such as annoyance, discomfort, and even panic, were also expressed, and in some cases the disruption brought people face-to-face with vulnerability in their home.

Heidenstrøm and Hansen (2020) and Heidenstrøm and Kvarnlöf (2018) find similar results, in studies of Scandinavian households affected by severe gas and electricity outages, lasting weeks in some cases. They find that 'preparedness' (and thus, to some extent, 'resilience') is often underestimated by studies which focus on formal actions such as buying an emergency kit; rather, in the reorganisation and repurposing of existing materials and competences, households reveal themselves to be more prepared than expected. They argue that households generally become better prepared after experiencing a disruption; this means there may be differences between rural and urban households (as rural tend to experience more outages), and between generations. This could also be extended to off-grid communities, who in some senses may be said to voluntarily experience a lower degree of supply reliability; Heidenstrøm and Kvarnlöf (2018) found that cabin holidays, often without electricity or running water, are an important part of life for many Scandinavians, and increases their preparedness for what to do during an outage. In the UK, rural households are often off the gas grid, meaning that they have other means of cooking and keeping warm available to them, such as wood fires (Ghanem et al., 2016; Rinkinen, 2013); meanwhile urban households may feel that future outages are unlikely (even after experiencing one), and that therefore it isn't worth preparing (Brayley et al., 2005; Rubin and Rogers, 2019). A Norwegian study found that people attach strong meanings of autonomy and even pride to their choice to live in a rural area which is prone to power outages, and that community autonomy exists alongside a sense of disdain for those unprepared or unable to cope (Wethal, 2020). Research in Norway also finds that urbanisation is negatively associated with local social relationships and a sense of community, which may decrease social resilience (Heidenstrøm and Hansen, 2020); however, this must be contrasted with the work from New York in 2003, which found an emerging sense of community amongst people who didn't know one another, at least for the duration of the blackout (Nye, 2010; Yuill, 2004).

The Norwegian studies also illustrate the importance of national context: Norway has abundant hydroelectricity, and the majority of heating and cooking is electric with very little household reliance on gas or oil. Rinkinen (2013), in a Finnish SPT study, finds that in disruptive situations, people change from passive consumers to active participants, which in turn opens up the boundaries of what is considered 'normal'. However, they also found very little evidence of any persistent behaviour changes after the event. Practices are dynamic, and what is 'normal' can shift over time; for example, the growth of Information and Communication Technology (ICT) has increased dependence on electricity services (Becker et al., 2016). There is a gap in the literature around how the societal impacts of outages might shift in response to expected changes in the energy system in the short- to medium-term, in particular as many significant changes will be required before 2030 in order to meet UK climate change goals (see section 4.5 on 'resilience').

Societal cohesion is a central theme in a study by Yuill (2004), who walked the streets of Brooklyn during the 2003 outage in the North-East US and identified a shared spirit of community not normally found in New York, along with a 'heightened sense of being'. Initial reactions to an outage often include anxiety, anger and frustration, but a Twitter sentiment study (Li et al., 2020) showed that sentiment normalises after approximately 90 minutes of outage, with negative reactions being balanced by positive ones including reports of altruistic behaviour and improvisation such as impromptu street performances. Several studies report low crime and an increase in 'social altruism'. Crime epidemics and looting are rare, and even in places where disaster victims are taking shelter, crime rates may remain stable despite drastic temporary demographic changes (Lemieux, 2014). Reports of 'looting' tend to be mainly opportunistic theft, showing that it is important to be cautious about media hyperbole when reading accounts based on media reports.

Storms provide valuable case studies for understanding what happens during an unplanned disruption. RAEng (2016) conducted a case study of a large floodinduced outage in Lancaster. This study drew on data from an expert workshop and is therefore missing insights from householders, but covers the impacts on communications, education, healthcare, retail & banking, transport, gas, water & sewage. Emergency backup in the water and sewage infrastructures generally functioned as expected, and water supplies were not impacted; however, many flats experienced a loss of water due to the loss of the pumps used to get water to higher floors. The gas stayed on throughout, largely due to portable generating sets used by the National Grid gas network, and the fact that most gas system assets were outside of the area of the outage. However, larger-area disruptions might be more vulnerable to gas supply problems if the area cannot benefit from supplies from outside the area. Furthermore, because the study only spoke to stakeholders, it may have missed the fact that most home boilers will not work without electricity, meaning that even if gas supplies are unaffected, many homes will still be without gas for heating (Ghanem et al., 2016).[1] This also illustrates the importance of adequate scenario setting, because impacts will be entirely dependent on what caused the outage in the first place: in Lancaster, some of the major damage was caused by flooding, which hampers restoration attempts, but an outage due to snow or severe cold could have more serious societal impacts due to lack of gas heating.

One of the main issues identified by RAEng was a lack of community gathering spaces, with hospitals becoming the default space for people to meet, charge phones and get information about the situation (see section 4.2 on 'health'). Further evidence from the UK comes from a Scottish Affairs Committee (2013) report into storm-induced outages in the West of Scotland in 2012. The submissions from members of the public give insight into the lived experience of an unexpected outage during a severe winter storm in a remote area, where some houses were without power, gas, water, communications or road access for more than seven days. Most praised the workers and emergency services, and spoke of community resilience, but also expressed anger at the power company. Villages felt 'forgotten about'; deliveries of hot food and drink never arrived; communications were disrupted. One villager argued that by day four of an outage, 'helping vulnerable people' is somewhat misplaced because everyone has become highly vulnerable by that point: for example, most people had run out of gas for their stoves, and food supplies were running low. These accounts contrast with the submissions from the Distribution Network Operator (DNO) and from Ofgem, who voice pride in a fantastic response to a particularly challenging weather situation, and view their societal and contractual obligations as having been fulfilled.

Most of our UK-based understandings of lived experience during unplanned disruptions are from rural areas, because most unplanned disruptions in urban areas are short-lived, our understanding of large disruptions in urban areas mainly stem

---

[1] The impact on cooking of a disruption to electricity, but not gas supply, is not entirely clear. Pry (2017) argues that stoves require electric ignition, yet it is unclear from their report why people can't simply use matches/lighters to light their hobs, if the gas supply stays on. However, dependency on electricity for cooking may be increasing with the introduction of induction stoves. Any disruption to gas supplies would create problems for heating and cooking for a large proportion of UK homes.

from non-UK contexts. Rubin and Rogers (2019) note that the evidence base for societal responses to outages is rather thin, because most rely on small, opportunistic samples, which may be skewed, for instance if some people feel they have a more interesting story to tell than others.

4.1.2 Historical accounts

The studies in this section generally seek to identify trends from large numbers of incidents, comprising disruptions of different causes, durations and size. Nye (2010), in an historical account of US power outages starting with the invention of electricity, argues (similarly to some of the SPT papers) that they constitute a 'liminal space' in which people cease to be customers, commercial activity ceases, and people improvise new activities. Yet overwhelmingly, historical comparison reveals that what happens depends on underlying social conditions. Accounts of community cohesion during the 2003 New York event (e.g. Yuill, 2004) can be contrasted with accounts of the 1977 New York blackout, which revealed a fractured society marked by opportunistic crime, looting, and chaos which rapidly outstripped the ability of the police forces to respond (Sugarman, 1978). Nye (2010) finds that there are many possible reactions, from panic and anger to solidarity and euphoria; which of these predominates is shaped by the historical context, meaning that the social impacts of one disruptive event will not predict the social impacts of the next. Pescaroli and Alexander (2016) argue that certain underlying societal factors, such as corruption, negligence, maximisation of profit, and the structural weaknesses of the global socio-economic system, can all act to increase vulnerability. Policy measures which decrease social capital are likely to increase vulnerability, as found in fuel poverty studies in the UK following austerity policies which cut funding to community services (Middlemiss and Gillard, 2015).

Matthewman and Byrd (2014) and Pry (2017) use media accounts from a large number of historical outages to predict what might occur in a large-scale outage of long duration. Both find that major impacts occur in terms of economic damage (covered further in section 4.3 on 'economic impacts'), food safety, water provision, crime, and transport; however, media reports should be treated with caution, as they are far more likely to report negative impacts. Pry finds that one of the largest issues is in provision of clean water, but that in most cases, the utilities managed to restore water service before it became a major health crisis (in Montreal, this restoration of power averted a State-planned evacuation of the entire city. Another key issue was heating food, which led to health impacts from burning charcoal and gas indoors, and an increase in house fires. Meanwhile Petermann et al. (2011) use media reports and other accounts to conduct a hypothetical account of a prolonged, wide-ranging power outage in Germany; the report is dystopian when compared to most case studies, particularly in its prediction of complete societal breakdown within four days, but the report could be useful as a 'worst-case' scenario. Finally, Pescaroli et al. (2017) describe the direct and indirect threats to life during an outage. They argue that emergency planning shouldn't focus on triggers, but on underlying vulnerabilities e.g. technical failures associated with management cultures and production pressure, and that wider attention should be given to societal resilience as a whole.

Many historical analyses focus on the causes of severe electricity/gas outages. This is not the focus of this project, and will therefore not be covered in detail here; however, a key aspect of this project will be in defining the relevant scenario or scenarios of interest, which could build on previous work on the causes of outages. Globally, the most common causes of electricity outages are transmission line failure, equipment malfunction, and bad weather; in almost all cases, an initial event leads to a series of trips which cascades causing a widespread power outage (CIGRE, 2015, 2010; Haes Alhelou et al., 2019). Matthewman and Byrd (2014), Nye (2010) and Perrow (1999) all note that outages are systemic failures, and that the likelihood of an outage doesn't increase linearly: there are 'tipping points', some within the electricity system itself, some within interdependent infrastructures (see section 4.4 on 'critical infrastructure'). In the UK, electricity outages tend to create problems with household gas supply, rather than the other way around (Pant et al., 2020)**.** An interesting question for this project will be how these interlinked systems develop in the future, particularly if hydrogen becomes a key heating fuel. This study conducted a specific search for papers on hydrogen, but did not find anything of relevance.

4.1.3 Survey studies

The majority of survey studies aim to identify the monetary value of security of supply, addressed in section 4.3 on 'economic impacts'. The review found relatively few survey studies on social impacts of outages – this may be due to methodological constraints, or it may be a deliberate choice of study authors, to use qualitative methods to understand *why* people act or respond in a certain way. Palm (2009) uses a combination of survey and follow-up interviews in Sweden, and found that people weren't prepared for a long loss of power and started to struggle with water, heat and light after around 24 hours. There were communication problems (see also Scottish Affairs Committee, 2013): the main platform used by the authorities was the internet, but most didn't have internet access during the outage, and contacting the grid company was impossible due to an overloaded switchboard. There was anger at the companies involved, and a widespread perception that outages should be considered unacceptable. Similarly, UK citizens feel that they pay for a constant supply and therefore that is what they should receive, and that energy is considered a modern necessity and even a basic human right (Brayley et al., 2005; Demski et al., 2018; Thomas et al., 2020). Interestingly, though, in a survey conducted 18 months after two brief outages in London and Birmingham, only 60% actually recalled the incident, and less than 50% were concerned about a repeat incident (Brayley et al., 2005). This illustrates the methodological challenges facing researchers of disruptions, in that people may struggle to recall details of incidents which happened in the past (see also Heidenstrøm and Kvarnlöf, 2018).

4.2 Health and vulnerability

Many studies on the societal impacts of outages mention, at least in passing, the potential for impacts on human health. Hospital admissions, emergency call-outs, and overall mortality have all been found to increase during outages (Anderson and Bell, 2012; Freese et al., 2006; Klein et al., 2005). Some of the most common health-related problems are fires caused by candles or gas stoves, carbon monoxide poisoning due to indoor cooking, food poisoning from lack of refrigeration or inability to heat food, trips and falls, traffic accidents due to loss of traffic signals, and cardiac arrest due to stress or exertion. During the New York blackout in 2003, 911 calls increased by 103%; despite the loss of traffic signals, response times remained good, but the call processing time increased five-fold due to lack of capacity at the 911 call centres (Freese et al., 2006). Mental health problems may also increase, particularly in socio-economically deprived areas with high existing rates of alcoholism and depression (Lin et al., 2016).

Hospitals are generally well-placed to cope with outages, although they struggle with the increased demand, and can experience congestion (Rubin and Rogers, 2019). During the 2003 New York blackout, all hospitals were able to provide adequate patient care for the duration of the blackout (Klein et al., 2005). Four of 75 hospitals in the area lost power, for a maximum duration of 2h45 (Beatty et al., 2006). Problems experienced by hospitals included internal and external communications, loss of heating and A/C, loss of elevators and equipment, and trouble accessing patient records due to loss of computers. Loss of transport and the closure of schools creates staffing problems, demonstrating the importance of considering knock-on impacts from other sectors. Backup generators for hospitals cannot be considered a fully adequate response; a review of several outages across 19 countries in 2011-12 found that backup generators often fail due to age or poor maintenance, or may be damaged by co-occurring problems such as flooding (Klinger et al., 2014). During Hurricane Rita in the US, five hospitals lost power for an average of 4.8 days; the longest hospital outage was 11 days (Ibid.).

Importantly though, a considerable proportion of the increase in hospital admissions and emergency calls is actually due to the loss of other services in the community. For example, people can’t access online medical services or their local doctor, so they call for an ambulance, or go to hospital as they know it will have backup power (Freese et al., 2006; Klein et al., 2005; Klinger et al., 2014). Many of the additional hospital admissions are related to failures of home equipment such as oxygen machines, dialysis, and medication refrigeration, a trend which is increasing as technology advances mean more people can be cared for in their own homes (Anderson and Bell, 2012; Smallbone and Staniland, 2011). Much of this could be mitigated via better community provision, such as distributing oxygen, distributing lists of open pharmacies and doctors surgeries, publicising available transport options, and ensuring that home carers know what to do in the event of an outage (Klein et al., 2005; Smallbone and Staniland, 2011).

As discussed above, there may be considerable differences in the impact of outages on different groups. In particular, certain groups might be more vulnerable. Vulnerability to disruptions is, broadly, determined by three things: exposure (for example, being in a location more susceptible to hazards); sensitivity (groups with characteristics meaning they are more likely to be affected such as the elderly); and ‘adaptive capacity’ (the ability to respond and recover from an event) (Connon, 2019;

Hinkel, 2011; Middlemiss and Gillard, 2015). Societal factors such as income and marginalisation play an important role in adaptive capacity. Studies from weather-related blackouts in the United States find that disruptions tend to compound existing vulnerabilities. For example, Chakalian et al. (2019) found that white, higher income, and households with fewer elderly or young inhabitants were the least vulnerable. Mitsova et al. (2018) found a positive correlation between outage duration and multiple social vulnerability indicators, with longer outages experienced by areas with high proportions of Hispanic and Latino residents. Liévanos and Horne (2017) found that disadvantaged communities experienced slower reconnection times, as they are located further away from priority reconnection zones such as central business districts; they are also more likely to have older houses and lower-quality infrastructure. However, it is unclear from the existing literature whether the same could be said for the UK, as higher population density and different history of urban planning in the UK means that poorer districts are not necessarily located on weaker parts of the network.

The UK has a particular issue with fuel poverty, due to old housing stock and generally poor home energy efficiency. The fuel poor have lower power consumption, but are more likely to be reliant on electric heating, and are more likely to have other vulnerabilities such as poor mental and physical health or small children (Electricity North West, 2018). Less energy efficient housing increases the likelihood of thermal discomfort in the event of an outage (Baniassadi and Sailor, 2018; Ghanem et al., 2016). Those in fuel poverty may also have less access to backup or preparedness options for heating and cooking, such as wood fires or camping stoves; in this way, it could be useful to explore the materials and competences available to those in fuel poverty, to see whether it contrasts with the experiences of those in the SPT studies above. Connon (2019) found that young migrants in the UK are a severely vulnerable group during outages, experiencing poor-quality housing, fuel poverty, and precarious employment; casualised labour and long hours mean that they often lack social ties in the local area, reducing their adaptive capacity. Experience of racism and hostility increases vulnerability, because people perceive that they are not welcome to make use of local services or community help in the event of an emergency. Older migrants on the other hand appear to be more resilient, with stronger local networks and knowledge of local services, as well as higher preparedness (see also Heidenstrøm and Hansen, 2020).

The relationship between age and vulnerability to outages is complex: older people could be a vulnerable group, but could also be more used to blackouts, or be better prepared (Rubin and Rogers, 2019)**.** A statistically representative Norwegian study found that older residents stated better preparedness relating to previous experience with outages (Heidenstrøm and Hansen, 2020). However, a disproportionate number of falls occur during outages (ibid), which can be fatal for elderly people. Households interviewed in Wales following an outage noted vulnerabilities relating to chronic illnesses and age (Ghanem et al., 2016). An Age UK (2016) report finds that many elderly people are proud of their independence, feel prepared for outages, and have community and family support they can rely on. However, others are extremely isolated, with 2.9 million elderly in the UK saying they have no-one to turn to. Their study participants reported many concerns regarding their reliance on electric heating, which implies that people may be unaware that gas boilers will also fail during an electricity outage. Priority Services Registers are designed to ensure that the most vulnerable get help in the event of a water or power outage, but they generally struggle with low registration; in the UK, most elderly people are unaware of the existence of the Register or of their DNO, and in the US, only 38% of home dialysis patients have notified their utility (Age UK, 2016; Klinger et al., 2014). Maintaining an up-to-date Priority Services Register is challenging, particularly because those most likely to benefit are sometimes isolated or without internet, and responsibility for identifying vulnerable individuals often falls to third sector organisations or the individuals themselves. Civic responses could provide low-cost resilience for vulnerable groups, for instance a 'buddy' system which would pair able-bodied volunteers with elderly, vulnerable and infirm residents for assistance during an outage. Some communities may already have similar systems of support, but these operate on an informal basis**,** and isolated individuals may not benefit (Ghanem et al., 2016; Heidenstrøm and Kvarnlöf, 2018; Palm, 2009).

4.3 Economic impacts

There is a large literature on the value of energy security and the monetisation of security impacts. This is not the focus of this project, but it does provide some necessary basis for understanding the existing research on societal impacts. There are a selection of recognised methods for valuing the economic impacts of disruptions, each of which have their share of limitations; see RAEng (2013) for a review. This section covers a small number of interesting papers which have emerged since that review.

The most common way of valuing loss of electricity is the 'Value of Lost Load' (VoLL), a figure in £/MWh, usually calculated using surveys in which electricity consumers (individuals, households or businesses) are asked how much they would be willing to pay to avoid an outage (WTP), or how much compensation they would be willing to accept to endure an outage (WTA). Recent VoLL studies from Electricity North West (a DNO) conclude that the average VoLL has increased, reflecting increased reliance on electricity (Electricity North West, 2018). High VoLL is found in rural areas, low-income households, and vulnerable groups. Regarding outage duration, they find (in line with previous VoLL work) that outage impacts do not increase linearly: the marginal hourly value declines steadily, flattening off completely for very long durations. Importantly, this is the opposite of the 'tipping points' view discussed in the Critical Infrastructure section. This may reflect a limitation of the WTA/WTP methodology, because people may view longer outages as outside of the control of the DNO and thus see less requirement for compensation, or it may be because people simply cannot envisage the impacts of a long outage. This disparity between the two bodies of literature represents a gap in knowledge. Finally, Electricity North West find higher VoLL amongst those with heat pumps and electric vehicles, demonstrating one way in which societal impacts increase with the introduction of new low-carbon technologies (see also Energy Research Partnership, 2018). However, it is important to note that WTA/WTP studies reflect *perceived* vulnerability, and this may differ from actual vulnerability, particularly amongst those households with very little outage experience. For example, those without heat pumps might assume that the gas heating will stay on during a power outage. However, there was no difference in VoLL for rooftop solar owners: this is surprising, because we might expect solar PV owners to feel less vulnerable, despite the fact that the array generally won't work during an outage (National Academies of Sciences, Engineering and Medicine, 2017), see section 4.5 on 'resilience'). The UK National Infrastructure Commission (2020) notes that WTP/WTA methods do not capture willingness or ability to cope with failure, and suggests that this constitutes a gap in our current understanding of UK resilience.

Electricity North West (2018) find that VoLL is lower amongst those who had experienced an outage, supporting research on outage preparedness by Heidenstrøm and Hansen (2020). However, von Selasinsky et al. (2017) argue that previous studies show conflicting results on the impact of experiencing an outage on valuations, and found the opposite in their study. They also suggest that outages increase perceptions of importance of security of supply relative to other objectives including environmental sustainability; therefore, frequent outages could erode support for low-carbon transitions. Becker et al. (2016) also make this point, noting that in policy trade-offs between objectives, there is never any attempt to capture the socio-psychological debate on the level of security of supply which might be societally *optimal.* Thus, monetary valuation is insufficient, and groups should instead be disaggregated according to their practices, preferences and goals. Several aspects other than timing, duration and location are important for valuing the cost, including the type of end-user, the degree of advanced notification received, the perceived reliability of the system, and expectation setting (Shivakumar et al., 2014).

A body of literature focuses on valuing costs to an entire economy, beyond simply households. This adds an additional layer of complexity, particularly in light of the infrastructural interdependencies discussed in the next section, but is not our main focus here. A few papers are of interest, though. Schmidthaler and Reichl (2016) present their 'blackout simulator', an ongoing, open-source website which can value the total economic costs of a given outage in the EU+UK, by region, date and duration. It uses a novel econometric approach, employing production-function data, VoLL calculations for indirect damages, and WTP survey data from >8000 households. Meanwhile Poudineh and Jamasb (2015) estimate 12-hour outage costs for Scotland using sophisticated modelling which takes account of sectoral interdependencies. They find that some sectors such as coal and gas are the least able to operate during an outage; however, the biggest economic losses occur in health, public administration, defence and education. Gas inoperability would be important, because of the reliance of UK households on gas for heating and cooking; interdependencies between electricity and gas are discussed in the following section. Interestingly, they find that the 'societal cost of energy not supplied' doesn't change much with the magnitude of the outage, although duration had a big impact. Electricity North West (2018) concluded that it is difficult to measure whether VoLL increases or decreases if a wider area is affected, although anecdotal evidence suggests that if the whole community is affected, societal cohesion may increase; yet some of the sociological accounts report people relying on those outside of the affected area for supplies and communication (e.g. RAEng, 2016). Clearly, more needs to be understood about the impact of size of area affected on outage impacts.

4.4 Critical Infrastructure

As noted above, one of the most challenging aspects to study is the interdependency between sectors, which is increasing over time. Such interdependencies may result in ‘tipping points’ whereby the impact of an outage becomes swiftly non-linear, for instance with the failure of a key linked sector such as water supply. This section first reviews the literature on critical infrastructure interdependencies, followed by a look at two of the most critical sectors, communications and natural gas.

Much of the literature on critical infrastructures focuses on electricity, because of its central role in almost every sector and its potential to cause cascading failures across multiple sectors. For example, Pant et al. (2020) aimed to model the impacts of single points of failure on other sectors, using different sets of assumed interconnections between sectors; they found that ~40% of modelled UK electricity failures led to further disruptions in other sectors, with a further 20% leading to further electricity system failures. Single failures in the electricity network had the potential to cause the largest disruption, of around eight million users per day across all networks, mainly due to the knock-on effect on the water network. Interestingly however, they suggest that even in the case of a four day outage, loss of water would not necessarily create further electricity losses from things like loss of water to cool power stations. They also find that electricity disruptions tend to cause gas disruptions, rather than the other way around; similarly, Portante et al. (2017) find that electricity disruptions due to loss of gas are generally small and can be managed using spinning reserves. Electricity system outages can have quite abrupt impacts on the gas system, whereas there is usually a notice period before gas disruptions start to impact the electricity system, during which time electricity system operators can take steps to limit the impact. However, Portante et al. also demonstrate that the exact impacts depend on the characteristics of the system, such as the proportion of gas-fired power in the generation mix, and the availability of alternative gas supply routes.

Chang et al. (2007) and McDaniels et al. (2007) developed a conceptual framework characterising the nature, extent and severity of Infrastructure Failure Interdependencies (IFIs), drawing on interdependency characteristics from Rinaldi et al. (2001). They characterise the impacts of IFIs in terms of impact, duration, the number of people affected, and the spatial extent, using subjective judgement of media reported impacts. Various alternative methods have been developed for identifying IFIs, many using workshops with experts. Seppänen et al. (2018) recommend an ongoing process of iterative workshops, which proceed until all participants are happy with the outcome, although there is a trade-off between this approach and cost/practicality (their study uses six workshops in total). Hogan (2013) used a similar process to define IFIs for a fictional town (loosely based on

London), using 103 stakeholders from 54 organisations. Their results give a good indication of the types of IFIs which are likely to arise from an electricity failure, across sectors including health, telecoms, water, transport, emergency services, and environment. However, they note the real challenges arising from lack of data availability and lack of strong evidence, which much of the available evidence being anecdotal. RAEng (2011) used expert elicitation to assess infrastructure interdependencies in the UK, focusing on changes in resilience which might occur as the result of climate change. Infrastructures are often co-located, meaning that some of the greatest future threats to interdependent infrastructures could be due to flooding of assets such as power stations and substations. Finally, Laugé et al. (2015) take an international approach, surveying critical infrastructure experts from multiple countries, and asking them to grade the dependency of their sector on other sectors on a scale from 0 to 5. They find that for a long-duration energy failure, most sectors' dependencies are at the maximum magnitude of "my sector cannot operate". The biggest interdependencies stem from loss of ICT, which would have a big impact on most critical infrastructures even for <2 hours. They also note the importance of second-order effects: for example, a health sector failure doesn't directly impact transport, but it does affect order and safety (1.67 magnitude), which in turn affects transport (0.8 magnitude). However, these sorts of questionnaire approaches cannot tell us what actually causes the interdependencies.

In the event of a large power disruption, water, natural gas, and communications systems will be impacted, and will have two-way interdependencies with electricity. Momeni et al. (2018) set out to map and model IFIs in the power-water-gas nexus, and argue that one of the biggest impacts is in disruption to the monitoring and control systems (SCADA), although most larger facilities have backup power. In Lancaster, which is fed by two reservoirs, backup power in the water sector generally worked effectively, although it is unclear what backup exactly was available where this was located, or how long supplies would have lasted for (RAEng, 2016)**.** The report also notes that the situation would have been very different in a community reliant on water towers which have a much lower capacity. Fedora (2004) finds that SCADA systems did indeed go down following the 2003 outage; on-site backup power was sufficient in this case to maintain gas supply, but the event took place in the summer when gas demand is generally low. All backup and safety systems at gas control/compression sites functioned correctly; however, at least one instance of gas derating directly affected the reliability of the New York System Operator. Comes and de Walle (2014) find that during Hurricane Sandy, oil refineries were shut down and gas tanks and pipelines were inoperable due to power loss.

Communications networks are reliant on electricity, yet they are vital for reducing the impacts of a disruption, allowing people to plan and prepare and reducing anxiety (Ghanem et al., 2016; RAEng, 2013)**.** However, increasingly people do not own radios or landline telephones, and are entirely reliant on the internet and social media for communication in the event of an outage**.** A San Diego case study (15h unplanned disruption) found that the cell phone system experienced considerable degradation and overloading, yet many respondents were surprised that their phone didn't work, and 60% attempted to use social media at least hourly (Jennex, 2012).

This might indicate important generational differences, which may partly explain the somewhat counter-intuitive finding by Chakalian et al. (2019) that households with elderly residents experienced lower anxiety, even when controlling for generator ownership. Mobile phone networks in the UK are not regulated to provide any specific amount of backup power, and Ofcom state that backup power for mobile networks would be 'prohibitively expensive' (RAEng, 2016). However, regulation is not a silver bullet: in the US, mobile providers are required to provide eight hours of backup power, yet in practice often fail to provide these hours of service (Jennex, 2012). Many protection measures also assume the use of mobile generators, which would be severely oversubscribed in the event of a large outage: in the West Scotland storms, the 30MW of mobile generation deployed included almost all large units north of London (Scottish Affairs Committee, 2013). Households impacted by that disruption commented that "the worst thing was not knowing what had happened" because of phone and internet failures, and a lack of effort by the DNOs to communicate using other channels; they suggest that resilience could be increased by providing battery radios for the most vulnerable households, and using leaflets and local notice boards to inform people.

Another important case study is the UK disruption which occurred in the UK on August 9, 2019. The recent occurrence of this event means that when this review was conducted, there was a lack of in-depth analyses of the incident, and no academic publications. However, it is important to mention, because it constitutes the largest UK electricity disruption in recent years, cutting off approximately 1.1 million people for around 40 minutes. Like many large disruptions, it occurred due to an unexpected combination of events occurring simultaneously (Bell, 2020; Bialek, 2020). The incident demonstrated the importance of critical infrastructure interdependencies, because the largest impacts to citizens and the economy occurred not because of the loss of electricity per se, but because of the resulting disruption to the rail network, with massive delays affecting thousands of passengers and people stuck on trains for hours (Bell, 2020). Digital on-board monitoring systems in some of the newer trains led to an automated shut-down in response to the drop in electricity supply frequency; due to a recent software upgrade, the trains could not be restarted, and had to wait for a technician to come out with a laptop (ORR, 2020). The stranded trains and resulting timetabling problems led to train delays and cancellations lasting several days. The incident demonstrates the potential for automated systems to increase reliance on electricity and vulnerability to outages, particularly in the case of new systems with which operators are unfamiliar. The event also revealed an important IFI which may not have been apparent otherwise, whilst demonstrating the challenges of predicting or avoiding IFIs, as they are often caused by an unfortunate and entirely unexpected combination of events occurring over a short space of time.

4.5 Resilience

Underpinning this project is the notion of 'resilience'. Bell (2019) reviews four existing perspectives on resilience, and notes that resilience is often misinterpreted as being only concerned with extreme events; yet the circumstances for an 'extreme' event are often created by a series of small, often unnoticed, events (see also CIGRE, 2010; Perrow, 1999). Certain forms of extreme weather are becoming more likely with climate change, and this is indeed a major potential stressor on the future system (RAEng, 2011); however, other important threats include increased reliance on technology and networks, more complex interdependencies between sectors, the growing economic importance of metropolitan centres, and cyber-security issues (Energy Research Partnership, 2018; National Infrastructure Commission, 2020). Bell also notes that conceptions of resilience are frequently only concerned with recovery from an event; yet more relevant to us is what happens *during* an event, and how people and equipment behave during unplanned disruptions. Thus Bell proposes a definition of resilience as “prevention + containment + recovery”. There may be a trade-off between resilience and efficiency: the RAEng (2016) Lancaster study notes that some actors in their case study had strategic incentives (such as profits) to pursue efficiency at the expense of resilience. As large-scale disruptions are rare, planning for future resilience may require us to ‘think the unthinkable’ (National Academies of Sciences, Engineering and Medicine, 2017) and it is often challenging to make the economic case for investing in measures such as backup capacity which might be used rarely or never (Pettit et al., 2013). A recent report by the UK National Infrastructure Commission (2020) recommends that government reviews the UK resilience standards, and that regular ‘stress tests’ are conducted to ensure that systems can meet these standards.

Numerous studies discuss how to build the resilience of systems, communities or individuals to disruptions. Broadly, these strategies can be viewed as two categories: system resilience, which includes backup generation, line hardening, distributed generation, microgrids, and islanding to limit the cascading of disturbances; and social resilience, defined as “the ability of communities to withstand external shocks to their social infrastructure” (Adger, 2016: 361), which might include communication networks, community spaces where people can gather, energy efficiency measures to ensure less heat loss (or gain) from buildings, community preparedness, and early warning systems (C2ES, 2018; Energy Research Partnership, 2018; Ghanem et al., 2016; National Academies of Sciences, Engineering and Medicine, 2017; National Research Council, 2012; RAEng, 2011). Backup capability can significantly improve resilience, particularly in the first 10-30 hours, and many of the worst impacts and failures in other infrastructures can be avoided if power is restored within 30 hours (Pant et al., 2020). C2ES (2018) note that many resilience measures may have co-benefits: for example, putting some of these systems in place before an outage occurs may reduce greenhouse gas emissions or air pollution, and many have benefits for public health. However, there may also be unexpected trade-offs; for instance, Distributed Generation such as rooftop solar doesn’t usually operate in the event of an outage, due to automatic safety mechanisms which ‘trip off’ the unit in response to an electricity network voltage or frequency fluctuation, yet owners usually assume that their panels will work during an outage, and are thus less prepared and may experience more anxiety or frustration (C2ES, 2018). The most common form of resilience is diesel generators, yet they need to be maintained, and the failure rate tends to be high; meanwhile microgrids may be dependent on gas

CHP, which would be vulnerable to a loss of gas supply (National Academies of Sciences, Engineering and Medicine, 2017).

Another way of enhancing overall resilience is to identify the key low-cost buildings, equipment or sectors which cause the most disruption when lost, and provide backup power to these only. National Research Council (2012) argue that backup could be provided for just a few ATMs and petrol stations, as well as traffic lights which use practically no power and can be supported with small trickle-feed batteries. Narayanan and Morgan (2012) model a widespread, long-duration power outage, and consider the technical specifications and cost of a distributed generation system which could provide power to a police station (which also serves as a community hub), several petrol stations, a grocery store, one school, cell phone towers, and street lights. However, their system relies on gas, on the assumption that gas supplies are not disrupted, which may not be the case for a long, widespread outage. For the UK, culture and population density mean that petrol stations may be less crucial than in the US (especially in the future, when more EVs could be in use); however, providing electricity and gas to one small shop or café could significantly increase resilience, because it could also function as a source of information, a phone charging point, and a place to get hot food and drinks. In the West of Scotland, a local tearoom became a vital community hub and a source of both physical and social resilience to the inhabitants (Scottish Affairs Committee, 2013). Similarly, in Lancaster, people converged on the hospital as the only place with power; providing a separate community hub would thus ease the strain on vital health services.

Finally, there is a body of literature examining the provision of resilience in response to longer-term outages, such as those caused by a major industrial accident, explosion, or chronic grid mismanagement or undersupply (IEA, 2005). Aggressive electricity demand reduction minimises the disruption and thus minimises the social and economic impacts, for example immediately following the Fukushima disaster in Japan, when electricity demand reduction was a key facet of power restoration. A city in Alaska achieved a 40% reduction in daily electricity consumption for around two months following an avalanche, equating to a 25-30% reduction in year-on-year electricity consumption when correcting for seasonal weather (Pasquier, 2011). A campaign in Brazil, in response to electricity shortfalls caused by a severe drought, cut total electricity consumption by 20% and sustained this for several months of total electricity demand, and during the California grid crisis in 2001, one third of homes managed to reduce their electricity consumption by >20% (Meier, 2006). In this sense, buildings can be a major source of resilience, because improving buildings efficiency can not only save power to allow faster restoration, but can also genuinely save lives in the event of an outage occurring during severe cold or hot weather: during Hurricane Sandy, 50 people died of hypothermia as a result of the power outage (C2ES, 2018). This literature also illustrates the importance of adequately defining the source of the disruption, because this affects whether changes to practices are needed at all times, or just at times of peak load.

It is worth briefly mentioning the potential importance of hydrogen in a future low-carbon system, and exploring the implications of this for system and societal resilience. The literature on hydrogen includes some papers on microgeneration, because using hydrogen for a stand-alone microgeneration system or fuel cell can provide power in the event of a blackout. This has also been explored in the context of telecoms, as potentially one of the key end-users for a hydrogen backup system (cf. Crouch, 2011). A Canadian study in the context of a two day blackout (Mukherjee et al., 2017) employs the implementation of the energy hub concept to optimally design and operate energy generation systems to meet energy loads of a community, using solar PVs, wind turbines, electrolysers, hydrogen tanks, fuel cells and fuel cell vehicles. The drawback is cost: even using existing market mechanisms for the power services offered, the system doesn't pay for itself before the end of its lifetime. Meanwhile Kwasinski and Krein (2007) argue that hydrogen is not a good option for long or large outages, because of the likelihood of damage to transportation systems in the event of a weather- or disaster-induced disruption, and thus problems of getting hydrogen delivered. The question of what happens to hydrogen-reliant infrastructures, including for heating and transport, appears to be unexplored in the current literature, although RAEng (2016) do note that diesel buses were quite resilient to the power cut, whereas it's unlikely that a fleet powered by electricity or hydrogen would have been so resilient. Finally, Pant et al. (2020) find that in modelled outage scenarios for interdependent UK infrastructures, heating systems based on hydrogen are more resilient than those based on electricity, because 20-40% of the disrupted load can be provided by bidirectional storage from electric vehicles (in other words, using electric vehicles as large batteries); in a system heavily dependent on electricity for heating, the domestic load is too great for this to be possible.

5. Discussion: areas for future work

This section seeks to identify gaps from the literature reviewed, and to set out directions for further research.

Many studies note differences between individuals and households with certain characteristics, which affects how they experience disruptions. However, these differences are not always well understood, and could be explored further. For instance, there may be differences between *urban* and *rural* areas, yet most of the information on outages comes from rural areas, and there is some disparity between the Social Practice Theory (SPT) literature, which suggests that rural households may be better prepared and more self-sufficient, and the economic literature, which suggests that VoLL is higher in rural areas. The majority of literature is based on rural areas, therefore we have little understanding about urban areas, which may possess lower social/community resilience. Rural areas are often off the gas grid, which could create major differences, because the rest of the UK is reliant on gas for heating and cooking. *Generational* differences might also be important, particularly due to differences in degrees of reliance on the internet and social media, differences in outage experience, and general vulnerability, and it is not entirely clear from the existing literature whether lived experience of unplanned disruptions is more or less severe for younger generations. The *area* of the disruption is underexplored in the existing literature, partly because large-area outages in the UK are exceedingly rare. Larger-area blackouts might be more vulnerable to gas, water and comms disruptions if the area cannot benefit from supplies from outside the area. Geospatial mapping of these linked infrastructures would be highly valuable, but may be outside the reasonable scope of this project. Finally, *duration* is crucial, yet most of the existing literature is based on short disruptions; Ghanem et al. (2016) note that in focusing on a shorter disruption, they were unable to capture the richer details of daily electricity use. The review also identified a disparity between the economic literature (in which value of supply security decreases with longer duration) and the critical infrastructures literature (in which longer durations result in 'tipping points' which increase the value of supply security). Exploring unplanned disruptions of longer durations with infrastructure interdependencies could help to shed light on this.

This review noted a number of gaps in our understanding of Infrastructure Failure Interdependencies (IFIs). Much of the existing literature on IFIs relies on media reporting of past events, which has a tendency to be somewhat dystopian. Identifying IFIs during a long, widespread outage has not been attempted for the UK previously, and there is clearly a need for better understanding of the degree of resilience of crucial systems, which could in turn facilitate an understanding of when 'tipping points' are likely to occur. For example, in the Lancaster case study, central water and sewage services were largely unaffected (RAEng, 2016), but it is unclear how long backup power would have lasted in the event of a longer duration, or what the impacts might have been if the outage took place over a larger area. Other sectors may also be important, and have generally not been explored in the IFI literature: for example, we know that the health sector is likely to be fairly resilient to outages as most large health centres have backup power, but the education sector has not been considered. If power or heating are disrupted in schools, key workers will need to stay home to take care of their children, which has a knock-on effect on other sectors, including power restoration. Overall, this review demonstrates that there are two bodies of literature, one on societal impacts and one on IFIs, which appear to operate almost entirely separately. Yet infrastructure failures, and the tipping points they imply, will have a considerable impact on the lived experience of outages, therefore there is a need to bring these two bodies of literature together into a more holistic understanding.

The review by Rubin and Rogers (2019) identifies some additional gaps in our understanding of how people behave during an outage: negative emotional impacts, particularly for longer outages; evacuation behaviours; effectiveness of communications campaigns; and impacts on fuel poor households. In terms of fuel poverty, we have evidence regarding valuation of supply security, but not necessarily on lived experience. Most studies exploring lived experience have been based either on disruptions of relatively short duration, or based on extreme weather (particularly Hurricanes) wherein it is difficult to disentangle the impacts of the power disruption from the impacts of the storm itself. Much UK experience stems from experience of flooding, which may indeed be a major cause of unplanned disruptions in the future, yet there are many other possible causes of future disruption, particularly as we transition to a low-carbon system. The evidence base for social impacts tends to rely on opportunistic samples which may be skewed, therefore research using other types of sample could be useful, for instance using topic-blind recruitment (in other words, recruiting people without telling them what the topic is in advance, thereby reducing sampling bias).

Adequate scenario setting is crucial, and it may be useful to include scenarios which do not involve extreme weather. In particular, disruptions caused by a changing energy system may impact large demand centres such as cities. Researching events which have not yet happened creates considerable methodological challenges, but the importance of creating a resilient energy system for the future means that attempting to fill this knowledge gap would be valuable for policy. Scenario setting will also need to include consideration of how interlinked electricity/gas/hydrogen systems are likely to develop in the future, and consideration of how user needs and expectations are changing, particularly around ICT technology. There may also be scope for exploring different scenarios for system restoration, thus exploring multiple aspects of 'resilience'; restart of essential services is often not accounted for in models, but is important, as illustrated by the failure of the trains to restart after the 2019 UK blackout. Finally, scenario setting could consider changing socio-political contexts, because the evolution of energy systems will be social as well as technical, and the social context is a crucial determinant of impacts. UKERC has previously conducted research on UK energy security under different socio-technical scenarios (Watson et al., 2018). For example, we could consider how the scenario might change in a context of nationalism (e.g. reduced interconnection, Bell et al., 2020), or a context of increased progressiveness (e.g. more funding for community-level resilience). Such scenarios might enable us to explore whether there are underlying societal factors in the UK which may increase vulnerability, and how to increase societal resilience to disruptions.

6. References

Adger, W.N., 2016. Social and ecological resilience: are they related?: Prog. Hum. Geogr. https://doi.org/10.1191/030913200701540465

Age UK, 2016. Older people and power loss, floods and storms. Age UK, London.

Anderson, G.B., Bell, M.L., 2012. Lights Out: Impact of the August 2003 Power Outage on Mortality in New York, NY. Epidemiology 23, 189–193. https://doi.org/10.1097/EDE.0b013e318245c61c

Baniassadi, A., Sailor, D.J., 2018. Synergies and trade-offs between energy efficiency and resiliency to extreme heat – A case study. Build. Environ. 132, 263–272. https://doi.org/10.1016/j.buildenv.2018.01.037

Beatty, M.E., Phelps, S., Rohner, C., Weisfuse, I., 2006. Blackout of 2003: Public Health Effects and Emergency Response. Public Health Rep. 121, 36–44. https://doi.org/10.1177/003335490612100109

Becker, S., Schober, D., Wassermann, S., 2016. How to approach consumers' nonmonetary evaluation of electricity supply security? The case of Germany from a multidisciplinary perspective. Util. Policy 42, 74–84. https://doi.org/10.1016/j.jup.2016.06.012

Bell, K., 2020. What happened on August 9th – the investigations. UKERC. URL https://ukerc.ac.uk/news/august-9-investigations/ (accessed 10.21.20).

Bell, K., 2019. Resilience and reliability.

Bell, K., Bedford, T., Colson, A., Barons, M., French, S., 2020. Elicitation of Structured Expert Judgement to estimate the probability of a major power system unreliability event (48th CIGRE session No. C1-112). CIGRE, Paris.

Bialek, J., 2020. What does the GB power outage on 9 August 2019 tell us about the current state of decarbonised power systems? Energy Policy 146, 111821. https://doi.org/10.1016/j.enpol.2020.111821

Brayley, H., Redfern, M.A., Bo, Z.Q., 2005. The Public Perception of Power Blackouts, in: 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific. Presented at the 2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific, IEEE, Dalian, China, pp. 1–5. https://doi.org/10.1109/TDC.2005.1547156

C2ES, 2018. Resilience strategies for power outages. Center for Climate and Energy Solutions, Arlington, VA.

Chakalian, P.M., Kurtz, L.C., Hondula, D.M., 2019. After the Lights Go Out: Household Resilience to Electrical Grid Failure Following Hurricane Irma. Nat. Hazards Rev. 20, 05019001. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000335

Chang, S.E., McDaniels, T.L., Mikawoz, J., Peterson, K., 2007. Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. Nat. Hazards 41, 337–358. https://doi.org/10.1007/s11069-006-9039-4

CIGRE, 2015. Lessons learnt from recent emergencies and blackout incidents (C2 Study Committee Report No. 608). Conseil international des grands réseaux électriques, Paris.

CIGRE, 2010. Planning to manage power interruption events (Working Group C1.17 Report No. 433). Conseil international des grands réseaux électriques, Paris.

Comes, T., Ven de Walle, B., 2014. Measuring Disaster Resilience: The Impact of Hurricane Sandy on Critical Infrastructure Systems, in: Proceedings of the 11th International ISCRAM Conference. University Park, Pennsylvania, p. 10.
Committee on Climate Change, 2019. Net Zero: the UK's contribution to stopping global warming. UK Committee on Climate Change, London.
Connon, I.L.C., 2019. Young, mobile, but alone in the cold and dark: Experiences of young urban in-migrants during extreme weather events in the UK, in: Rivera, F.I. (Ed.), Emerging Voices in Natural Hazards Research. Butterworth-Heinemann, Oxford, pp. 357–391. https://doi.org/10.1016/B978-0-12-815821-0.00021-7
Cox, E., 2020. The psychology of disruptive events: finding a 'new normal.' UKERC. URL https://ukerc.ac.uk/news/psychology-of-disruptive-events/ (accessed 10.23.20).
Crouch, P., 2011. Fuel Cell Systems for Base Stations: Deep Dive Study. GSMA Green Power for Mobile, London.
Demski, C., Poortinga, W., Whitmarsh, L., Böhm, G., Fisher, S., Steg, L., Umit, R., Jokinen, P., Pohjolainen, P., 2018. National context is a key determinant of energy security concerns across Europe. Nat. Energy 3, 882–888. https://doi.org/10.1038/s41560-018-0235-8
Electricity North West, 2018. Value of Lost Load to Customers (Customer Survey (Phase 3) Key Findings Report No. NIA ENWL010). Electricity North West, Warrington.
Energy Research Partnership, 2018. Future resilience of the UK electricity system: Are we resilient to meet the needs of this rapidly changing world? Energy Research Partnership, London.
Evans, S., Pearce, R., 2019. How the UK transformed its electricity supply in just a decade [WWW Document]. Carbon Brief. URL https://interactive.carbonbrief.org/how-uk-transformed-electricity-supply-decade/ (accessed 9.3.20).
Fedora, P.A., 2004. Reliability review of North American gas/electric system interdependency, in: 37th Annual Hawaii International Conference on System Sciences, 2004. Proceedings of The. Presented at the 37th Annual Hawaii International Conference on System Sciences, 2004. Proceedings of the, IEEE, Big Island, HI, USA, p. 10 pp. https://doi.org/10.1109/HICSS.2004.1265195
Freese, J., Richmand, N.J., Silverman, R.A., Braun, J., Kaufman, B.J., Clair, J., 2006. Impact of Citywide Blackout on an Urban Emergency Medical Services System. Prehospital Disaster Med. 21, 372–378. https://doi.org/10.1017/S1049023X00004064
Ghanem, D.A., Mander, S., Gough, C., 2016. "I think we need to get a better generator": Household resilience to disruption to power supply during storm events. Energy Policy 92, 171–180. https://doi.org/10.1016/j.enpol.2016.02.003
Haes Alhelou, H., Hamedani-Golshan, M., Njenda, T., Siano, P., 2019. A Survey on Power System Blackout and Cascading Events: Research Motivations and Challenges. Energies 12, 682. https://doi.org/10.3390/en12040682
Heidenstrøm, N., Hansen, A.R., 2020. Embodied competences in preparedness for blackouts: Mixed methods insights from rural and urban Norwegian households. Energy Res. Soc. Sci. 66, 101498. https://doi.org/10.1016/j.erss.2020.101498

Heidenstrøm, N., Kvarnlöf, L., 2018. Coping with blackouts: A practice theory approach to household preparedness. J. Contingencies Crisis Manag. 26, 272–282. https://doi.org/10.1111/1468-5973.12191
Hinkel, J., 2011. "Indicators of vulnerability and adaptive capacity": Towards a clarification of the science–policy interface. Glob. Environ. Change 21, 198–208. https://doi.org/10.1016/j.gloenvcha.2010.08.002
Hogan, M., 2013. Anytown: Final Report (A DEFRA funded project - Community resilience funding for local resilience forums in England). London Resilience Team, London.
IEA, 2005. Saving electricity in a hurry - dealing with temporary shortfalls on electricity suppliers. International Energy Agency, Paris.
Jennex, M.E., 2012. Social Media – Viable for Crisis Response?: Experience from the Great San Diego/Southwest Blackout. Int. J. Inf. Syst. Crisis Response Manag. 4, 53–67. https://doi.org/10.4018/jiscrm.2012040104
Klein, K.R., Rosenthal, M.S., Klausner, H.A., 2005. Blackout 2003: Preparedness and Lessons Learned from the Perspectives of Four Hospitals. Prehospital Disaster Med. 20, 343–349. https://doi.org/10.1017/S1049023X00002818
Klinger, C., Landeg, O., Murray, V., 2014. Power Outages, Extreme Events and Health: a Systematic Review of the Literature from 2011-2012. PLoS Curr. https://doi.org/10.1371/currents.dis.04eb1dc5e73dd1377e05a10e9edde673
Kwasinski, A., Krein, P.T., 2007. Telecom power planning for natural and man-made disasters, in: INTELEC 07 - 29th International Telecommunications Energy Conference. Presented at the INTELEC 07 - 29th International Telecommunications Energy Conference, IEEE, Rome, Italy, pp. 216–222. https://doi.org/10.1109/INTLEC.2007.4448770
Laugé, A., Hernantes, J., Sarriegi, J.M., 2015. Critical infrastructure dependencies: A holistic, dynamic and quantitative approach. Int. J. Crit. Infrastruct. Prot. 8, 16–23. https://doi.org/10.1016/j.ijcip.2014.12.004
Lemieux, F., 2014. The impact of a natural disaster on altruistic behaviour and crime. Disasters 38, 483–499. https://doi.org/10.1111/disa.12057
Li, L., Ma, Z., Cao, T., 2020. Leveraging social media data to study the community resilience of New York City to 2019 power outage. Int. J. Disaster Risk Reduct. 51, 101776. https://doi.org/10.1016/j.ijdrr.2020.101776
Liévanos, R.S., Horne, C., 2017. Unequal resilience: The duration of electricity outages. Energy Policy 108, 201–211. https://doi.org/10.1016/j.enpol.2017.05.058
Lin, S., Lu, Y., Justino, J., Dong, G., Lauper, U., 2016. What Happened to Our Environment and Mental Health as a Result of Hurricane Sandy? Disaster Med. Public Health Prep. 10, 314–319. https://doi.org/10.1017/dmp.2016.51
Matthewman, S., Byrd, H., 2014. Blackouts: a sociology of electrical power failure (Working Paper).
McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., Reed, D., 2007. Empirical Framework for Characterizing Infrastructure Failure Interdependencies. J. Infrastruct. Syst. 13, 175–184. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:3(175)
Meier, A., 2006. Operating buildings during temporary electricity shortages. Energy Build. 38, 1296–1301. https://doi.org/10.1016/j.enbuild.2006.04.008
Middlemiss, L., Gillard, R., 2015. Fuel poverty from the bottom-up: Characterising household energy vulnerability through the lived experience of the fuel poor. Energy Res. Soc. Sci. 6, 146–154. https://doi.org/10.1016/j.erss.2015.02.001

Mitsova, D., Esnard, A.-M., Sapat, A., Lai, B.S., 2018. Socioeconomic vulnerability and electric power restoration timelines in Florida: the case of Hurricane Irma. Nat. Hazards 94, 689–709. https://doi.org/10.1007/s11069-018-3413-x
Momeni, A., Prasad, V., Dharmawardena, H.I., Piratla, K.R., Venayagamoorthy, K., 2018. Mapping and Modeling Interdependent Power, Water, and Gas Infrastructures, in: 2018 Clemson University Power Systems Conference (PSC). Presented at the 2018 Clemson University Power Systems Conference (PSC), IEEE, Charleston, SC, USA, pp. 1–8. https://doi.org/10.1109/PSC.2018.8664050
Mukherjee, U., Maroufmashat, A., Ranisau, J., Barbouti, M., Trainor, A., Juthani, N., El-Shayeb, H., Fowler, M., 2017. Techno-economic, environmental, and safety assessment of hydrogen powered community microgrids; case study in Canada. Int. J. Hydrog. Energy 42, 14333–14349. https://doi.org/10.1016/j.ijhydene.2017.03.083
Narayanan, A., Morgan, M.G., 2012. Sustaining Critical Social Services During Extended Regional Power Blackouts: Sustaining Critical Social Services. Risk Anal. 32, 1183–1193. https://doi.org/10.1111/j.1539-6924.2011.01726.x
National Academies of Sciences, Engineering and Medicine, 2017. Strategies for reducing the harmful consequences from loss of grid power, in: Enhancing the Resilience of the Nation’s Electricity System. National Academies Press, Washington, DC.
National Infrastructure Commission, 2020. Anticipate, React, Recover - resilient infrastructure systems. National Infrastructure Commission, London.
National Research Council, 2012. Strategies for securing crucial services and critical infrastructure in the event of an extended power outage, in: Terrorism and the Electric Power Delivery System. National Academies Press, Washington, DC.
Nye, D.E., 2010. When the Lights Went Out: A History of Blackouts in America. MIT Press, Cambridge, MAS.
ORR, 2020. Report following railway power disruption on 9 August 2019. Office of Rail and Road, London.
Palm, J., 2009. Emergency Management in the Swedish Electricity Grid from a Household Perspective. J. Contingencies Crisis Manag. 17, 55–63. https://doi.org/10.1111/j.1468-5973.2009.00557.x
Pant, D.R., Russell, M.T., Zorn, D.C., Oughton, D.E., Hall, J.W., 2020. Resilience study research for NIC - Systems analysis of interdependent network vulnerabilities. Environmental Change Institute, Oxford University.
Pasquier, S.B., 2011. Saving Electricity in a Hurry: Update 2011. International Energy Agency, Paris.
Perrow, C., 1999. Normal Accidents: Living with High Risk Technologies. Princeton University Press, Princeton, NJ.
Pescaroli, G., Alexander, D., 2016. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Nat. Hazards 82, 175–192. https://doi.org/10.1007/s11069-016-2186-3
Pescaroli, G., Turner, S., Gould, T., Alexander, D., Wicks, R., 2017. Cascading effects and escalations in wide area power failures (No. 2017– 01), UCL IRDR and London Resilience Special Report. Institute for Risk and Disaster Reduction, University College London.
Petermann, T., Bradke, H., Lüllmann, A., Poetzsch, M., Riehm, U., 2011. What happens during a blackout: consequences of a prolonged and wide-ranging

power outage (No. 4), Technology Assessment Studies Series. Office of Technology Assessment at the German Bundestag, Berlin.
Pettit, T.J., Croxton, K.L., Fiksel, J., 2013. Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. J. Bus. Logist. 34, 46–76. https://doi.org/10.1111/jbl.12009
Portante, E.C., Kavicky, J.A., Craig, B.A., Talaber, L.E., Folga, S.M., 2017. Modeling Electric Power and Natural Gas System Interdependencies. J. Infrastruct. Syst. 23, 04017035. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000395
Poudineh, R., Jamasb, T., 2015. Electricity supply interruptions: Sectoral interdependencies and the cost of energy not served for the Scottish economy (OIES Paper No. EL 12). Oxford Institute for Energy Studies, Oxford.
Pry, P.V., 2017. Life without electricity: storm-induced blackouts and implications for EMP attack (Report to the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack). US Congress, Washington, DC.
RAEng, 2016. Living without electricity: one city's experience of coping with loss of power. Royal Academy of Engineering, London.
RAEng, 2013. Counting the cost: the economic and social costs of electricity shortfalls in the UK (A report for the Council for Science and Technology). Royal Academy of Engineering, London.
RAEng, 2011. Infrastructure, Engineering and Climate Change Adaptation – ensuring services in an uncertain future. Royal Academy of Engineering, London.
Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K., 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. IEEE Control Syst. Mag. 21, 11–25. https://doi.org/10.1109/37.969131
Rinkinen, J., 2013. Electricity blackouts and hybrid systems of provision: users and the 'reflective practice.' Energy Sustain. Soc. 3. https://doi.org/10.1186/2192-0567-3-25
Rubin, G.J., Rogers, M.B., 2019. Behavioural and psychological responses of the public during a major power outage: A literature review. Int. J. Disaster Risk Reduct. 38, 101226. https://doi.org/10.1016/j.ijdrr.2019.101226
Schmidthaler, M., Reichl, J., 2016. Assessing the socio-economic effects of power outages ad hoc: An application of BLACKOUT-SIMULATOR.com covering 266 European regions, 9 economic sectors and households separately. Comput. Sci. - Res. Dev. 31, 157–161. https://doi.org/10.1007/s00450-014-0281-9
Scottish Affairs Committee, 2013. Power outages in the West of Scotland (Written Evidence). House of Commons, London.
Seppänen, H., Luokkala, P., Zhang, Z., Torkki, P., Virrantaus, K., 2018. Critical infrastructure vulnerability—A method for identifying the infrastructure service failure interdependencies. Int. J. Crit. Infrastruct. Prot. 22, 25–38. https://doi.org/10.1016/j.ijcip.2018.05.002
Shivakumar, A., Welsch, M., Taliotis, C., Howells, M., Dražen, J., Tomislav, B., 2014. Estimating the socio-economic costs of electricity supply interruptions (Rapid Response Energy Brief No. 2). Insight_E, KTH, Stockholm.
Smallbone, C., Staniland, K., 2011. Care in the community: what would happen if the lights went out? Br. J. Community Nurs. 16, 342–346. https://doi.org/10.12968/bjcn.2011.16.7.342

Sugarman, R., 1978. Power/energy: New York City's blackout: A $350 million drain: Ripple effects off the July 13, 1977, lightning stroke cost the public dearly in lost property, services, end income. IEEE Spectr. 15, 44–46. https://doi.org/10.1109/MSPEC.1978.6367753
Thomas, G., Demski, C., Pidgeon, N., 2020. Energy justice discourses in citizen deliberations on systems flexibility in the United Kingdom: Vulnerability, compensation and empowerment. Energy Res. Soc. Sci. 66, 101494. https://doi.org/10.1016/j.erss.2020.101494
von Selasinsky, A., Schubert, D.K.J., Meyer, T., Möst, D., 2017. Valuing security of supply: does experience matter? Int. J. Energy Sect. Manag. 11, 195–207. https://doi.org/10.1108/IJESM-03-2015-0001
Watson, J., Ketsopoulou, I., Dodds, P.E., Chaudry, M., Tindemans, S., Woolf, M., Strbac, G., 2018. The security of UK energy futures (UKERC Research Report). UK Energy Research Centre, London.
Wethal, U., 2020. Practices, provision and protest: Power outages in rural Norwegian households. Energy Res. Soc. Sci. 62, 101388. https://doi.org/10.1016/j.erss.2019.101388
Yuill, C., 2004. Emotions after Dark - A Sociological Impression of the 2003 New York Blackout. Sociol. Res. Online 9, 34–41. https://doi.org/10.5153/sro.918

7. Appendix 1

Synthesis table from Rubin & Rogers review of the literature on types of public reactions to outages, key patterns within the literature, and implications (2019: 3)

Type of reaction	Key patterns	Implications
Preparedness	• Possession of supplies and knowledge are beneficial • Barriers to preparedness include belief that power outage is unlikely • Prior experience of an outage and a sense of self-sufficiency lead to greater preparedness	Attempts to increase preparedness should address risk perceptions
Changes in daily routine	• Need for warmth is a key driver of behaviour changes, with a risk of carbon monoxide poisoning if heaters are used incorrectly • Poor food hygiene behaviours are likely, leading to increased gastrointestinal illness • Loss of communication is likely to be distressing • Other behaviour changes relate to attempts to adapt, rather than radically alter, existing routines	Public health messages are needed to reduce the health effects of some behaviours Restoring communication will reduce levels of distress
Evacuation	• Limited data suggest any evacuation is likely to be calm, and becomes more likely to occur as an outage continues	Policy makers should not focus on mass panic as a key concern
Information seeking	• Key information needs are “what has happened” and “when will power be restored” • Trust in information sources is partly determined by their perceived level of knowledge about the situation	Prioritise information about what has happened and when the supply will return
Altruism and criminality	• Panic is not reported in the literature • Reports of altruism and helping behaviours are common, and might be increased by official encouragement to help one another • Widespread criminality is rare	Policy makers should not focus on mass panic as a key concern Seeking ways to promote altruism may be beneficial
Emotional impact	• Power outages can trigger a sense of ‘cosiness’ • This is less likely for those with caring responsibilities, livestock, or poor preparedness. • Longer outages are more likely to induce anger	Attempts to increase preparedness are important
Potentially vulnerable groups	• Potentially vulnerable groups include older adults, those with mental illness and people reliant on electrically powered medical devices. • Risks include failure of medical devices, need for medication, falls, and reduced social support.	Helping potentially vulnerable groups prepare should be a priority