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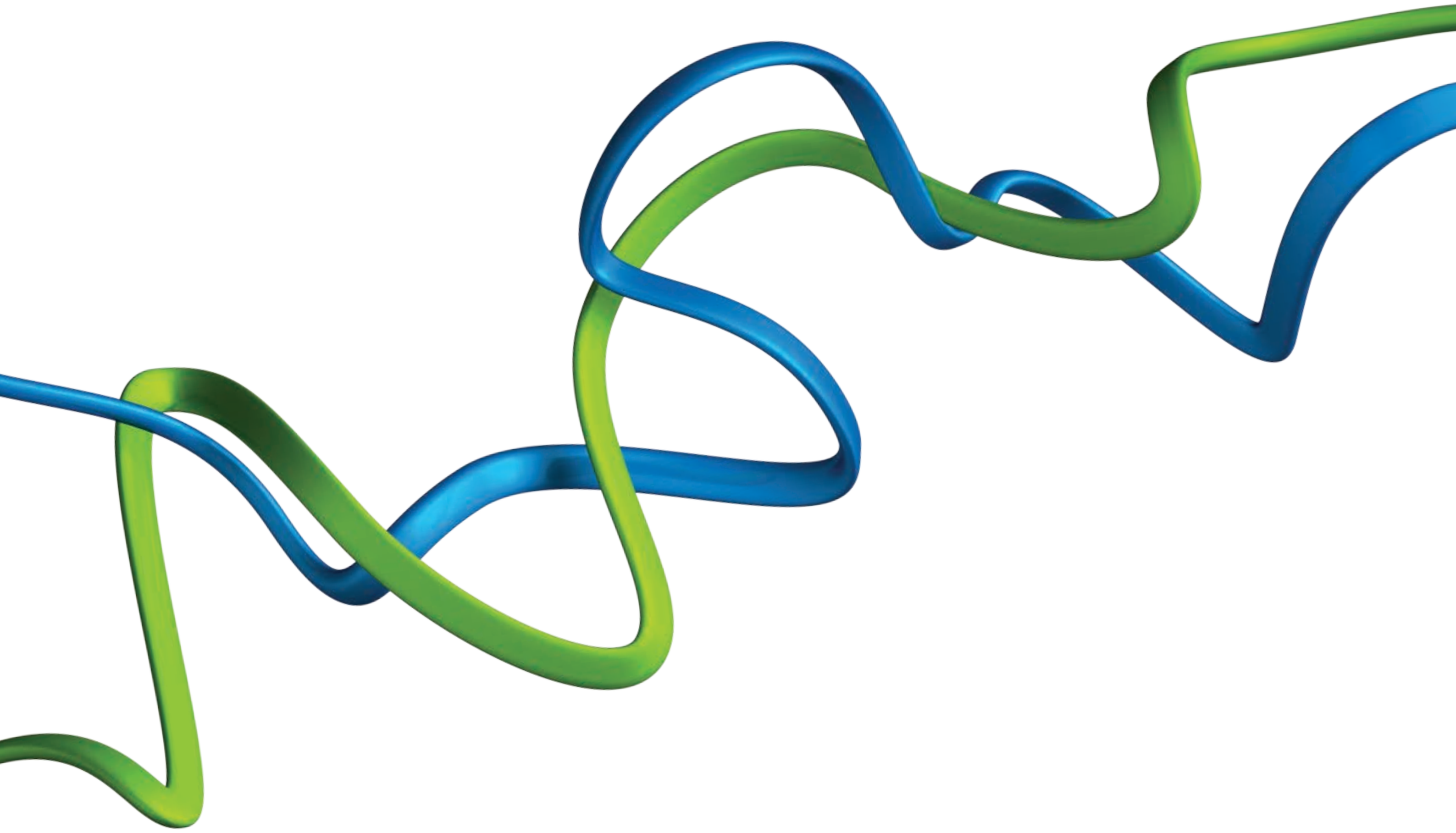
# **Counting the cost:** the economic and social costs of electricity shortfalls in the UK

## A report for the Council for Science and Technology

November 2014



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# Executive summary

The Royal Academy of Engineering was invited by the Prime Minister's Council for Science and Technology (CST) to undertake research into the economic and social costs and impacts that would result from shortfalls in electricity supply, within specific sectors and across the UK economy as a whole. The objective of this report is to assess the available evidence base on the potential costs of electricity shortfalls. This is useful because it helps policymakers to understand the cost/benefit trade-off from investing in greater levels of capacity or resilience to disruption.

Research on the costs and impacts of electricity shortfalls in the UK is relatively limited compared to much of Western Europe. This report aims to identify and provide insight into existing research in this area, in particular some of the key uncertainties that arise when attempting to quantify the economic impacts of shortfalls. This report considers some of the broader economic and social concerns that might arise, and identifies areas in which further research would be beneficial. It should be noted that this report does not seek to assess the likelihood of outages arising from lower capacity margins and does not imply that the kinds of outages and shortfalls discussed in the report are likely to occur in the UK.

The study was carried out by means of a workshop and interviews with Fellows of the Royal Academy of Engineering, the electricity and manufacturing industries, experts from academia, think tanks and consultancies. Analysis of case studies of relatively recent blackouts from elsewhere in the world offer qualitative insight into potential economic and social impacts. Desk-based research was carried out to provide an overview of existing research on this topic.

## Key findings

Any significant interruption to electricity supply in the UK will have severe economic consequences. The UK is becoming rapidly more dependent on electricity, and networks, processes and value chains are becoming increasingly complex and interdependent. These trends are magnified by increasing reliance on electronic communications technologies and the internet. The potential economic and social impacts of electricity shortfalls will, therefore, only continue to increase in the future. However, the pace of change means that our understanding of the potential magnitude of these impacts is constrained by limited knowledge about the knock-on consequences that could occur across the economy and society. Evidence from previous economic modelling and from international case studies suggests that the economic impact of a severe and widespread outage (ie affecting the vast majority of the UK, including major cities for at least 12 hours during a weekday) would potentially cost billions of pounds; however, estimates are complicated by high uncertainty and lack of reliable and comparable data. Finally, it is worth noting that future shifts in the energy system may further increase the UK's dependence on electricity, particularly if heating and transport become more electrified. This could heighten the detrimental impacts of electricity outages in the future.

In general terms, there are two main ways of examining the potential economic and social costs of electricity shortfalls. The first uses economic methods to assess the costs to consumers and to the economy as a whole; several possible technical methodologies, that are discussed in Section 3 of the report. The most commonly-accepted means of assessing the economic costs of electricity supply interruptions is through estimating the value of lost load (VoLL), in £/MWh. This report finds very high levels of uncertainty within existing estimates of VoLL in the UK. In particular, considerable discrepancies exist between cost estimates from different methods of calculation. Moreover, estimates of VoLL are highly sensitive to the characteristics of the outage, in particular the timing, duration, location and sector or social grouping affected. VoLL should therefore be viewed as a range that is dependent upon all these factors, rather than a single-point figure. Evidence on the costs of more frequent outages is extremely limited, meaning that there would be very high uncertainty in attempting to estimate VoLL in the context of a capacity shortage.

The second means of examining potential costs involves looking at real-world examples of previous outages. There are several relatively recent examples of severe blackouts from around the world; analysis of these case studies can provide a broader overview of impacts and can be a useful corollary to technical economic analysis. Six case studies are presented in Section 5 of the report, and are described in detail in Appendix B. Overall, existing data on these examples are found to be somewhat patchy, but there is significant consistency between the case study evidence and other evidence presented in the report.

The large variation between different estimates of VoLL means that, from existing research, no concrete conclusions can be made on the cost of electricity supply interruptions. It is important to note that VoLL is not a value-neutral measure; it is a measure of people's *perceptions* of the value of a unit of electricity. This report aims to highlight the risks of basing high-value cost/benefit decisions on such uncertain estimates of VoLL; developing a robust assessment of the costs of electricity shortages will require significantly more in-depth consideration.

The study has not revealed any recent real-world examples of blackouts leading to considerable social unrest; indeed people generally appear to cope fairly well with short-duration disruptions. A nationwide outage lasting for longer than 48 hours could, however, have a severe impact on society; however, this type of scenario is so unlikely in the UK that the actual impacts are impossible to model with any degree of robustness. Nevertheless, it is likely that significant adverse political impacts would result from any kind of electricity shortfall, especially because historically high levels of security of supply mean that people are accustomed to – and feel that they have a right to – continuous power supply.

Perceptions of decreasing security of supply could have considerable implications for policies by reducing confidence in the government to manage the electricity infrastructure effectively, which, in turn, could put pressure on government policy and potentially deter investment. If the UK were perceived or demonstrated to have an unreliable energy infrastructure, this would be factored into future siting or investment decisions by global companies. Industry representatives interviewed for this study expressed the view that energy security issues are climbing up the industry agenda in the UK, because of the increasing complexity of manufacturing processes, increasing interdependency between sectors and within supply chains, and a perceived decrease in security of supply. It is important to note that many industrial and commercial processes are increasingly reliant on a continuous, high-quality power supply, especially where just-in-time supply chains are used. Because of this, interruptions or voltage sags for even a couple of seconds could have an extremely detrimental impact upon operations, and therefore would impact GDP and could deter investment. This is an important area for more in-depth research and consideration.

There are a number of relatively low-cost measures that can be taken to mitigate economic and social costs of shortfalls. Costs can be significantly reduced by improving communication, and it is vital that plans for communication in the event of an outage are regularly reviewed and updated in light of the rapid advancement of state-of-the-art communications technology. Costs can also be mitigated by improved planning and phasing of outages, in particular to avoid peak load times for various sectors. Demand-side response represents a promising low-cost option for reducing both the likelihood and impact of electricity shortfalls. Finally, communities and social networks are vital resources for increasing resilience to disruptions and for mitigating impacts, especially for the most vulnerable members of society.

## Key uncertainties and areas for further analysis

Considering the high costs involved, this topic would benefit greatly from more in-depth analysis, in particular into the following areas:

- the longer-term macroeconomic impacts of decreased security of supply, for instance if security of supply issues were to deter investment
- the psychological and behavioural impacts of outages on households
- the resilience of supply chains and the extent to which resilience is being impacted by the increasing complexity of supply chains and their increasing reliance on continuous electricity supply
- the social impacts of the long blackouts which some residents and businesses experienced due to the flooding in the Southwest earlier this year
- moving from stated preference methods for estimating VoLL to a combination of stated and revealed preferences, using data about how people actually act in the market for electricity security
- a better understanding of the digital economy, both for understanding the potential losses arising from loss of data and damage to systems and equipment and for improving communication in the event of an outage.

# 1. Background and introduction

Recent research has highlighted the fact that the high level of spare capacity in the UK electricity system is set to reduce quite rapidly in the coming years, as a result of the closure of old coal and nuclear plants and increasing penetration of intermittent renewable energy sources (Ofgem 2012[57]; Ofgem 2014[59]; National Grid 2013; DECC 2012). Such historically high capacity margins were largely a result of unexpected reductions in demand following the economic recession, and led to a highly inefficient and costly electricity system.

The implications of such reductions in spare capacity have been the subject of recent debate, and, in 2013, The Royal Academy of Engineering was invited by the Prime Minister's Council for Science and Technology to undertake an investigation into the capacity margin of the GB electricity system. The objective of that study was to explore the question of whether the capacity margin of the GB electricity system could reach dangerously low levels within the next five years, and importantly to explore some of the underlying uncertainties within the detailed empirical work carried out by Ofgem, National Grid and DECC (Royal Academy of Engineering 2013[72]). The report and the pre-existing empirical work outlines the institutional and political context of the wider discussion around UK capacity margins.

This report considers a different issue. Security of supply comes at a cost; be it in building power stations or making investments to improve the resilience of the network. In order to understand how much it is worth investing in security of supply, policymakers need to know the potential costs of disruptions. Only by understanding these costs can they make informed judgements about the level of security of supply that it is economically efficient to buy. Therefore, the objective of this study is to look into the economic and social costs and impacts of supply interruptions, both within different sectors and across the economy as a whole.

It should be noted that this report does not seek to assess the likelihood of supply interruptions arising from either technical problems with the network or lower capacity margins, and does not imply that the kinds of electricity outages and shortfalls discussed in the report are likely to occur in the UK. Moreover, the objective of this report is not to assess the suitability of new policy mechanisms such as the Capacity Market to address the issue of declining levels of spare capacity.

Work has already been commissioned by DECC on the value that customers place on security of supply, measured in the 'value of lost load' (VoLL) in £/MWh (London Economics 2013[49]). This report aims to add to this work, in particular by highlighting some of the key uncertainties that arise when attempting to calculate VoLL, by analysing some of the potential broader economic and social concerns that may arise, and by identifying areas in which further research would be beneficial.

Section 2 describes the results of a literature review of existing research on this topic, and gives an overview of methodologies for calculating the cost of supply interruptions. Section 3 introduces a selection of estimates of VoLL in the UK using different methods. Section 4 presents views from consultation with experts in this field, which were elicited through one-to-one interviews and a workshop. Section 5 presents case study research of blackouts from elsewhere in the developed world. Finally, Section 6 discusses some of the potential longer-term and macroeconomic impacts of electricity shortfalls. Sections 7 and 8 conclude and highlight important areas for further research.

# 2. Literature review

Literature on the costs of electricity shortfalls has existed since the energy security scares in the 1970s. However, in terms of recent research, most is from elsewhere in Western Europe.

Electricity outages create two main types of damage (Praktiknjo *et al* 2011[65]):

- direct damages (loss of *value* caused by direct loss of assets such as products or food)
- indirect damages (loss of *opportunity* caused by loss of time or productivity).

There is no market in which power supply interruptions are traded; therefore other methods need to be used to identify the value of electricity shortfalls and outages (Baarsma and Hop 2009[4]; de Nooij *et al* 2007[22]). There are three main methods for calculating the economic cost of an interruption:

| **Approach** | **Examples** | **Advantages** | **Disadvantages** |
|---|---|---|---|
| Theoretic economic modelling | GDP<br>Gross-value-added of companies<br>Production-function approach | Uses broadly available data | Can only give aggregated data; not as good for disaggregating by sector, consumer group, location, time etc.<br>Only shows indirect losses; can't show direct losses (such as material losses to goods) |
| Revealed preferences | Choices made in actual markets<br>Interruptible contracts for large consumers | High validity as it shows actual behaviour | Information not readily available, especially for smaller consumers<br>Consumers do not usually get any choice about their level of energy security<br>Only shows the past; forecasts are difficult |
| Stated preference | Contingent valuation surveys<br>Conjoint analysis<br>Choice experiments | Use hypothetical choices, therefore obtain more information<br>Good for making predictions | Based on subjective choices<br>Low validity<br>VoLL could deviate from real cost methods<br>Require lots of time and money to do |

Stated preference methods show considerable variation in the specific methods used:

- Contingent valuation asks people directly what money they would be willing to pay to avoid an outage (willingness-to-pay or WTP), or what money they would wish to be given in order to experience an outage (willingness-to-accept or WTA)
- Conjoint analysis elicits WTP and WTA by asking respondents to rank different options in order of preference
- Choice experiments provide respondents with a series of scenarios for people to choose between; statistical methods are then used to extrapolate WTP and WTA from the choices made.

The various methods in the table above often give fairly consistent results when replicated by other studies using similar methods (Praktiknjo *et al* 2011[65]). However, comparisons between multiple methods often reveal large disparities (see, for example, Zachariadis and Poullikkas 2012[89]). VoLL estimates tend to be highly skewed for both households and businesses, with the majority of consumers having relatively low VoLL and a small minority with very high VoLL (Praktiknjo *et al* 2011[65]; Praktiknjo 2014[64]). Section 3 contains an illustration of the potential uncertainty between estimates; Appendix A has a detailed overview of methods for estimating VoLL, including the main advantages and drawbacks of each method.

**The costs of supply interruptions are determined by several factors:**

### Sectoral characteristics

Research has shown large disparities between VoLL in different sectors. Most studies look at residential, public, and industrial and commercial sectors separately; a common finding is that residential VoLL is higher than industrial and commercial VoLL. However, this needs to be weighed against potential macroeconomic impacts of commercial outages, such as the potential to deter investment (Zachariadis and Poullikkas 2012[89]). Section 6 looks at this topic in more detail.

### Duration and timing of the interruption

Timing is crucial, as the VoLL increases considerably at peak times. Peak times are also when blackouts or brownouts are most likely in a situation of low capacity margins.[i] However, Leahy and Tol (2011)[48] suggest that peak demand does not always coincide with *peak* VoLL; for example, in their study of Ireland in 2008, peak demand was at 5pm on a December evening, yet on that same day, VoLL was more than twice as high at 8–9am than it was at 5pm.[ii] A German survey found that households are very concerned about the impact of supply interruptions on computing technology (for instance, data loss from a PC cutting out during an unplanned outage, or power surging after power is restored and causing damage to hard drives) and the need to reconfigure electronic equipment. This results in a certain fixed cost for even very short durations, and means that average estimates of VoLL are unsuitable for very short interruptions (Praktiknjo 2014[64]). However, this also illustrates the importance of people's perceptions of losses, as the actual economic costs of data loss in households may be less significant than people perceive.

### Geographical characteristics

Residential users in different areas have different incomes, and may have different usage patterns (Accent 2008[1]; de Nooij *et al* 2007[22]). De Nooij *et al* (2008)[23] argue that overall social costs can be minimised by disconnecting users according to differing VoLL; however, this raises a host of equity issues (Section 4 contains more on this subject). Stated preference approaches tend to extrapolate data out from a specific geographical area to a wider area, making the sample potentially non-representative (LaCommare and Eto 2006[46]). Certain sectors, most notably data companies, are highly concentrated geographically (Lyons *et al* 2013[50]).

### Frequency of outages

On the one hand, repeated interruptions may constitute a quasi-permanent obstacle to regular economic activity, and therefore VoLL could be much higher than is shown in estimates. On the other hand, there is evidence that households and companies can adapt, and therefore VoLL could be much lower (Zachariadis and Poullikkas 2012[89]). The study found very little published literature on the impact of more frequent interruptions; however, the experts consulted in Section 4 offer some more information on this aspect.

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[i] A brownout is a drop in voltage. Brownouts can be used for load reduction in an emergency; they can also happen unexpectedly. Lights may flicker and dim, or some consumers may be cut off. However, this is more of an issue of power quality than power quantity.

[ii] This suggests that there is considerable opportunity for minimising both social and economic impacts through load shifting in the event of low margins; see Section 4.2 for more on this.

### Experience

The amount of historical experience consumers have with outages has an impact on their VoLL; however, there is uncertainty over the direction of this correlation. Carlsson *et al* (2011)[14] analysed WTP in Sweden, before and after outages caused by a severe storm; average WTP was lower after the storm, and it was found that this could not be explained simply by increased contingency measures. This suggests that lack of experience led people to overestimate the potential negative consequences of an outage. Conversely, Von Selasinsky *et al* (2014)[85] found precisely the opposite when they measured WTP after an outage which affected around half the inhabitants of Munich; they found that WTP was almost 60% higher for those who *had* experienced the outage.

### Mitigation measures taken

Precautionary and mitigation measures can significantly reduce the cost of outages. Zachariadis and Poullikkas (2012)[89] suggest that under good planning and communication of planned interruptions, households can adapt and can reschedule their daily plans without losing too much of their time.

# 3. Estimates of VoLL for the UK

The graph in *Figure 1* below provides an illustration of the potential range of estimates that occur when combining different methodologies. The graph shows estimates of the value of avoiding a one-hour supply interruption from a range of methodologies. The range of countries shown means that these numbers are non-comparable with the VoLL results shown in Sections 3.1 and 3.2; however, they do provide a good high-level view of the magnitude of the uncertainties involved.

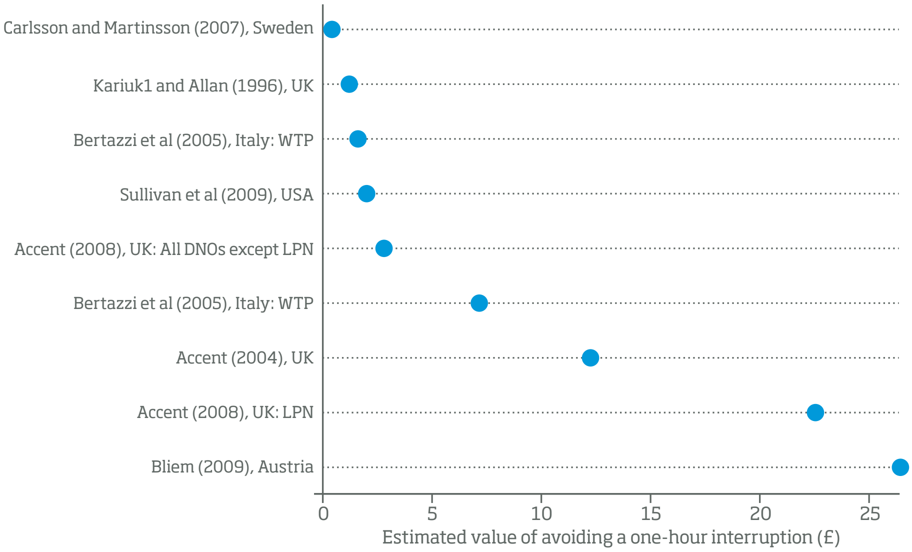

**Figure 1**: meta-analysis of the value of avoiding a one-hour interruption (£).

Note that these figures are in £ per event; as such, in order to estimate the VoLL in £/MWh, they would need to be divided by electricity consumption under normal operating conditions.

*Source: Reckon 2012*[67]

## 3.1 Blackout simulator

An online cost-simulation tool has been developed that uses the data from thousands of surveys and valuations in each of the EU-27 countries to estimate the overall costs of a supply interruption for a specified area, time and duration. The tool uses a combination of 'soft data' from surveys, and 'hard data' from official Eurostat statistics. The methods used are explained in more detail in Appendix A, and the detailed methodology and assumptions are given in Reichl and Schmidthaler (2014a)[68]. The online tool is available at www.blackout-simulator.com/.[iii]

Some results from the online tool are shown below. All outages shown are for the whole of the UK; however, the tool can also be used to calculate the cost of outages in specific areas.

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[iii] This research was funded by the European Commission, and carried out by researchers from the Johannes Keppler Universität, Linz

|  | Winter |  |  | Summer |  |  |
|---|---|---|---|---|---|---|
|  | **Peak** | **Off-peak** | **Weekend** | **Peak** | **Off-peak** | **Weekend** |
| 1 hour | £6,495.69 | £6,525.70 | £5,634.43 | £6,268.91 | £5,727.02 | £5,178.49 |
| 12 hours | £4,381.59 | £4,960.35 | £4,079.17 | £3,920.55 | £4,433.08 | £3,749.33 |

**Figure 2**: Average VoLL for the UK, for interruptions of one-hour and 12-hour duration (£/MWh)

The VoLL figures above are derived from the total cost to the economy, divided by the total energy unserved during the interruption. It should be noted that this methodology compounds uncertainties, because the simulator uses data from individual consumers and businesses, which are then extrapolated up to the whole economy, and then extrapolated back down to generate VoLL per MWh. Such uncertainties are not well illustrated by the precise results shown by the simulator. More detail on the advantages and drawbacks of the blackout simulator method are given in Appendix A.

## 3.2 London Economics VoLL report

The consultancy London Economics was recently commissioned by DECC to estimate the VoLL for residential, small-medium enterprise (SME) and industrial and commercial sectors, using choice experiment methods to elicit both WTP and WTA for a variety of outage characteristics. The choice experiments were conducted in a highly rigorous fashion; however, they represent just one possible method among a number of options, and are subject to the uncertainties inherent in stated preference methods. London Economics was tasked with identifying a weighted average VoLL for the UK, which it calculated at £16,940/MWh for residential and SMEs, using WTA responses. It has been noted by several of respondents interviewed for this report that this figure needs to be viewed with care, especially because of the disaggregation of SMEs from the larger industrial and commercial sector and the impact of a very high estimate for SMEs. This high estimate for SMEs may be due to a number of factors, including fewer opportunities for activity substitution, and possible fixed costs resulting from direct damages.

The table in *Figure 3* clearly shows the large disparity between WTP and WTA estimates; the possible reasons for this disparity are explained in detail in Appendix A. The VoLL figures for the industrial and commercial sector were derived using a production-function approach, using gross-value-added (GVA) data from 2011. The 'totals' are a weighted average, assuming a split of 40% domestic consumption, 40% large industrial and commercial sector, and 20% SME; this weighting is derived from Ofgem's interpretation of the same report (Ofgem 2013[58]). The numbers in italics were not statistically significant. Similarly to the blackout simulator, it should be noted that the precise figures in the table below do not illustrate the inherent uncertainties in the estimates.

It is important to note that VoLL calculations give a value in £/MWh, that, when compared to normal wholesale or retail prices, seems very high. However, such outages only occur on rare occasions, for a short period of time; the London Economics study, for example, looked at a one-hour outage every 12 years. This means that this figure in £/MWh does not necessarily translate into examples across the year, because in terms of overall GDP, it is actually fairly small. This makes it difficult to put these numbers into context.

| | | Winter | | | Summer | | |
|---|---|---|---|---|---|---|---|
| | | **Peak** | **Off-peak** | **Weekend**[iv] | **Peak** | **Off-peak** | **Weekend** |
| Residential | WTA | £10,289 | £9,100 | £10,982 | £9,257 | £6,957 | £9,550 |
| | WTP | *£208* | *£315* | £2,240 | *£105* | *£101* | £2,766 |
| SME | WTA | £35,488 | £39,213 | *£44,149* | £33,358 | £36,887 | *£37,944* |
| | WTP | £21,685 | £21,325 | £26,346 | £20,048 | £19,271 | £21,864 |
| Industrial & commercial | GVA | £1,654 | £1,654 | £1,654 | £1,654 | £1,654 | £1,654 |
| Total | WTA | £11,874 | £12,144 | £13,884 | £11,036 | £10,822 | *£12,070* |
| | WTP | *£5,082* | *£5,053* | £6,827 | *£4,713* | *£4,556* | £6,141 |

**Figure 3**: Stated preference VoLL for different sectors (£/MWh)
*Source: London Economics (2013)*[49]

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[iv] London Economics (2013)[49] define the peak time in their report as 3pm–9pm. Therefore the 'weekend' figures given are off-peak, in order to maintain consistency with the weekend figures from the blackout simulator (1pm)

# 4. Notes from relevant experts

One of the major components of this study has been consultation with relevant experts, both from within the UK and from elsewhere in Western Europe. This took the form of a number of one-to-one interviews and a workshop.

## 4.1 Methods for estimating VoLL

The issue of discrepancy between different methods, and between WTP and WTA values in stated preference methods, was noted and well understood by all respondents. The respondents pointed out that as far as possible, stated preference methods should be designed to be based on people's actual experiences, and that this can increase the robustness of estimates. However, several respondents noted that in the case of power outages, stated preference responses are to some extent hypothetical and are highly dependent on perceptions. The problem is that perceptions can change very quickly; this has major implications for policymakers seeking to use the data for long-term decision-making. It was felt that householders are generally poor at assessing risk, tending to place much higher risk factors (and therefore much higher value) on high-risk/low-probability events. People often tend to overestimate the negative impacts of disruption, especially when they have limited experience of the scenario in question.

It was also noted that WTP and WTA do not actually value security of supply; instead, they value the extent to which consumers feel they have the *right* to security of supply. One respondent suggested that research shows that most people would not actually be willing to accept compensation for outages in a real-world situation. It was also pointed out that, in the context of the capacity market, the government is asking people to **pay** for improved reliability; this means that using WTA as a basis for estimates is questionable.

It was felt that revealed preference methods can be much more robust, if the data is available. New data sources such as smart meters and time-of-use tariffs could provide this kind of information.

It was suggested by the respondents that it would make more sense to disaggregate the VoLL by industrial and commercial sector, rather than between large industrial and commercial and SMEs; however, methodological choices have to be made in order to generate VoLL estimates, especially in the absence of actual market data. It was also noted that stated preference responses from companies can be very unreliable.

## 4.2 Characteristics of the outage

Respondents emphasised the importance of distinguishing between outages caused by faults, and outages caused by low capacity. Network problems usually appear randomly, whereas capacity shortages can usually be more predictable. However, the impact of capacity shortages tends to be greater, because the outage will generally happen at peak time when VoLL is very high. People's reaction to loss of supply depends significantly on the length of time and the frequency with which it occurs; it therefore follows that VoLL is a range rather than a single point figure.

## Sectoral and geographical characteristics

There are big differences between VoLL for different sectors (including residential, public, and industrial and commercial sectors). This is especially pronounced within the industrial and commercial sectors, with the majority of consumers having a relatively low VoLL, and a minority having an extremely high VoLL. It was also noted that the impact on a company is dependent on its ability to buy back-up capability; for smaller companies with lower turnover, the capital expense is often unfeasible. The geographical aspect is also important, because people's previous experiences, their incomes, and their patterns of usage differ depending on where they are located. Urban areas may be more vulnerable than rural areas, because more of the infrastructure relies on electricity (for instance for transport, heating and lifts). However, it was noted that if the purpose of the calculation is to carry out a cost-benefit calculation for increased resilience for the country as a whole, then using a weighted average VoLL is sufficient.

There is considerable scope for minimising impacts through geographical and sectoral optimisation, as illustrated in *Figure 4* below. However, this creates a trade-off between economics and politics, and could be unequitable because VoLL is linked to incomes and therefore optimisation would mean that people on lower incomes would be the first to be cut off. Moreover, challenges are raised by the increasing fragmentation of work patterns, especially due to a rise in the number of people working from home; this means that the presumption that residential areas generate less economic wealth is increasingly inaccurate.

## Timing of the outage

Probably the most important factor in determining the cost of an outage is the time of day. This therefore raises promise for reducing VoLL significantly by load-shifting and peak-shaving (ie shifting certain types of demand to different times of day, and thereby reducing the peaks in demand which cause the system to struggle). In this regard, the respondents emphasised the cost savings that could accrue from increased use of demand-side response for both the industrial and commercial sector and for domestic consumers.

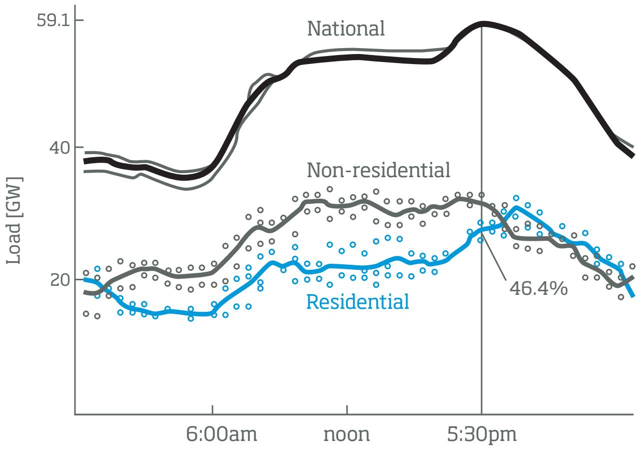

**Figure 4**: peak demand (and therefore high VoLL) is at different times of day for different sectors. Consumers' VoLL could be minimised by ensuring that outages are planned to avoid coinciding with their peak demand.

*Source: Grünewald and Torriti 2012*[34]

### Outage duration

The impact of outage duration is generally better captured by stated preference methods than other aspects. However, stated preference only has utility up to around 24 hours of outage; beyond this, people's experience is too limited. It is therefore worth noting that the maximum 'acceptable' duration is entirely dependent upon people's perceptions, communication before, during and after the outage, and on how the issue is framed in society and in the media. For businesses, many short outages have a more pronounced impact than one long outage, whereas households are more affected by one long outage. Both households and businesses are very concerned about data loss and damage to computing equipment; it is worth noting that this can occur even if the outage is just for one second. One important point which was raised is that there may be 'critical thresholds' of duration, such as the time it takes for food to go off in a fridge, or for a generator to run out of diesel.

### Frequency of outages

More frequent outages, for instance in the context of an ongoing capacity shortage, probably mean that VoLL estimates no longer follow a linear pattern. However, it is uncertain whether these non-linearities will lead to higher or lower VoLL. It is likely that more frequent outages will encourage contingency measures (= lower VoLL), but at the same time, they could create a barrier to normal economic activity and might deter investment (= higher VoLL). A good analogy for this is traffic in a city – if congestion worsens significantly, more people might take contingency measures such as buying a bike; however, businesses might be deterred from buying premises in the city, and people might be less willing to come to work in the city. Therefore, more frequent outages would potentially result in a lower VoLL for individuals, but a higher cost to the economy as a whole. However, none of the existing VoLL studies attempt to measure frequent or repeated outages, and the lack of information or experience available means that there would be very high uncertainty in attempting to estimate VoLL in the context of a capacity shortage.

## 4.3 Social and political impacts

The study has not revealed any recent real-world examples of outages leading to considerable social unrest. The only example found is from the Bronx riots in the 1970s, in which case it is evident that there were underlying socioeconomic factors involved, with the outage merely acting as a catalyst. Since then, the overriding theme is of co-operation rather than unrest. One respondent characterised this by noting that during an incident such as an outage, people change from being 'consumers' to 'citizens'. Several respondents suggested that people can generally cope with disruptions and that the social impacts of outages lasting less than around 24 hours would be minimal. The UK's previous experience of outages occurring over a large geographical area for 24 hours or more is so limited that projections cannot really be made with confidence.

Nevertheless, demand for electricity is notoriously inelastic. Electricity shortfalls lead to rising prices, which could increase fuel poverty. Moreover, several respondents suggested that there is evidence that outages lead to considerable knock-on effects between sectors, especially as economies are now so interconnected. However, the knock-on effects are dependent on value chains; the higher up the value chain, the greater the impact to the economy as a whole. So for example, an outage at a company supplying vital components for a large manufacturing firm could have knock-on effects to all the companies in that supply chain, and in turn could have an impact on huge numbers of consumers; on the other hand, an outage at the end of the supply chain (for instance, a retail unit) would probably only affect the staff and users of that specific company.

Outages push energy security right to the top of the political agenda, and can put considerable strain on government policy and on political legitimacy. Respondents repeatedly mentioned the three-day week in the UK in 1974; the political impacts of this were enormous and long-lasting, contributing to a change of government and to shifts in UK energy policy that still echo today. It was also noted that the impacts of a similar situation would likely be much greater today, due to increasing reliance on electronic equipment. A more recent example given was that of Norway in 2006 (which experienced shortfalls arising from a lack of water for hydropower), in which the actual impact on standards of living was fairly minimal, but the political impacts were considerable. Another example is the present-day situation in Germany, in which a perceived reduction in security of supply is putting considerable pressure on their plans for a transition to a low-carbon energy system (the 'Energiewende'). Once again, it is vital to note that the magnitude of the impact derives from *perceptions* of shortages, rather than from shortages per se. It was pointed out that it is impossible to generalise about human behaviour, and that there would be significant differences in the way that different people react.

The importance of 'tipping points' on the impacts of longer outages was discussed. Examples could include cash in circulation running out because of a lack of power for ATMs, or emergency back-up generators running out of diesel. Because of this, estimates from Europe have suggested that an outage of more than four days' duration would lead to highly unpredictable societal consequences. However, all these impacts would involve outages of 48 hours or more over a very large geographical area, a scenario that is highly unlikely and would only occur as the result of a low-probability/high-impact event or combination of events which would be impossible to predict.[v]

## 4.4 Minimising the impact

The respondents suggested a number of ways in which VoLL could be reduced, thus minimising the cost of an outage. Four main methods were suggested:

- good communication, especially utilising modern communications methods and social media, can significantly minimise both the social and economic impacts of electricity outages. People expect information to be available immediately and for government bodies to be online 24/7, and concerns were raised that much of the contingency planning in the UK has not been updated since the 1970s.
- planning can help to reduce impacts by allowing people to plan around an outage; moreover, this assists some SMEs who can then undertake a cost-benefit analysis of buying back-up capability such as a generator
- demand-side response, smart meters, and shifting the electricity load can reduce problematic demand peaks and can help to mitigate the increase in costs at peak times
- communities can act as a vital resource for increasing resilience and for mitigating impacts, especially for the most vulnerable members of society. Good communication within local areas and communities can help to overcome the difficulty of ensuring that information reaches vulnerable demographics such as the elderly.

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[v] These types of events are termed 'black swans' (Taleb 2007[76]). As they are impossible to predict, the security literature recommends focusing on strategies to improve resilience, for instance through good communication and flexible demand.

# 5. Case studies

Six incidences of large outages in other developed economies were chosen as case studies. The outages occurred for a variety of reasons and with different characteristics. Overall, it is noted that the literature on the impacts of previous outages is extremely limited; most literature focuses on assessing the causes, rather than the impacts. Detailed case study information is given in Appendix B, including more detail on the causes and impacts of each of the incidents and more detail on the availability and reliability of the data presented.

## CASE 1 **Canada / Northeast US, August 2003**

**Cause**: technical fault, human error
**Area affected**: eight US states, one Canadian province,
**Number of people affected**: ~50 million
**Duration**: between one and four days' blackout; rolling blackouts for up to a week in parts of Ontario
**Costs**: between $4.5 billion and $8.2 billion
**Cost data**: good availability of data; poor reliability of estimates
**Major impacts**: high number of calls to 911; fires caused by candles; crime was lower than usual; minimal social unrest.

## CASE 2 **California 2000/2001**

**Cause**: capacity crisis
**Area affected**: California
**Number of people affected**: >1.5 million
**Duration**: rolling blackouts for nearly one year
**Costs**: ~$40 billion in additional energy costs (2001-03); estimated GDP loss of 0.7–1.5%
**Cost data**: good energy cost data; poor reliability of GDP loss data
**Major impacts**: increase in electricity retail prices of 30–40% after the crisis; economic impacts including California being placed on negative credit watch; political pressure on State energy policy.

## CASE 3 **Japan 2011**

**Cause**: natural disaster leading to shutdown of multiple power stations
**Area affected**: all of Japan
**Number of people affected**: up to 45 million
**Duration**: rolling blackouts for ~6 weeks; ongoing electricity shortages
**Costs**: difficult to disaggregate from the costs of the disaster as a whole
**Cost data**: very limited
**Major impacts**: ambitious schemes reduced demand by 25% (see Appendix B for details). Security of supply pushed right to the top of the political agenda, both in Japan and globally.

## CASE 4 Europe 2006

**Cause**: network failure
**Area affected**: 20 countries in Western and Eastern Europe and North Africa
**Number of people affected**: ~15 million
**Duration**: up to two hours
**Costs**: no data available on overall economic costs; ~$100m costs to service industry in spoiled products
**Cost data**: very limited
**Major impacts**: rescue services under strain due to tripping of alarm systems and people trapped in lifts; political debate over the future of European electricity transmission integration.

## CASE 5 Italy/Switzerland 2003

**Cause**: network failure
**Area affected**: Italy and parts of Switzerland
**Number of people affected**: ~56 million
**Duration**: between one-and-a-half and 19 hours
**Costs**: economic impacts estimated at €1,182m
**Cost data**: very limited
**Major impacts**: around 30,000 people were trapped on trains and underground transport; up to four deaths (unofficial).

## CASE 6 Cyprus 2011

**Cause**: explosion leading to the shutdown of a large power plant
**Area affected**: Cyprus
**Number of people affected**: up to 1 million
**Duration**: two to four hour residential rolling blackouts for one month
**Costs**: estimated losses between €196 million and €30,598 million
**Cost data**: methods robust but very high uncertainty
**Major impacts**: social and political impacts were minimised through effective communication, planning and optimisation of rolling outages.

## SUPPLEMENTAL CASE Somerset 2014

A very recent example of severe blackouts occurred in the UK over winter of last year (2013/14), albeit in a relatively localised area. Storms hit the UK on 23 December 2013, causing around 750,000 homes to lose power. According to Secretary of State Owen Paterson, "electricity companies restored power to 90% of those within a day. A number of properties remained disconnected for longer in some cases owing to dangers connected to flooding and the complexity of the faults" (Hartwell-Naguib and Roberts 2014[37]). Over Christmas 2013, 16,000 households suffered cuts for more than 48 hours, and around 500 were without supply for more than five days (Macalister 2014[51]). In early 2014, properties in the Southwest were affected by further flooding, and some areas were without power for days or even weeks.

As with other blackouts caused by natural disasters, there are no existing data on the overall economic costs of the blackouts themselves, as it is not possible to unpick this data from estimates of the damages caused by the storms themselves. However, distribution network operators (DNOs) in the two worst-hit areas paid out a total of £8 million in compensation (Bachelor 2014[5]). The DNOs came under fire for responding too slowly to the outages at Christmas and for failing to communicate with consumers effectively; in an Energy and Climate Change Committee hearing, Tim Yeo MP accused the DNOs of "utter complacency" and an "astonishing" degree of neglect of their customers (Energy and Climate Change Committee 2014[37]). For many members of the public, this was the first time that DNOs had been in the spotlight regarding security of supply. Ofgem was also criticised for its failure to ensure that the DNOs responded effectively to the incident (Energy and Climate Change Committee 2014[37]). This case study therefore reveals the potential pressure which blackouts can place onto operators and regulators; it also reveals the consequences of poor communication with customers in the event of an outage.

This is a very recent case study, meaning that the majority of information is from media and parliamentary sources; in-depth research has not yet been published. It would be beneficial to carry out qualitative research with people and businesses that lost power for more than a day, for instance, using a large number of interviews combined with a survey. This could provide highly useful data on the social and psychological impacts of longer outages, especially as it represents a recent example of severe outages here in the UK.

## 5.1 Case study conclusions

The case studies analysed show the disparities that exist between previous examples of electricity shortfalls and outages. Large-scale outages occur for a number of reasons, including network failures, natural disasters and capacity shortages; in several cases, numerous causes are experienced simultaneously. This also leads to significant disparities between the area, duration and number of people affected. Because of this, and because of a general lack of reliable economic data, making direct cost comparisons between case studies is challenging. Moreover, as with most serious system failures, the impacts shown in these case studies are the result of compounds of factors; as such, it is persistently difficult to unpick the economic impacts of the outage itself from wider economic impacts, both within the energy system and within the wider economy. The cost estimates given above generally come with a high degree of uncertainty.

The case studies indicate that social impacts are perhaps more limited than may have been expected; it appears as if the trend in a crisis is towards societal co-operation, and this study did not reveal evidence of an outage directly causing social unrest. However, the case studies illustrate that the longer-term impacts on both policy and the economy may be significant. Finally, the case studies underline the importance of good communication in the event of outages. These findings are all in accordance with the responses from experts reported in Section 4.

# 6. Longer-term economic impacts

It was pointed out by many of the experts we consulted that one of the key uncertainties over the economic cost of electricity shortfalls is on longer-term economics. For example, in a situation of capacity shortages leading to decreased security of supply, there are concerns that investment in the country or the area could be deterred. It was noted that people in Germany are currently very concerned that decreasing security of supply could have an adverse impact on foreign direct investment. However, the study revealed very little published research in this area. It seems to be commonly accepted that ICT firms locate in areas with good security of supply; however, there is no publically-available research on this. Interviews were therefore undertaken with a small number of manufacturing firms with high electricity demand, in order to try and establish how they factor security of supply into their investment decisions. A conclusion of this report is that this represents a vital area for more in-depth research.

Several respondents said that security of electricity supply is climbing up the industry agenda in the UK, mainly because of two drivers:

- increasing complexity of manufacturing processes, leading to increasing importance of stable and continuous electricity supply
- increasing concerns about UK security of supply because of declining capacity margins, a perceived lack of coherent energy strategy, and an increasing likelihood of disruptions caused by volatile weather.

One company has carried out an in-depth cost-benefit analysis of back-up generation at each of their UK facilities, while another company has created a department that has this issue as part of its role; these examples in themselves demonstrate the increasing importance of security of supply to the industry. Nevertheless, one respondent suggested that *local* capacity constraints on the distribution network are still more concerning to industry than national capacity constraints.

Unsurprisingly, all respondents agreed that unplanned outages would be more damaging than planned regular outages; one respondent stated that an unplanned outage would have "completely unacceptable economic and operational consequences" and a potential restart time of more than five days. In manufacturing, some components take days to build and many processes would have to be scrapped if the power is interrupted unexpectedly. However, planned outages would also be "highly inconvenient"; several processes are difficult to start up again after even a planned outage, while other processes run 24/7 and therefore can't be shifted, meaning that even planned outages would carry a cost. Planned outages could also result in large numbers of temporary staff lay-offs. One respondent suggested that an interruption would cost them roughly £2 million a day. It is also important to note that power *quality* issues such as voltage sags (for example, in the event of a brownout) could also have a detrimental impact on many processes, especially where processes are dependent on sophisticated computing equipment; as such, it is important to remember that many sectors are highly dependent upon consistent good-quality electricity supply.

As well as the manufacturing processes themselves, supply chains are also becoming increasingly reliant on uninterrupted electricity supplies, especially in the context of just-in-time supply chains. It is worth noting that delays in even a single widget can stop complex production lines completely, and that delays can increase costs along the entire supply chain. Some respondents said that they would try to cooperate with their suppliers to resolve any issue, while others suggested that any companies suffering delays would be quickly dropped from the supply chain. One respondent stated that their company has a lot of factories in its supply chain, and if any of them demonstrated unreliable electricity supply, they would be ruled out very quickly. It is possible that supply chains are becoming less resilient due to their increasing dependence on continuous electricity supply; this represents an important area for further research.

In terms of choosing where to site a new facility, security of supply was noted to be in the top list of considerations; however, most of the concerns expressed were related to local distribution networks. It was noted that companies routinely factor in the costs of back-up when looking into less developed countries (India and Brazil being two of the examples given). The UK has typically had high supply security, yet for the first time, companies are starting to look into the costs of back-up for UK facilities. Clearly, back-up increases costs, and one respondent suggested that the industry would simply “vote with its feet”. It was noted by one respondent that “if the UK were perceived or demonstrated to have an unreliable service infrastructure, this would undoubtedly be factored into future siting or investment decisions”. It was pointed out that an unreliable electricity supply suggests an inherent flaw with a country’s infrastructure, which would have a severe impact on investor confidence. The electricity shortages in California evidently had an impact on FDI, although it was noted that this was bound up in wider economic and political factors that make direct comparisons difficult.

# 7. Conclusions

Advanced societies and processes are becoming rapidly more dependent on a continuous supply of good-quality electricity. The pace of change of modern technological advancement, and the increasingly interconnected nature of the economy, mean that our understanding of the potential consequences of electricity shortfalls is constrained by limited knowledge about the knock-on impacts which could occur across different sectors. Evidence from previous economic modelling and from international case studies suggests that the economic impact of a severe, widespread outage affecting the majority of the UK (including major cities) would be of the order of millions of pounds for an outage of an hour or two. At the upper end of the range, a longer outage (12+ hours) affecting the majority of the UK could result in costs stretching into the billions. However, cost estimates suffer from large discrepancies between estimates using different methodologies, and international cost comparisons should be treated with caution due to limited reliable data and the contingent nature of outage costs.

In terms of research into the VoLL, the UK is currently not as advanced as much of the rest of Western Europe. The research that does exist needs to be better disseminated: none of the workshop participants was aware of the London Economics VoLL report, despite the fact that it is a major report in their area of interest. Considering this, the report would probably benefit from peer review.

There is wide variation in estimates of VoLL, meaning that no concrete conclusions can be made on the cost of electricity shortfalls from existing research. It is very important to note that VoLL is not a value-neutral measure; it is a measure of people's *perceptions* of the value of a unit of electricity. The perception of a problem can have a greater impact than the problem itself. Therefore, the behavioural and psychological aspect of this topic requires more research. The UK's history of high security of supply over the past four decades means that UK consumers are especially vulnerable to outages, as most will not have contingency measures in place. It also means that WTP and WTA estimates from surveys are completely hypothetical, and people may tend to overestimate the negative consequences of outages. Moreover, estimates of VoLL in £/MWh appear very high when compared against the average wholesale or retail price for electricity; however, outages are relatively rare and only occur for short durations, meaning that the overall cost when spread across a much longer period of time would be significantly lower.

The economic impact completely depends on the characteristics of the outage. Impacts of a loss of supply vary according to the length of the interruption and the frequency with which it occurs; VoLL should therefore be viewed as a range, rather than a single point figure. Frequent outages (for instance, in the case of an ongoing situation such as a capacity shortage) have not been analysed in previous UK research into VoLL. Higher outage frequency creates extremely high uncertainties. This kind of ongoing capacity situation has not arisen in the UK for 40 years, during which time dependence on electricity has increased greatly and living patterns have become much more fragmented and complex; this makes it very difficult to make a valuation of the overall costs to the economy.

The economic impact is also completely dependent on the cause of the outage. Certain causes have certain characteristics, which then lead to certain consequences, which directly impact the costs. Outages caused by shortages in capacity are generally more predictable, and therefore VoLL is reduced by the ability of people to plan better; however, these types of outage tend to occur at peak times, when the VoLL is much higher.

One of the key uncertainties in estimates of economic impacts lies in the potential for actual or perceived issues with security of supply to deter investment in the UK. Modern industrial and commercial processes are increasingly complex, and often depend upon continuous, high-quality power provision; for many sectors, the impact of even a brief power interruption would be catastrophic. Moreover, supply chains are increasingly interlinked, and our understanding of the knock-on impacts of power interruptions on supply chains is incomplete. At present, the majority of industry concerns relate to constraints on the local distribution networks; however, national energy security issues are rising up the industry agenda in the UK, meaning that the reliability of the electricity supply is increasingly factored into investment decisions. More in-depth research needs to be carried out into the longer-term macroeconomic impacts of electricity shortfalls on investment and GDP.

There is very little evidence that outages result in adverse social impacts such as crime and disorder, and our research indicates that emergency services will almost certainly be able to cope using existing back-up provision. It is essentially impossible to predict the societal impacts of an outage affecting a large geographical area for more than about 48 hours duration, but such long and widespread outages are so improbable and unpredictable that they are outside the scope of this report. However, it is probable that outages would cause adverse *political* consequences, for instance, by increasing levels of public scrutiny over existing energy policy; this would be even more apparent if people perceive that the outage is the result of mismanagement rather than an exogenous incident.

Despite the high uncertainty, there are some relatively low-cost options for mitigating the impact of electricity shortfalls:

- Costs can be reduced significantly by improving communication, especially if up-to-date communications technology is understood and utilised effectively alongside more traditional communication methods. Good communication can help to reduce costs by allowing consumers to plan better, reducing stress and anxiety and thus reducing the pressure on emergency services, and reducing political and macroeconomic impacts by improving people's perceptions. There is an expectation in today's electronically-equipped society that information will be immediately available; it is therefore imperative that plans for communication in the event of an electricity shortfall are regularly reviewed and updated
- Demand-side response and peak shaving (ie reducing peaks in electricity load by shifting or reducing demand) can reduce both the likelihood and cost of outages. Reducing demand peaks can significantly reduce the potential for all kinds of outage;

this is especially important as outages that occur during peak demand will coincide with very high VoLL. Demand-side response can reduce whole-economy costs by allowing industry to choose what to switch off and thus avoid product damage, and by allowing public, commercial and residential sectors to avoid outages at peak times

- Communities and local social networks can increase societal resilience to disruptions, can mitigate impacts for the most vulnerable consumers, and can assist in effective communication. Mitigation efforts should recognise the importance of bottom-up and decentralised networks and governance.

Finally, it is important to put this work into context. It is clear that there is a gap in existing knowledge of the potential impacts of outages in the UK, and this is, therefore, a valuable avenue of research to pursue. The costs of some measures to mitigate capacity shortages are very high, meaning that the price of getting a cost-benefit analysis wrong is potentially serious; for a more detailed assessment of these issues see Newbery and Grubb (2014)[54]. This report aims to highlight concerns that basing these kinds of cost-benefit decisions on such uncertain estimates of VoLL is risky, because the costs of error are so high; efforts should, therefore, be made to increase robustness of VoLL estimates, for example through the use of revealed preference methods for households. However, notwithstanding this, it is important to note that despite the projected decline in capacity margins in the UK, this is unlikely to lead to the 'lights going out'; currently, the vast majority of outages in the UK are caused by problems on the distribution networks, rather than lack of generating capacity. This report on the impacts of electricity shortfalls is in no way intended to imply that the likelihood of shortfalls is increasing in the UK.

# 8. Areas for further research

This project has highlighted that there is very high uncertainty in estimating the economic and social impacts of electricity shortfalls. As noted above, considering the high costs involved, this topic would benefit greatly from some in-depth research into the following areas:

- The longer-term macroeconomic impacts of electricity shortfalls, such as deterring investment. This could be carried out using surveys of companies, for instance by asking them to rank several different factors for consideration when siting a facility. This area would also benefit from field research of countries that have experienced recent decreases in security of supply
- The psychological and behavioural impacts of outages on households: this would require in-depth qualitative research, including semi-structured interviews
- The resilience of supply chains, both for manufacturing and for other products such as food, and the extent to which resilience is being impacted by the increasing complexity of supply chains and their increasing reliance on continuous electricity supply
- The impacts of the outages in the UK over winter 2013/14, with particular focus on the long-duration blackouts experienced by some consumers in the Southwest as a result of flooding. This would require in-depth qualitative research, for instance, using interviews and surveys of those affected. This research would provide useful insight into the social impacts of long outages
- Moving from stated preference methods for estimating VoLL to a combination of stated and revealed preferences, using data about how people actually act in the market for electricity security. This could be carried out using emerging data from smart meters, and from pilot studies into people's economic behaviour when offered different time of use tariffs
- A better understanding of the digital economy: this would enable us to understand the potential value of data loss and damage to computing equipment, and would assist in developing an effective strategy for communication in the event of an outage. This area would also benefit from psychological research into people's ability to cope without a constant flow of information.

# References

1 **Accent (2008)** *Expectations of DNOs and willingness to pay for improvements in service: report for Ofgem*. Accent MR, London

2 **Anderson, P.L. and Geckil, I.K. (2003)** Northeast blackout likely to reduce US earnings by $6.4 billion. *Anderson Economic Group Working Paper, 2003-02*

3 **ANRE (2010)** *FY 2010 Annual Energy Report*. Agency for Natural Resources and Energy, Tokyo

4 **Baarsma, B.E. and Hop, J.P. (2009)** Pricing power outages in the Netherlands. *Energy*, Vol. 34: 1378-1386

5 **Bachelor, L. (2014)** "Ofgem unveils huge increase in compensation for blackout victims". *The Guardian*, 24 July 2014

6 **Becker, G.E. (1965)** A theory of the allocation of time. *The Economic Journal*, Vol. 75: 493-517

7 **Beenstock, M., Goldin, E. and Haitovsky, Y. (1998)** Response bias in a conjoint analysis of power outages. *Energy Economics*, Vol. 20: 135-156

8 **Berizzi, A. (2004)** *The Italian 2003 blackout*. Paper presented at the IEEE Power Engineering Society General Meeting, 6-10 June 2004, Denver

9 **Bialek, J. (2007)** *Why has it happened again? Comparison between the UCTE blackout in 2006 and the blackouts of 2003*. Paper presented at the IEEE Power Engineering Society "PowerTech" conference, 1-5 July 2007, Lausanne

10 **Billinton, R. and Ghajar, R. (1994)** Evaluation of the marginal outage costs in electric generating systems. *Utilities Policy*, Vol. 4 (2): 155-164

11 **Blackout simulator (2014)** Available at: www.blackout-simulator.com

12 **Bushnell, J. (2004)** Viewpoint: California's electricity crisis: a market apart? *Energy Policy*, Vol. 32: 1045-1052

13 **Cambridge Energy Research Associates (2001)** *Short Circuit: Will the California Energy Crisis Derail the State's Economy?* UCLA Anderson Business Forecast, Los Angeles, California

14 **Carlsson, F., Martinsson, P. and Akay, A. (2011)** The effect of power outages and cheap talk on willingness to pay to reduce outages. *Energy Economics*, Vol. 33: 790-798

15 **Carlsson, F. and Martinsson, P. (2008)** Does it matter when a power outage occurs? A choice experiment study on the willingness to pay. *Energy Economics*, Vol. 30: 1232-1245

16 **Castle, S. (2006)** "Europe suffers worst blackouts for three decades". *The Independent Newspaper*, 6 November 2006

17 **CBO (2001)** *Causes and lessons of the California electricity crisis*. Congressional Budget Office and US Congress, Washington DC

18 **Corsi, S. and Sabelli, C. (2004)** *General blackout in Italy, Sunday September 28, 2003, h 03:28:00*. Paper presented at the IEEE Power Engineering Society General Meeting, 6–10 June 2004, Denver

19 **Coursey, D. L., Hovis, J.L. and Schulze, W.D. (1987)** The Disparity Between Willingness to Accept and Willingness to Pay Measures of Value. *Quarterly Journal of Economics*, Vol. 102: 679–90

20 **CRO forum (2011)** *Power blackout risks: risk management options. Emerging risk initiative position paper*. CRO forum, Amsterdam

21 **DeBlasio, A.J., Regan, T.J., Zirker, M.E., Lovejoy, K. and Fichter, K. (2004)** Learning from the 2003 blackout. *Public Roads*, Vol. 68 (2)

22 **de Nooij, M., Koopmans, C. and Bijvoet, C. (2007)** The value of supply security: the costs of power interruptions: economic input for damage reduction and investment in networks. *Energy Economics*, Vol. 29: 277–295

23 **de Nooij, M., Lieshout, R. and Koopmans, C. (2008)** Optimal blackouts: empirical results on reducing the social cost of electricity outages. *Energy Economics*, Vol. 31: 342–347

24 **Djavid, H.P. and Jalilian, A. (2010)** Developing a new distribution test system to estimate customer outage costs using accurate and approximate procedures. *Energy*, Vol. 35: 1300–1311

25 **ELCON (2004)** *The economic impacts of the August 2003 blackout*. Electricity Consumers Resource Council, Washington DC

26 **Energy and Climate Change Committee (2014)** Oral evidence: "Power disruption due to severe weather"

27 **FERC (2003)** *Final report on price manipulation in Western markets: fact-finding investigation of potential manipulation of electric and natural gas prices*. Federal Energy Regulatory Commission, Washington DC

28 **Forte Jr, V., Putnam Jr, R., Pupp, R.L. and Woos, C. (1995)** Using customer outage costs in electricity reliability planning. *Energy*, Vol. 20 (2): 81–87

29 **Froggatt, A., Mitchell, C. and Managi, S. (2012)** Reset or restart? The impact of Fukushima on the Japanese and German energy sectors. *Chatham House Briefing Paper, EERG BP 2012/13*

30 **Fujimi, T. and Chang, S. (2014)** Adaptation to electricity crisis: businesses in the 2011 Great East Japan triple disaster. *Energy Policy*, Vol. 68: 447–457

31 **Ghajar, R.F. and Billinton, R. (2006)** Economic costs of power interruptions: a consistent model and methodology. *Electrical Power and Energy Systems*, Vol. 28: 29–35

32 **Grosfield-Nir, A. and Tishler, A. (1993)** A stochastic model for the measurement of electricity outage costs. *The Quarterly Journal of the IAEE's Energy Economics Education Foundation*, Vol. 14 (2): 157–174

33 **Growth Analysis (2011)** Restarting Japan: A first assessment June 2011 on the road to recovery after the Great East Japan earthquake. *Growth Analysis working paper no. 2011/15*

34 **Grünewald, P. and Torriti, J. (2012)** Demand response: a different form of distributed storage? Paper submitted to IEEE International Conference on Smart Grid Technology, Economics and Policies, Nuremberg, 3–4 December 2012

35 **Hanemann, W.M. (1991)** Willingness to pay and willingness to accept: how much can they differ? *American Economic Review*, Vol. 81 (3): 635–647

36 **Hartman, M.J., Doane, M.J. and Woo, C. (1991)** Consumer rationality and the status quo. *The Quarterly Journal of Economics*, 1991

37 **Hartwell-Naguib, S. and Roberts, N. (2014)** Winter floods 2013/14. *House of Commons Standard Note, SN/SC/06809*

38 **Hausman, J. (ed.) (1993)** *Contingent Valuation: A Critical Assessment*. North-Holland Publishing Company, Amsterdam

39 **Horowitz, J.K. and McConnell, K.E. (2002)** A review of WTA/WTP studies. *Journal of Environmental Economics and Management*, Vol. 44: 426–447

40 **Johnson, C.W. (2007)** Analysing the causes of the Italian and Swiss blackout, 28th September 2003. *Proceedings of the 12th Australian workshop on safety critical systems and software and safety-related programmable systems*, Vol. 86: 21–30

41 **Johnston, J. (2007)** California's electricity crisis: background information. Berkeley University, California. Available at: http://josiah.berkeley.edu/2007Fall/ER200N/Readings/CA_Crisis_Background.pdf (Last accessed 02.09.2014)

42 **Joskow, P. (2001)** California's electricity crisis. *Oxford Review of Economic Policy*, Vol. 17 (3): 365–388

43 **Joskow, P. and Kahn, E. (2002)** *A Quantitative Analysis of Pricing Behaviour in California's Wholesale Electricity Market During Summer 2000: The Final Word*. Department of Applied Economics, University of Cambridge

44 **Kahneman, D. and Tversky, A. (1979)** Prospect Theory: An Analysis of Decision Under Risk. *Econometrica*, Vol. 47: 263–91

45 **Kim, C., Jo, M. and Koo, Y. (2014)** Ex-ante evaluation of the economic costs from power grid blackout in South Korea. *Journal of Electrical Engineering Technology*, Vol. 9: 742

46 **LaCommare, K. H., Eto, J.H. (2006)** Cost of power interruptions to electricity consumers in the United States (US). *Energy*, Vol. 31: 1845–1855

47 **Lagendijk, V. and van der Vleuten, D. (2008)** *An anatomy of transnational European vulnerability: the 2006 European blackout in historical perspective*. Paper presented at the EUROCRIT Stockholm workshop, 21–24 May 2008, Stockholm

48 **Leahy, E. and Tol, R.S.J. (2011)** An estimate of the value of lost load for Ireland. *Energy Policy*, Vol. 39: 1514–1520

49 **London Economics (2013)** *The Value of Lost Load (VoLL) for electricity in Great Britain: Final report for Ofgem and DECC*. London Economics, London

50 **Lyons, S., Morgenroth, E. and Tol, R.S.J. (2013)** Estimating the value of lost telecoms connectivity. *Electronic Commerce Research and Applications*, Vol. 12: 40–51

51 **Macalister, T. (2014)** "Energy regulator threatens fines over Christmas blackouts". *The Guardian*, 6 March 2014

52 **METI (2011)** *Economic impact of the Great East Japan earthquake and current status of recovery*. Ministry of Economy, Trade and Industry, Tokyo

53 **Minkel, J.R. (2008)** "The 2003 Northeast blackout: five years later". *Scientific American*, 13 August 2008

54 **Newbery and Grubb (2014)** The Final Hurdle?: Security of supply, the Capacity Mechanism and the role of interconnectors, *University of Cambridge, EPRG Working Paper 1412*

55 **Newsbatch (2011)** Electricity regulation. Available at: www.newsbatch.com/electric.htm (Last accessed 09.09.2014)

56 **Norton, J. (2013)** *Do 'black swans' fly in flocks? Societies' vulnerability to infrastructure failures*. Presentation at the University of Bath Institute for Policy Research, 22 October 2013, Bath

57 **Ofgem (2012)** *Electricity capacity assessment*. Ofgem, London

58 **Ofgem (2013)** *National Grid's proposed new balancing services: draft impact assessment*. Ofgem, London

59 **Ofgem (2014)** *Electricity capacity assessment report 2014*. Ofgem, London

60 **Oppel Jr, R.A. and Gerth, J. (2002)** "Enron forced up California prices, documents show". *The New York Times*, 7 May 2002

61 **Parks, B. (2003)** *Transforming the Grid to Revolutionize Electric Power in North America*. Paper presented at the Edison Electric Institute Fall Conference "Transmission, Distribution and Metering", 13 October 2003, Ohio

62 **Pasquier, S. (2011)** *Saving energy in a hurry: update 2011*. International Energy Agency, Paris

63 **Pepermans, G. (2011)** The value of continuous power supply for Flemish households. *Energy Policy*, Vol. 39: 7853–7864

64 **Praktiknjo, A.J. (2014)** Stated preferences based estimation of power interruption costs in private households: an example from Germany. *Energy* (Article in Press)

65 **Praktiknjo, A.J., Hähnel, A., and Erdmann, G. (2011)** Assessing energy supply security: outage costs in private households. *Energy Policy*, Vol. 39: 7825–8833

66 **Rashbaum, W.K. (2003)** "The blackout: crime: this time, fewer arrests as the city stayed dark". *The New York Times*, 16 August 2003

67 **Reckon** (2012) *Desktop review and analysis of information on Value of Lost Load for RIIO-ED1 and associated work*. Reckon LLP, London

68 **Reichl, J. and Schmidthaler, M. (2014a)** Methodology, assumptions, and an application of blackout-simulator.com. *Energie Institut / Johannes Kepler University Working Paper*

69 **Reichl, J. and Schmidthaler, M. (2014b)** *The European electricity system: ad hoc power outage costs assessment and the issue of social acceptance*. Presentation at the OSCE conference "Sharing best practices to protect electricity networks from natural disaters", 2 July 2014, Vienna

70 **Reichl, J., Schmidthaler, M and Schneider, F. (2013)** The value of supply security: the costs of power outages to Austrian households, firms and the public sector. *Energy Economics*, Vol. 36: 256–261

71 **Richtel, M. and Romero, S. (2003)** "The blackout of 2003: communications". *The New York Times*, 15 August 2003

72 **Royal Academy of Engineering (2013)** *GB electricity capacity margin: a report by the Royal Academy of Engineering for the Council for Science and Technology*. Royal Academy of Engineering, London

73 **Scawthorn, C. and Porter, K. (2011)** *Reconnaissance report: aspects of the 11 March 2011 eastern Japan earthquake and tsunami*. SPA Risk, Denver

74 **Sforna, S. and Delfanti, S. (2006)** *Overview of the events and causes of the 2003 Italian blackout*. Paper presented at the IEEE Power Engineering Society conference "Power Systems Conference and Exposition", 29 October – 1 November 2006, Atlanta

75 **Sweeney, J. (2002)** *The California electricity crisis: lessons for the future*. Hoover Institution Press, Stanford, CA

76 **Taleb, N.N. (2007)** *The black swan: the impact of the highly improbable*. Random House, London

77 **Tillväxtanalys (2011)** *After the quake: energy crisis management in Japan*. Swedish Agency for Growth Policy Analysis, Östersund, Sweden

78 **Tishler, A. (1993)** Optimal production with uncertain interruptions in the supply of electricity: estimation of electricity outage costs. *European Economic Review*, Vol. 37: 1259–1274

79 **Tol, R. (2007)** The value of lost load. *Working Paper, The Economic and Social Research Institute (ESRI)*, Dublin, No. 214

80 **Tuttle, H. (2013)** "Blackouts". *Risk Management*, 1 September 2013

81 **UCTE (2004)** *Final report of the Investigation Committee on the 28 September 2003 blackout in Italy*. Union for the Coordination of Transmission of Electricity (now ENTSO-E), Brussels

82 **UCTE (2006)** *Final report: system disturbance on 4 November 2006*. Union for the Coordination of Transmission of Electricity (now ENTSO-E), Brussels

83 **U.S.-Canada Power System Outage Task Force (2004)** *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*.

84 **Valeri, L. and Tol, R. (2006)** Electricity shortages in Ireland: probability and consequences. *Quarterly Economic Commentary*, Winter 2006

85 **Von Selasinsky, A., Schubert, D.K.J., Meyer, T. and Möst, D.M (2014)** Valuing security of supply: does experience matter? *Technische Universität Dresden Working Paper*, 27 May 2014

86 **Weare, C. (2003)** *The California electricity crisis: causes and options*. Public Policy Institute of California, San Francisco

87 **Widin, D. (2009)** *"2003 Blackout Held to Involve 'Property Damage' Sufficient to Support Claim Under Property Policy"*. ReedSmith, 'The Policyholder Perspective', 15 June 2009

88 **Willis, K.G. and Garrod, G.D. (1997)** Electricity supply reliability: estimating the value of lost load. *Energy Policy*, Vol. 25 (1): 97–103

89 **Zachariadis, T. and Poullikkas, A. (2012)** The cost of power outages: a case study from Cyprus. *Energy Policy*, Vol. 51: 630–641

# Appendix A: Commonly used methods for assessing VoLL

Macroeconomic approaches can calculate the value of direct damages simply by dividing a country's GDP by the total electricity consumed. However, this approach doesn't manage to account for indirect losses, to either households or businesses (Willis and Garrod 1997[88]). Therefore, there are three main ways of calculating the cost of an outage to consumers:

- Stated preferences (eg WTP, WTA)
- Revealed preferences (via actual economic behaviour eg GDP)
- Economic modelling (for example, using production-function GVA)
- Combination methods: the blackout simulator.

Whichever method is being used, a weighted average can be achieved using weightings for individual consumers' consumption. For a short outage, annual peak demand is used, whereas for a longer outage (> 30 minutes), annual energy consumption is generally used as the weighting variable (Ghajar and Billinton 2006[31]).[vi]

## Method 1: Stated preference approach

There are three main methods of stated preference analysis:

- Contingent valuation: asking consumers directly how much they are willing to pay (WTP) or willing to accept (WTA)
- Conjoint analysis: respondents are given a selection of outage scenarios, and asked to rank different scenarios in order of preference. A cost element is often included as part of the scenarios. As far as possible, scenarios should be based upon people's actual experiences of energy costs and plausible outage characteristics
- Choice experiment: the research team draws up a large set of hypothetical outage scenarios, including a cost element and usually other characteristics such as duration, time of day etc. Respondents are asked to choose between different scenarios. Statistical methods are then used to derive the VoLL from combinations of people's responses. Similarly to conjoint analysis, more robust data can be achieved by basing scenarios on people's actual experiences.

### Advantages and drawbacks of stated preference methods

Stated preference methods usually find a big disparity between people's willingness-to-pay to avoid an outage and their willingness-to-accept to experience an outage. For example, Horowitz and McConnell (2002)[39] found a mean WTA/WTP ratio of around 7 in a meta-analysis of 200 contingent valuation studies. Theories from the field of microeconomics state that the higher the demand elasticity for a good, the lower the discrepancy will be between WTP and WTA (Hanemann 1991[35]; Praktiknjo 2014[64]); as such, services such as electricity which have extremely low elasticity of demand suffer from an extremely high disparity.[vii]

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[vi] This can also be carried out backwards, to extrapolate from a society-wide cost (from production-function approach) to individual households .

[vii] It is possible to hypothesise that the higher the demand elasticity, the lower the discrepancy between WTP/WTA figures and the actual price of the good. Therefore electricity = low elasticity = large discrepancy between WTA and WTP, and also large discrepancy between WTP/WTA and the market value of electricity.

Stated preference methods usually find much higher values for WTA. This is probably due to considerable loss aversion and status quo effects (Beenstock *et al* 1998[7]; Hartman *et al* 1991[36]). Kahneman and Tversky (1979)[44] suggest that when asked to make valuations under conditions of uncertainty, consumers create a 'value function' rather than a utility function, which is kinked at the level of the status quo, being concave for gains and convex for losses ('Prospect theory'). Results from contingent valuation studies support this theory (e.g. Pepermans 2011[63]). Households are found to be highly conservative when asked to make a choice between different reliability plans, showing a strong status quo effect. This is probably partly to do with the *unfamiliarity* of the good being valued (Coursey, Hovis and Schultze (1987[19]); despite the efforts of survey designers to base their scenarios of people's experiences, most people have little actual experience of power outages.

As well as behavioural effects such as loss aversion, there may also be psychometric biases induced by the designs of the options given to respondents. In particular, there may be an 'anchoring effect' that is potentially triggered by the range of prices built into the options (Hausman 1993[38]). However, Beenstock *et al* (1998[7]) tested for framing and anchoring effects, and found that they weren't present in their study. Extensive piloting can help to overcome potential framing effects (London Economics 2013[49]).

Stated preference measures suffer considerably from the hypothetical nature of the choice in question. Moreover, with goods such as electricity, people who are accustomed to reliable supply feel that they have an inalienable right to this supply; this leads to frequent 'protest' valuations, in which people state that they are not willing to pay or to accept anything for a change in the reliability level, and high levels of non-response. In one study (Beenstock *et al* 1998[7]), 51% of respondents gave WTA=£0, 13% didn't respond, and 11% gave identical WTA for each different outage type and duration tested. In the case of WTP it was even worse, with these proportions being 53%, 7% and 25% respectively. Moreover, stated preference methods are potentially subject to strategic bias, in which respondents think that by giving higher estimates they may be able to impact policy (for instance, to get high compensation for future outages). Using choice experiments may help to reduce this (Carlsson and Martinsson 2008[15]).

There are also important demographic and socioeconomic effects which impact stated preference methods. For instance, older participants are generally found to be more conservative, meaning that their status quo effect is stronger. This is also the case for smaller households, especially those with single occupancy (Beenstock *et al* 1998[7]). A study by Accent (2012)[1] found that 73% of the fuel poor in the survey were unwilling to pay anything for improvements in service.

## Method 2: Revealed preference approach

Revealed preference approaches use data derived from the actual economic activity of actors in an existing market. For example, several large industrial and commercial consumers have interruptible contracts, in which they agree to accept outages at certain times (for instance, during peak times between 4pm and 7pm), in exchange for reductions on their electricity bill. The value of these interruptible contracts thus provides a real-world example of the value of security of supply for that company.

### Advantages and drawbacks of revealed preference methods

It is generally accepted that revealed preference methods provide the most accurate estimates of VoLL. However, the disadvantage is that the data are usually not readily available, especially for the residential and public sectors. Interruptible contracts are less widespread in the UK than they are elsewhere; for example, in the US, distribution operators are beginning to experiment with offering people financial incentives for interruptible contracts. However, data from new technologies such as smart meters could provide a promising avenue for gathering revealed preference data.

## Method 3: Production-function approach

The production-function approach stems from Becker (1965)[6]. Becker suggested that people don't just gain utility from money and goods, but from a combination of goods and *time*. The more money someone has, the more the marginal value of money decreases relative to time, and vice versa. As such, a common application of the production-function approach is to assume that the value of lost leisure time for working people is equal to the average net wage. For unemployed, young and retired, it is generally assumed to be half the net average wage (see de Nooij *et al* 2007[22]; 2008[23]).

### Advantages and drawbacks of production-function methods

Production-function approaches usually return estimates much lower than stated preference methods. This is largely because production-function approaches only capture *indirect* losses, such as loss of productivity and loss of leisure time. They don't capture *direct* losses, such as food spoilage in a fridge, data losses etc. It could therefore be suggested that the difference between a stated preference estimate and a production-function estimate would represent the value of direct losses; however, this suggestion rests heavily on the idea that consumers are able to accurately estimate the value of their direct losses.

The production-function approach rests on the assumption that productivity (both of work and of leisure) effectively stops during an outage. Therefore, production-function methods may overestimate VoLL, because some productive activities may still be able to occur during an outage. On the other hand, they may underestimate VoLL, because they don't take into account the time taken to start production back up after an outage (de Nooij *et al* 2007[22]; 2008[23]). Furthermore, production-function approaches probably don't accurately capture the costs of repeated outages, because they don't capture the obstacles to regular economic activity that repeated outages could create, and they also don't capture potential adaptation by consumers (Zachariadis and Poullikkas 2012[89]).

For households, it is important to try and understand how people spend their leisure time, and how electricity-dependent their activities are (de Nooij *et al* 2007[22]). One major drawback of the production-function approach is that it assumes that a marginal hour of time is lost. However, the lost time might be during a World Cup final, when the VoLL would be far higher; it might also be during rush hour, when there would be considerable impacts from anxiety or stress (de Nooij *et al* 2008[23]; Zachariadis and Poullikkas 2012[89]).

## Method 4: The blackout simulator

The blackout simulator tool described in section 3.1 of the report is described in detail in Reichl and Schmidthaler (2014a)[68]. The tool uses a combination of stated preference methods for households and production-function and revealed preference methods for businesses and the public sector.

### Methods

Costs for businesses and public sector: the simulator reports the average from two methods:

- Production-function approach using productivity data from firms and public sector
- Typical damages per kWh-not-supplied in certain industries and sectors

Costs for households: survey of 8,336 households used to elicit willingness-to-pay to avoid an outage.

### Advantages and drawbacks of the blackout simulator

The creators of the blackout simulator report that the range of their estimates for non-household costs "is very much in line with international studies … [therefore] the validity of this approach is strongly supported" (Reichl and Schmidthaler 2014:7 [68,69]). The tool uses a combination of 'soft data' from surveys and 'hard data' from official statistics, which can help considerably in ironing out inconsistencies. The large number of households surveyed also helps to iron out uncertainties regarding the WTP of individual households.

However, the data for non-households is still subject to the large uncertainties caused by possible differences between WTP and WTA estimates. The study did not elicit WTA information from the respondents; however, given the disparity between WTA and WTP estimates from other studies, it is reasonable to assume that a similar level of uncertainty would apply. It is also worth noting that the early stage of this research means that there has been no opportunity as of yet for other academics to test or comment in the published literature on the approach used.

As with any model, the blackout simulator is dependent on numerous assumptions. Probably the key assumption to mention is that it assumes that all industrial, commercial and public sectors are productive, and that productivity stops entirely during an outage. This may result in a higher cost estimate, as some productivity may be able to continue during an outage; however, this is counterbalanced by the fact that extra time taken to start up after an outage is also not taken into account.

Another potential drawback of this method is that it involves calculating a very large number (total electricity unserved, which is translated into total cost to the economy); this must then be translated down into a VoLL for specific users (by diving total cost by total electricity unserved), in order to make it comparable to the £/MWh figures used by London Economics. This approach fails to take into account interdependencies between sectors, for which uncertainty is so high that meaningful estimates cannot be made. It is also worth noting that running the calculation the other way (ie multiplying up from a £/MWh figure to a total cost figure for the entire economy) encounters the same problems with robustness.

It is to be noted that the energy unserved figures in the simulator are due for revision, with minor changes due to be implemented in November 2014. This change may decrease the lost energy, thus decreasing the overall economy costs and increasing the VoLL, although specific revisions for the UK are as yet unknown.

# Appendix B: Case study overview

## CASE 1 **Network failure, U.S./Canada 2003**

### What happened?

On 14 August 2003, a high-voltage line in northern Ohio, which had been softened by the heat, sagged and brushed against a tree. This caused the line to trip, and the alarm system which was set up to identify the cause of the fault also failed. As system operators attempted to identify the fault, over the next 90 minutes three other lines sagged into trees, forcing an increased load on other power lines.

At 4.05pm, the load became too high and the lines cut out, causing a cascade of failures throughout eight Northeastern states and across southern Canada (Minkel 2008[53]). Large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout.

The outage affected an area with an estimated 50 million people and 61,800 MW of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey and the Canadian province of Ontario.

The blackout began a few minutes after 4pm (Eastern Daylight Time) and power was not restored for four days in some parts of the United States (CRO forum 2011[20]). Parts of Ontario suffered rolling blackouts for more than a week before full power was restored.

### Impacts on economy

The U.S. Department of Energy (DOE) has published a total cost estimate of about $6bn. This number is the most frequently cited cost estimate in press coverage of the blackout (Parks 2003[61]). Canada experienced a net loss of 18.9 million work hours. GDP fell by 0.7% in August, with losses mainly related to perishable goods spoilage, production and computer equipment shut down and business income losses (ELCON 2004[25]).

In the US, likely costs were estimated at being between $4.5 and $8.2bn (Anderson and Geckil 2003[2]). This estimate included:

- $4.2bn in lost income to workers and investors
- $15m to $100m in extra costs to government agencies, for instance due to overtime and emergency service costs
- $1-2bn in costs to the affected utilities
- Between $380m and $940m in costs associated with lost or spoiled commodities.

A post-blackout survey was undertaken by CrainTech (a business news publisher), Case Western Reserve University's Center for Regional Economic Issues and Mirifex Systems LLC (ELCON 2004[25]). The survey approached businesses in Ohio, New York, Pennsylvania, Michigan, Wisconsin and southern Canada. Their findings included:

- 24% of businesses lost more than $50,000 per hour of downtime (ie $400,000 for an 8-hour day)
- 4% of the businesses lost more than $1m for each hour of downtime
- Almost 11% of firms say the blackout will affect their decision-making with regards to either growth at the current location or relocation to another.

The blackout happened after trading on the stock exchange had closed for the day, meaning that the impact on financial services from the blackout on Wall Street was limited.

## Impacts on society

The outage immediately affected water supplies and transportation. Subway systems halted and traffic became snarled. Freeways were tied up in Detroit, and the governor of Michigan had to attend an emergency meeting without the use of lights or computers. Altogether, over 1,000 flights were cancelled (DeBlasio *et al* 2004[21]). Telephone services were severely disrupted, with disruption to mobile phones caused by a sudden surge of demand on the mobile networks (Richtel and Romero 2003[71]). Cashpoints failed, meaning that people without cash couldn't access money to buy supplies of candles or batteries.

Up to 11 deaths were linked to the blackout (numbers vary according to different news sources). Hospital admissions from respiratory attacks increased, and calls to 911 soared (Norton 2013[56]). However, hospitals managed to use back-up generators to maintain service. It is also worth noting that of the thousands of calls to 911, many were connected to people's initial fears of a terrorist attack, and the tripping out of alarm systems. There were reports of 300 fires caused by candles (Norton 2013[56]). There were some isolated (and unofficial) reports of looting; however, crime was minimal, and New York actually recorded a lower crime rate than usual (Rashbaum 2003[66]).

At first, residents were concerned that this was another terrorist attack. However, officials soon made announcements, and once residents' fears were allayed, and people realised that the kind of rioting and looting which had been experienced in the 1970s wasn't happening, there were reports of a 'party atmosphere' as residents went out into the streets.

## Impacts on industry (CRO forum 2011[20]; ELCON 2004[25])

- Daimler Chrysler: lost production at 14 plants. The company estimated that ~10,000 cars that were moving through the paint shops at the time of the outage had to be scrapped
- Ford: at one Ford plant, the outage caused molten metal to solidify inside one of the furnaces. It took them a week to repair the furnace
- Marathon Oil: a refinery had to be shut down. During this process, a small explosion was caused by the improper shutdown of a carbon monoxide boiler. As a precaution, a one-mile strip around the compound was evacuated, including hundreds of residents
- Nova Chemicals Corporation: reported that plant outages reduced Q3 profits by $10m (12¢ per share)
- Duane Reade Inc: New York's largest drugstore closed all 237 stores. The company estimated lost sales of $3.3m

- New York restaurants: the restaurant association estimated that restaurants lost between $75 and $100m in wasted food and lost business.

### Data quality and reliability

The New York blackout is one of the best-documented examples, and the overall cost data comes from a government source (Bill Parks, US DOE). However, it is worth noting that this figure is sourced from a presentation which gives no methodological detail (Parks 2003[61]). The cost range cited in the official post-blackout documentation is sourced from ELCON 2004[25], which in turn cites a non-peer-reviewed working paper (Anderson and Geckil 2003[2]). This paper estimates lost earnings (using GVA data) and assumes a 5–10% spoilage rate for grocery store goods. The cost to industry (~$1.5 billion) is a "base-level guess before diagnostic info available" (Anderson and Geckil 2003[2], footnote, p.6).

## CASE 2 **Capacity crisis, California 2000/2001**

### What happened?

In 1994, California began deregulating its electricity market. The aim was to reduce wholesale prices by increasing competition in the market. In the mid-1990s, capacity had exceeded demand by roughly 20%, meaning that there was a clear incentive to attempt to reduce oversupply (CBO 2001[17]).

However, a combination of events led to demand increases and supply decreases. The summer of 2000 was extremely hot, leading to an increase in demand for cooling; incomes in California increased, leading to further increases in demand; there were delays in building new capacity; and there was a decrease in hydropower imports from the northeast (Sweeney 2002[75]; Weare 2003[86]). In a well-functioning market, this tightening should have led to increases in retail prices in response to the rising wholesale prices. However, the market had been created with strict price controls, meaning that additional supply was not incentivised (Sweeney 2002[75]). This led to a capacity crisis.

In June 2000, the utility PG&E interrupted service for the first time in its history, affecting 100,000 people in the San Francisco area. In December 2000, the California System Operator declared a number of Stage 3 emergency situations, as electricity reserves fell beneath 1.5% of demand (CBO 2001[17]). From December 2001 onwards, there were frequent rolling blackouts affecting all areas of California. During 2001, load shedding occurred on 31 days, nine of which incurred involuntary rolling blackouts for a total of 42 hours (Weare 2003[86]). Blackouts occurred in December 2000 (affecting 100,000 customers in San Francisco), 17–18 January 2011 (affecting several hundred thousand customers), 19–20 March 2001 (affecting around 1.5 million customers), and 7–8 May 2001 (affecting more than 160,000 customers).

On 17 January 2001, PG&E and SCE had their credit ratings downgraded to junk, and the system operator ordered rolling blackouts. Governor Davis declared a state of emergency, and began using State money to buy electricity from the struggling utilities, at a cost of nearly $400/MWh.

The blackouts largely ceased by mid-summer 2001, assisted by lower temperatures and lower-than-expected demand. In September 2001, energy prices finally normalised. In May 2002, a criminal inquiry was initiated following the emergence of evidence that Enron manipulated the market in order to cause the electricity crisis. All market players were accused of price fixing.

## Impacts and costs

Prices for electricity spiralled out of control; at one point in December, California was paying wholesale prices of $1400/MW, compared with $45/MW the year before. Weare (2003[85]) suggests that the crisis cost the State an estimated $40bn in additional energy costs from 2001 to 2003. Retail prices increased by 30–40% in June 2001.

As the cash-flow problems of the utilities became evident, unregulated suppliers of wholesale power stopped selling to them. Eventually (after a series of emergency orders issued by the US DOE), the state of California stepped in and used state funds to buy power from unregulated wholesale suppliers to avoid widespread blackouts. This cost the state between $7bn and $8bn (Joskow 2001[42]; Sweeney 2002[75]). From 1 February 2001 onwards, the State was spending around $2 million per hour on alleviating the crisis (Johnston 2007[41]). However, it is worth noting that the State had an existing surplus of around $8bn, so the crisis merely decimated the surplus.

The long-term contracts negotiated during this period (January to May 2001) are reported to involve commitments of around $60bn. As these long-term contracts are paid off, retail prices will remain high (Joskow 2001[42]). The contracts were set to continue until at least 2011, and to cost around $4bn per year (Sweeney 2002[75]).

**Figure B1**: California average wholesale electricity price, 1998 to 2002.

*Source: Joskow and Kahn 2002[43]*

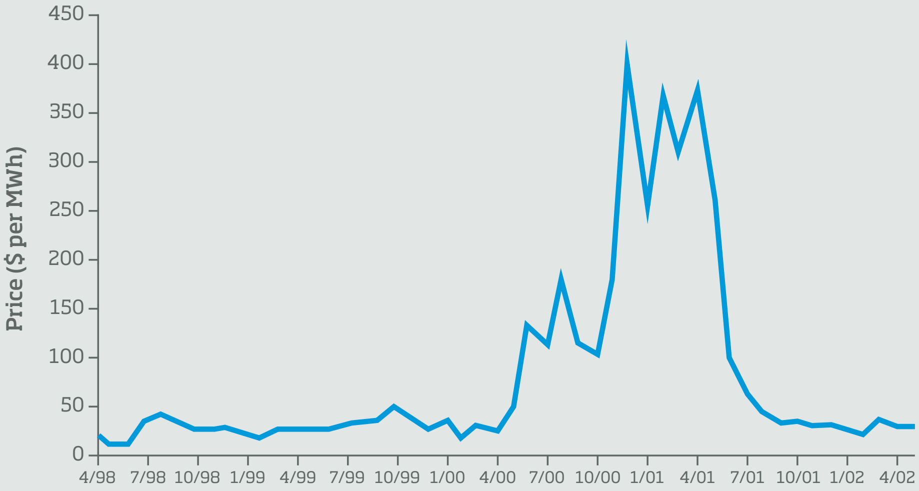
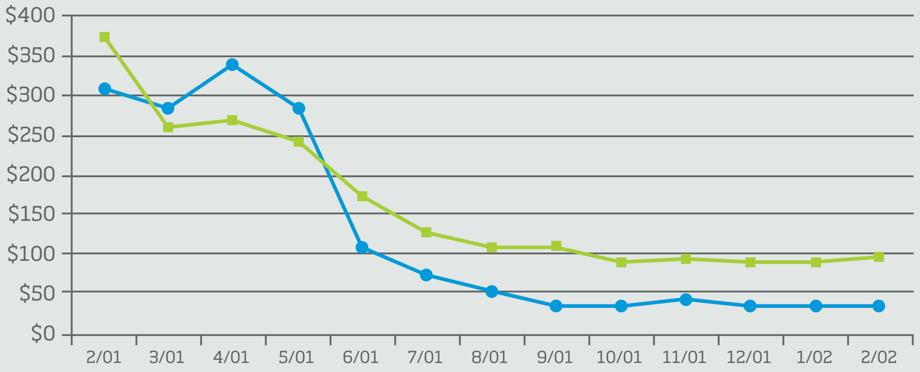


**Figure B2**: Comparison between average spot price and the price paid by the state of California for electricity during the crisis (in $/MWh).
*Source: Newsbatch 2011*[55]



**California wholesale electricity prices, February 2001 to Febrauary 2002**

## Longer-term impacts

The overall economic impact of the blackouts themselves is uncertain, and has been complicated by the global recession. However, in June 2001, UCLA projected that the crisis would slow the Californian economy in 2002 by between 0.7% and 1.5% and would increase unemployment by 1.1% (Cambridge Energy Research Associates 2001[13]). It is estimated that the impact of the blackouts on Silicon Valley cost millions of dollars in lost revenue. There is also possible evidence of longer-term economic impacts. Bushnell (2004:1045[12]) argues that "California has earned a reputation as an incubator of bad public policy ideas; it's experience with electricity industry restructuring has contributed substantially to this reputation." In April 2001, Moody's put California on negative credit watch.

There was lasting chaos for the financial and electricity markets. California's attempt at deregulation was a disaster, and after the crisis the private utilities were no longer the main purchasers of power, leaving the state more entangled with the electricity market than ever, with the state of California agreeing to buy SCE's transmission lines in April 2001 (Weare 2003[86]).

One interesting impact of the electricity crisis was that it illustrated many ways *not* to go about a restructuring of an electricity market. The freeze on retail prices meant that during the tight market, there was no incentive for consumers to reduce their consumption; reduced levels of demand would have assisted greatly in avoiding the blackouts which occurred. The demand elasticity of electricity is low; nevertheless, experiences in Japan have shown how ambitious demand-reduction programs can help to avoid a lasting electricity crisis. California relied on a market mechanism which gave no price signals to consumers to reduce their demand, meaning that the market did not function adequately. The US Congress (CBO 2001[17]) suggested that one of the key messages of the crisis was that consumers need to face the real costs of their electricity usage.

### Lessons for the UK?

California provides us with a rare recent example of capacity shortages caused by market mismanagement, and therefore clearly other markets will seek to learn lessons from this incident. However, California's previous history of market manipulation by the generators (FERC 2003[27]; Oppel Jr and Gerth 2002[60]) creates problems for cost comparisons. It is estimated that generators overcharged $6.3 billion between May 2000 and February 2001 (Johnston 2007[41]); this artificially pushed the wholesale price up. Moreover, the California experience is different in many ways to the current situation in the UK; for a start, the UK does not have an arbitrary retail price cap in place. As such, it could be argued that the experience in California would almost certainly not occur in the same way.

### Data quality and reliability

The wholesale price crisis is well-documented, and comes from highly reliable official market sources, as do the retail price data. The central cost estimate of the blackout is from Weare (2003)[86], in a Think Tank paper; this paper uses a robust comparison between energy prices before and during the crisis to estimate the extra cost to the state of California.

The estimates of overall GDP costs are from projections made during the crisis in 2001, and as such are subject to the high uncertainties associated with all economic projections. Making estimates of the impact on GDP after the event was complicated by wider economic trends, including the boom/bust leading to the financial crisis.

However, the cost estimates of the long-term contracts which were negotiated with the utilities are far less certain. The cost estimate of $60 billion in long-term contracts (Joskow 2001[42]) suffers from the high uncertainty associated with any economic projection. The longer-term cost estimates also suffer from a lack of data due to low transparency from official sources in the wake of the crisis. This report has not found any estimates of the final cost of the long-term contracts.

## CASE 3 **Natural disaster, Japan 2011**

### What happened?

On 11 March 2011, a 9.0 magnitude earthquake took place under the ocean 231 miles away from Tokyo. The earthquake caused a 30ft tsunami, which struck Eastern Japan, forcing several nuclear and thermal power stations out of action. By 21 March, over 27GW of generation – around 30% of total capacity – was estimated to be out of action:

**Figure B3**: Power plants damaged by the disaster.
*Source: Tillväxtanalys 2011*[77]

| Tohoku EPCO | | TEPCO | | Jointly owned | |
|---|---|---|---|---|---|
| **Nuclear power plant** | | | | | |
| Onagawa | 2.17 | Fukushima I and II | 9.1 | | |
| Total | 2.17 | Total | 9.1 | Total | 0 |
| **Thermal power plant** | | | | | |
| Hachinohe | 0.25 | Hitachinaka | 1 | Shinchi | 2 |
| Sendai | 0.44 | Kashima | 4.4 | Nakoso | 1.6 |
| Shin Sendai | 0.95 | | | Kashima | 1.4 |
| Haramachi | 2 | | | Sumitomo Metal/Kashima | 0.65 |
| | | | | Ksahimakita | 0.65 |
| | | | | Kashimaminami | 0.19 |
| Total | 3.64 | Total | 5.4 | Total | 6.49 |
| **Total Tohoku EPCO** | **5.81** | **Total TEPCO** | **14.5** | **Total jointly owned** | **6.49** |

By the end of April, the situation had improved somewhat, and some power stations had reopened; however, nearly 23GW was still out of action, comprising both nuclear and thermal plant (Scawthorne and Porter 2011[73]).

The energy grids in Eastern and Western Japan are essentially separate. This meant that the electricity shortfall could not be made up by imports from elsewhere in the country (Scawthorne and Porter 2011[73]).

Tokyo Electric Power (TEPCO) was forced to implement rolling blackouts (METI 2011[52]).

Frequency of 'rolling blackouts'

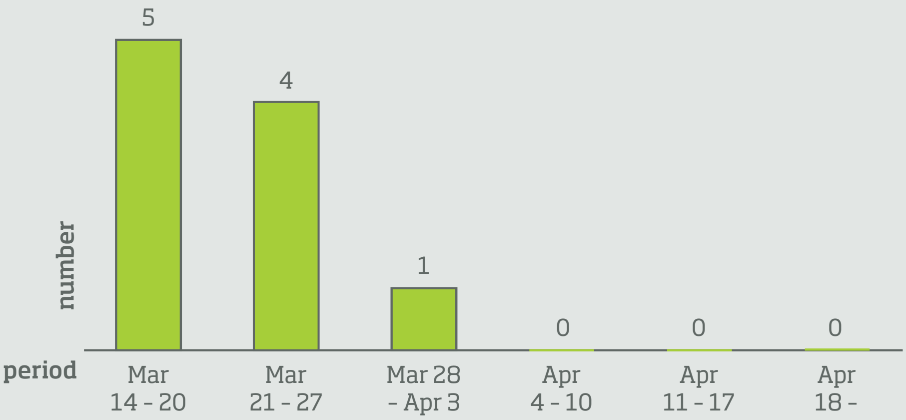
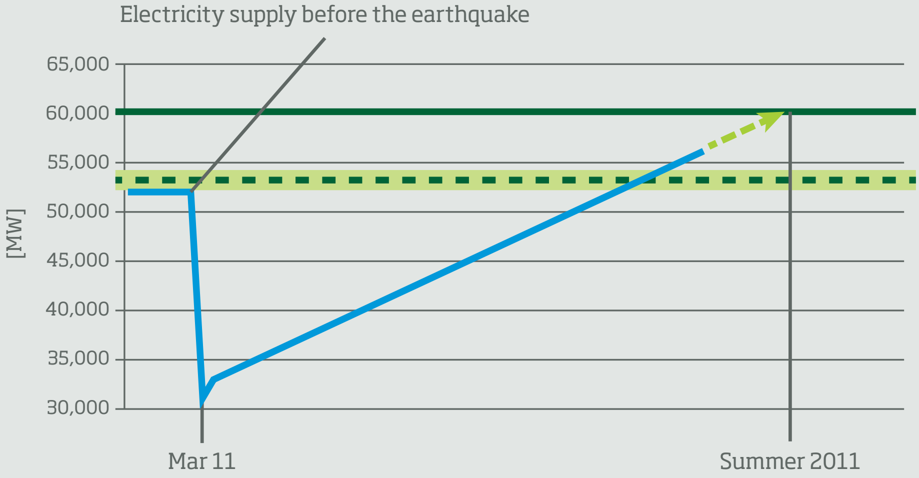


**Figure B4**: TEPCO's electricity supply capacity in 2011.
*Source: METI 2011[52]*



## Impacts and costs

The blackouts affected millions of households. Mobile phone and internet networks were cut off. Medical facilities were also hit; several medical facilities and hospitals lost power. Transportation was paralysed and 100,000 commuters were stranded in Tokyo (Fujimi and Chang 2014[30]).

Although TEPCO tried to put in place a schedule for the blackouts, this schedule often wasn't maintained. This uncertainty caused extra pressure on industry and services.

The rolling blackouts ended within a matter of weeks. However, supply remained tenuous, largely due to the difficulties of restarting the offline nuclear power plants. From July to September 2011, only 10 out of 54 nuclear plants were operating. Prior to the disaster, nuclear power had provided 30% of Japanese power capacity (ANRE 2010[3]).

Growth Analysis (2011)[33] suggests that in the short term, the impacts of electricity shortages caused the biggest problems for Japan's economic recovery. Costs to the economy are difficult to estimate, and some of the longer-term costs (eg damage to Japan's international 'brand') could be some of the gravest. Japan's industrial production fell by as much as 15% in March 2011. Growth forecasts were revised heavily downwards; the Bank of Japan estimated economic growth of just 0.6% for 2011 (Growth Analysis 2011[33]). However, it is extremely difficult to separate the costs of the blackouts from the costs of the disaster itself, because the damages from the incident as a whole are highly interconnected; it is also difficult to untangle the impacts from the economic pressures which Japan was already experiencing (for instance, due to the global recession and high gas import prices).

## Demand reduction response

In order to try and avoid further blackouts, the government decided to implement an energy saving strategy. In May 2011, the government published energy-saving targets of 15% for most sectors. Targeted recommendations were made for each sector, depending on their load curve and their safety requirements. Some noise regulations were relaxed to allow companies to shift their operations to overnight (Pasquier 2011[62]).

For industry consuming over 500kW, the government restricted electricity use via regulations, cutting industrial demand by 15% between 9am–8pm. Companies faced fines of up to 1m yen ($12,500) for each hour when the reduction target was not met. For households and SMEs, the government implemented a huge education campaign. This included live load updates on websites, in train stations and on TV. The government publicised energy-saving tips and promoted cooler clothing to reduce the use of air conditioning. They also launched a power-saving contest in the residential sector, and offered rewards for households and SMEs. SMEs were provided with checklists for energy-saving actions (Froggatt *et al* 2012[29]; Fujimi and Chang 2014[30]; Tillväxtanalys 2011[77]).

Interestingly, among industry, the levels of energy saving were broadly similar in the mandatory and voluntary areas. The most common types of energy saving were behavioural, such as adjusting light levels and reducing air conditioning. This may be because Japan was already very energy efficient, meaning that the 'low-hanging fruit' of efficiency improvements were not an available option (Fujimi and Chang 2014[30]).

### Data quality and reliability

As noted above, the cost of the blackout is extremely difficult to untangle from the costs of the disaster as a whole. This report found a lack of recent estimates of costs, and most estimates were made very soon after the disaster, meaning that they suffer from high uncertainty due to projections.

## CASE 4 Network failure, Western Europe 2006

### What happened?

On 4 November 2006, the German system operator E.ON Netz had to switch off a high voltage line to let a ship pass underneath. Simultaneously, there was a high amount of wind electricity which fed 10,000MW into the Western and Southern European grids. A last-minute change in the timing of the routine switch-off and a lack of communication between E.ON and neighbouring utilities and system operators led to frequency instabilities in the grid and overloaded the Landesbergen-Wehrendorf interconnector (Bialek 2007[9]).

An uncoordinated attempt to re-route the load flow resulted in the loss of the Landesbergen-Wehrendorf interconnector. The tripping of several high voltage lines, starting in Northern Germany, led to the splitting of the network into three zones, with significant power imbalances between the zones (UCTE 2006[82]). The power imbalance in the western area led to a severe drop in frequency. Supply was interrupted for around 15 million consumers, mainly in Germany, France, Italy, Spain and Austria. Grids in Belgium, the Netherlands and Croatia were also strained, causing some local outages (Tuttle 2013[80]). There were even cases of lines tripping as far away as Morocco, Algeria and Tunisia; overall, around 20 countries were affected (Lagendijk and van der Vleuten 2008[47]).

After the event, adequate countermeasures by individual system operators prevented the incident from turning into a Europe-wide blackout. Full resynchronisation was achieved 38 minutes after the blackout. Normal service resumed for all consumers around two hours after the incident (UCTE 2006[82]).

| Nr. | Zeit | kV | Leitung |
|---|---|---|---|
| 1 | 22:10:13 | 380 | Wehrendorf-Landesbergen |
| 2 | 22:10:15 | 220 | Bielefeld/Ost-Spexard |
| 3 | 22:10:19 | 380 | Bechterdissen-Elsen |
| 4 | 22:10:22 | 220 | Parderborn/Süd-Bechterdissen/Gütersloh |
| 5 | 22:10:22 | 380 | Dipperz-Großkrotzenburg 1 |
| 6 | 22:10:25 | 380 | Großkrotzenburg-Dipperz 2 |
| 7 | 22:10:27 | 380 | Oberhaid-Grafenrheinfeld |
| 8 | 22:10:27 | 380 | Redwitz-Raitersaich |
| 9 | 22:10:27 | 380 | Redwitz-Oberhaid |
| 10 | 22:10:27 | 380 | Redwitz-Etzenricht |
| 11 | 22:10:27 | 220 | Würgau-Redwitz |
| 12 | 22:10:27 | 380 | Etzenricht-Schwandorf |
| 13 | 22:10:27 | 220 | Mechlenreuth-Schwandorf |
| 14 | 22:10:27 | 380 | Schwandorf-Pleinting |

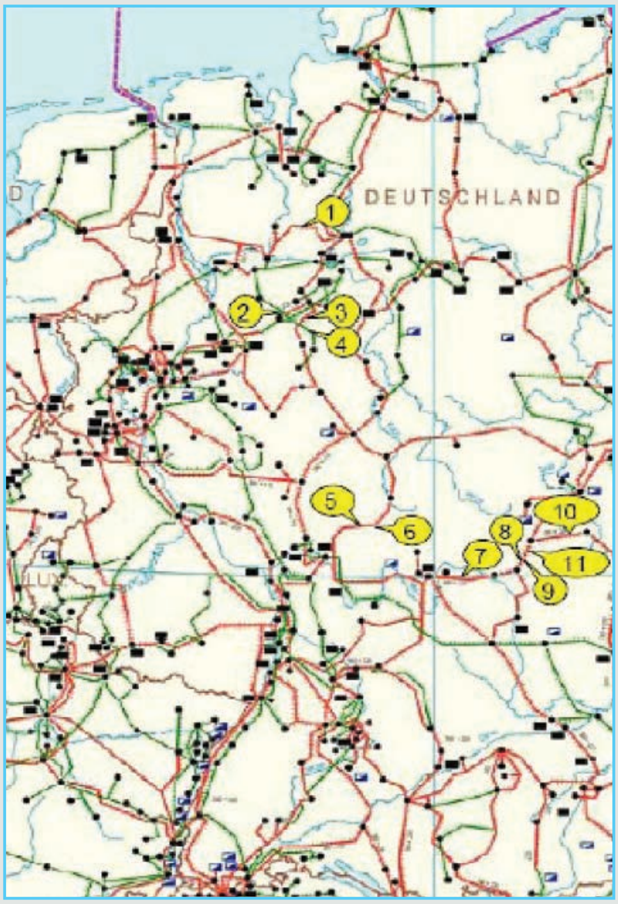


**Figure B5**: Cascade of line trips in Germany between 22:10:23 and 22:10:27 (a total of 4 seconds!)
*Source: Lagendijk and van der Vleuten 2008*[47]

## Impacts

As with other blackouts, reports of social impacts vary according to different news sources. However, Lagendijk and van der Vleuten (2008)[47] collate the following reports of impacts from various newspapers:

- In Coburg, Germany, four men broke into a hardware store
- In Cologne, 70 people were trapped for half an hour in a cable car above the Rhine
- Der Spiegel reported that "rescue workers were in constant use", partly due to the tripping of alarm systems
- In France, firemen responded to around 40 calls from people stuck in lifts.

There were long delays in rail transport, affecting about 100 trains mainly in Germany. Subways had to be evacuated. Costs to restaurants and bars in spoiled products and lost sales totalled around €100m (CRO forum 2011[20]).

There were no reports of injuries due to the blackout. However, the impacts could have been greater had the blackout happened on a weekday.

### Political impacts

This blackout illustrates the fact that often, the major impact from a blackout is not so much the direct social or economic consequences, but the ensuing political debate. This incident sparked heated debate on the validity of the existing governance structure of the European electricity network. On the one hand, some called for increasing coordination, in order to overcome the issues called by the partial decentralisation of the network in the hands of national system operators; this would lead to an increased role for the EU in electricity provision. Various newspapers cited the Italian Prime Minister Romano Prodi saying that there was a "contradiction between having European links and not having one European authority" (Castle 2006[16]). However, in response to this, the system operators argued that their actions following the initial incident had acted effectively to prevent a Europe-wide blackout. They argued that decentralisation, far from being the root cause of the problem, actually acted as a hedge against more serious cascading outages (UCTE 2006[82]).

### Data quality and reliability

This report has not found any data on the costs of the blackout. The literature focuses overwhelmingly on the causes of the blackout and the impacts on the transmission networks and system operators, rather than the economic costs. The €100m in spoiled products estimates is from the CRO Forum (2011)[20], an insurance industry trade group, who offer a disclaimer that "all liability for accuracy and completeness… is expressly excluded".

## CASE 5 Network failure, Italy / Switzerland 2003

### What happened?

On 28 September 2003, a fault on the Swiss power system caused the overloading of two Swiss lines close to the Italian border. The loss of vital interconnecting lines caused cascading outages in both Switzerland and Italy (Berizzi 2004[8]).

The Italian power system faced its worst disruption in 50 years, which also affected parts of Switzerland with around 56 million people in total (CRO Forum 2011[20]). The total energy not delivered was roughly 180GWh (Corsi and Sabelli 2004[18]).

Electricity was restored after between 1.5 hours in the North-West, and 19 hours in Sicily (Berizzi 2004[8]; UCTE 2004[81]). The main reason for the difference in timings was the failure of several hydro plants in southern Italy to black-start. During the restoration in central Italy, a lack of supply was experienced, as several large thermal units were not yet in operation and the pumped storage units were not yet filled. Rolling blackouts were experienced between 11am and 6pm in Central and Southern Italy (Sforna and Delfanti 2006[74]). Finally, major problems were experienced reconnecting Sicily, due to the danger of high voltage transfers to areas without power. This illustrates the fact that restarting the system in the event of an outage is sometimes fraught with difficulty, and if managed incorrectly can result in long delays for power restoration in some areas.

## Impacts

The blackout happened overnight, meaning that impacts were less severe than they could have been otherwise. However, it was the night of the annual Nuit Blanche carnival in Rome, meaning that more people were on the streets at night than usual. 30,000 people were trapped on trains, and several hundred passengers were stranded on underground transit systems. The subway had to be evacuated. All flights were cancelled (CRO forum 2011[20]; Johnson 2007[40]).

Despite the disruption, the police reported no serious incidents; however, there were unofficial reports of three deaths attributed to the blackout, mostly elderly people falling down the stairs in the dark. Some news sites reported traffic chaos on the roads as traffic lights failed, possibly causing one death. Hospitals used back-up generators successfully, meaning that no hospital operations were affected.

Significant knock-on effects occurred across other critical infrastructures. Commercial and domestic users suffered disruption up to 48 hours. Cost to restaurants and bars in spoiled products and lost sales totalled up to ~$139m (CRO forum 2011[20]).

| | Primary sector | Secondary sector | Tertiary sector | Households | Total |
|---|---|---|---|---|---|
| **North** | 5.3 | 136.7 | 60.8 | 43.1 | **246** |
| **Center** | 20.6 | 217.6 | 154.6 | 98.2 | **491** |
| **South** | 20.9 | 82.8 | 97.6 | 94.3 | **296** |
| **Sicily** | 12.4 | 33.7 | 54.6 | 49.5 | **150** |
| **Total** | **59.2** | **470.8** | **367.5** | **285.0** | **1,182** |

**Figure B6**: Damage impacts in million Euros, estimated by theblackout simulator model.
*Source: Reichl and Schmidthaler 2014b[69]*

## Data quality and reliability

Similarly to the European 2003 blackout (Case 4), the majority of information focuses on the causes of the blackout and the impacts on the transmission networks, rather than the overall economic costs. This report found no evidence of cost estimates carried out after the blackout.

The cost estimates given in the table above are from a presentation by Reichl and Schmidthaler (2014b[69]; see also Reichl and Schmidthaler 2014a[68]), and are used as a demonstration of the blackout simulator described in Section 3 of the report. The uncertainties in simulator estimates are described in Appendix A, Section 4. The paper does not compare the simulator estimates with actual cost estimates of the blackout; this report could not find any estimates made after the incident of the actual costs.

## CASE 6 **Daily interruptions, Cyprus 2011**

### What happened?

The largest power station in Cyprus is located next to a military naval facility. In July 2011, a large explosion damaged the plant and knocked out 390MW of steam turbines and 440MW of CCGT.

This represented nearly 60% of the island's total generating capacity. The island has no interconnection with other islands or the mainland; therefore this created an emergency electricity situation.

The state-owned electricity utility on Cyprus (EAC) implemented emergency measures, including daily power interruptions (Zachriadis and Poullikkas 2012[89]). Power to 'vital' areas of the economy (including tourism) was maintained, but power to residential areas was cut for 2–4 hours per day for one month. The government informed citizens by SMS of the timings of the planned interruptions. Emergency demand-side reduction was called for, with an emphasis on domestic load shifting. Generators rented from neighbouring principalities arrived within a few weeks, and electricity was imported from the north of the island.

After a month, normal service was resumed; however, if no emergency measures had been taken, the crisis would have taken about a year to resolve.

### Impacts and costs

The example of Cyprus shows how difficult it is to accurately measure the costs of a blackout, even when carrying out an assessment after the event.

Zachariadis and Poullikkas (2012)[89] use three different methods:

- A demand-function approach using econometric modelling
- A production-function approach which assumes that the VoLL is equal to the GVA of firms, and to the average net annual wage (after tax) for households, or half the net annual wage for unemployed and retired
- A bottom-up approach which estimates the costs and losses to the electricity utility from the emergency measures which had to be implemented.

As shown in *Figure B7*, the two top-down estimates differ almost by an order of magnitude:

| | Demand-function approach | | Production-function approach | Estimated cost of emergency measures |
|---|---|---|---|---|
| | With emergency measures | Without emergency measures | With emergency measures | |
| Industry | 0 | 2.3 | 2861 | 139.6 |
| Services | 100.2 | 215.4 | 18935 | 0 |
| Residential | 91.6 | 179.7 | 15614 | 0 |
| **Total** | **192** | **397** | **30,598** | **139** |

**Figure B7**: Estimated economic losses to sectors and to the utility company (million Euros).
*Source: Zachariadis and Poullikkas 2012*[89]

### Data quality and reliability

The estimates above are from a peer-reviewed study which was carried out after the incident. Three robust methods are used; however, this study has not been replicated elsewhere in the literature, and the disparity between the three different estimates illustrates the large uncertainties in these figures.

# Appendix C: List of abbreviations

**CCGT**: Combined Cycle Gas Turbine

**CST**: Council for Science and Technology

**DECC**: Department of Energy and Climate Change

**DNO**: Distribution Network Operator

**FDI**: Foreign Direct Investment

**GVA**: Gross Value Added

**GW**: Gigawatt (1,000,000,000 Watts)

**I&C**: Industrial and Commercial Sectors

**ICT**: Information and Communications Technology

**kWh**: Kilowatt-hour

**MW**: Megawatt (1,000,000 Watts)

**MWh**: Megawatt-hour

**SME**: Small / Medium Enterprise

**US DOE**: United States Department of Energy

**VoLL**: Value of Lost Load

**WTA**: Willingness-to-Accept

**WTP**: Willingness-to-Pay

# Appendix D: List of interviewees and respondents

**Stefan Bouzarovski** (Manchester University)

**Michiel de Nooij** (University of Amsterdam)

**Nick Eyre** (Environmental Change Institute Oxford)

**Caroline Holman** (Jaguar LandRover)

**Tooraj Jamasb** (University of Durham)

**Tim James** (Jaguar LandRover)

**Greg Marsden** (Leeds University)

**Miranda Mayes** (Accent MR)

**Edgar Morgenroth** (Economic and Social Research Institute, Dublin)

**Aaron Praktiknjo** (Institut für Energietechnik, TU Berlin)

**Johannes Reichl** (Johannes Keppler Universität, Linz)

**Colin Smith** CBE FREng (Rolls Royce)

**Dr Liane Smith** FREng (InteTech)

**Greg Swinand** (London Economics)

**Richard Tol** (University of Sussex / Vrije Universiteit Amsterdam)

**Gareth Williams** (Airbus)

**Simon Wright** (Energy Savings Trust)

# Appendix E: Project team

**Dr Alan Walker** (RAEng)

**Emily Cox** (RAEng / University of Sussex)

**Prof John Loughhead** OBE FREng

**Dr John Roberts** CBE FREng

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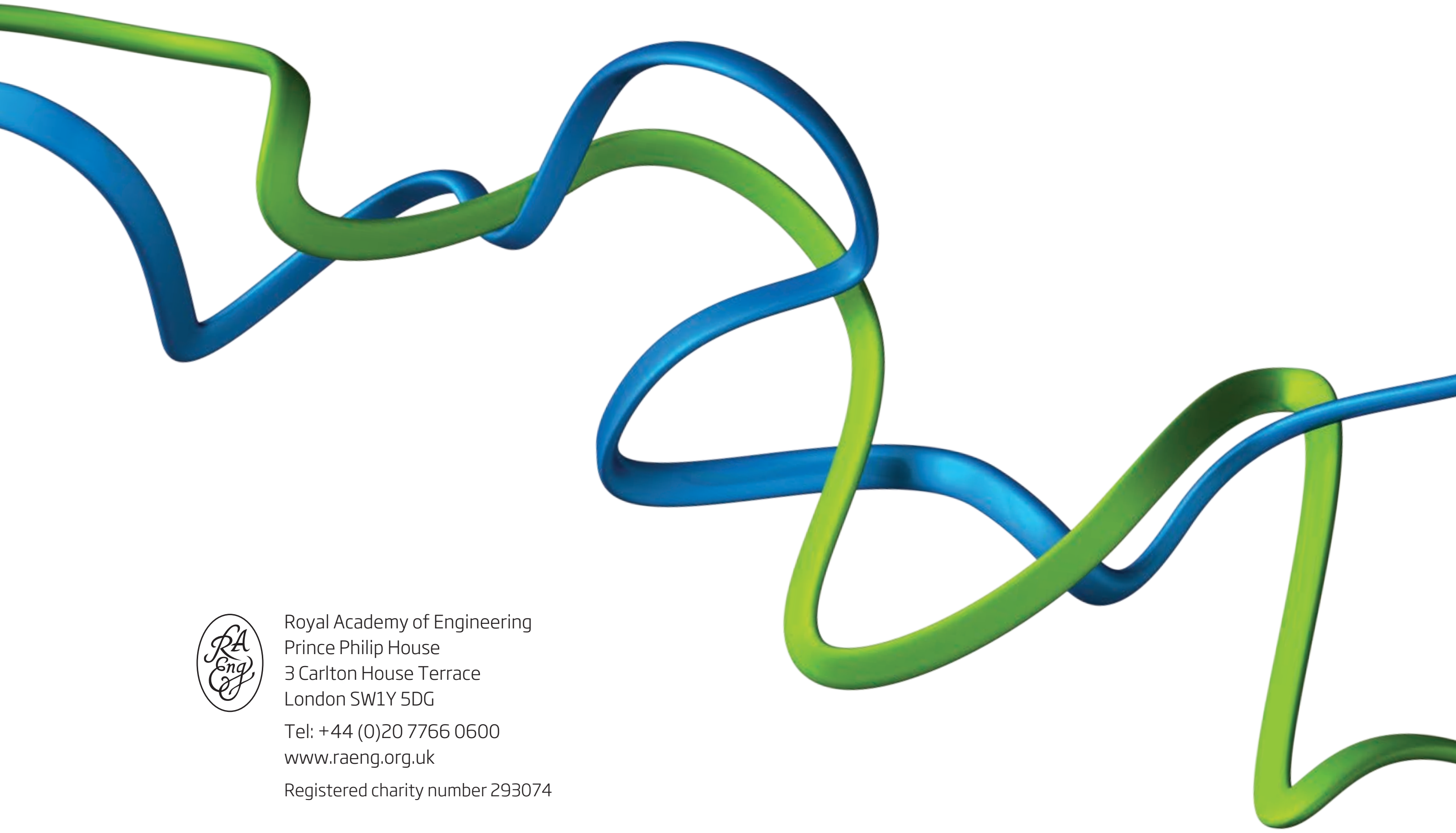

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