Scenarios for Extreme Events

Cost Benefit Analysis

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Executive Summary

This report develops a statistical approach to derive a conservative estimate for the value of the costs that could be avoided through improvements in the knowledge that underpins GB whole energy network resilience investments.

The Scenarios for Extreme Events Strategic Innovation Fund project will develop an energy systems model and resilience metrics to improve understanding of whole-energy system resilience, thereby enabling better identification of vulnerabilities and more effective resilience investment. The model will span both the electricity and gas networks and will capture the linkages between these and other elements of essential UK infrastructure to allow insights into aspects of whole system vulnerability that would be missed through traditional siloed approaches to modelling energy system resilience, which typically only consider each system in isolation.

The benefits of improved whole energy system resilience result from the possibility of avoiding or mitigating the significant costs incurred when large-scale disruptive events occur. Given the breadth of possible impacts, it would be impossible to comprehensively estimate the future savings that would result from preventing such an event from occurring. Rather than tackling the whole evaluation, here we develop a model that views the resilience investment as a mechanism to reduce the frequency and severity of large electricity outage events. From this we are able estimate the portion of the total benefit that derives from reducing the number of customers who suffer electricity disconnections. The estimates should be regarded as highly conservative, particularly in the case of the costs associated with the very largest events.

Our analysis is based on over 23 years of distribution system fault data for Scotland, with results scaled to give cost savings for the whole UK. The data is used to derive statistical parameters that allow the simulation of current patterns of fault occurrence and numbers of customer disconnections. This forms the counterfactual, baseline case. These parameters are then modified in a variety of scenarios to reduce both the number of events that occur and the likelihood that an event will be severe. Comparison of outage numbers between the counterfactual and scenario cases allows the benefit of a more resilient system to be estimated. The value of a prevented or less severe outage is calculated through applying assumptions around the unmet demand and the value of lost load. Savings are aggregated over a 25-year period, with future savings discounted at the social discount rate of 3.5%.

Using this approach, we estimate that the outputs from the Scenarios for Extreme Events project could provide cost savings due to reductions in customer disconnections in the order of £200m - £400m across the UK over 25 years.

Analysis of the Scottish fault data indicates that, in common with other similar international data, the severity of outage events follows a power law distribution. This leads to a small but finite probability of a random event bringing unexpectedly large consequences. A review of literature reveals that such events are typically found to result from faults cascading across power systems. This behaviour has been linked to properties of networked systems rather than the reliability or resilience of its component parts, which suggests that the most effective measures for avoiding such very large events may not be 'traditional' resilience measures that aim to cut failure rates, but rather strategies aimed at lowering cascade risks.

The statistical model developed here supports this. Results indicate that, for power law parameters derived from the Scottish fault data, improving everyday reliability and resilience by reducing the frequency of outage events gives no protection against the occurrence of a very large event. Suggested interventions from the literature include:

- Prioritising fault recovery times to reduce the length of time for which the system is under stress.
- Developing 'fire breaks' within and between networks (e.g. Strategically positioned battery storage) that could slow or prevent cascade events.

If the whole energy system model being developed as part of this project can shed light on how the energy networks can build resilience against cascading failures, then its potential value through avoided costs could be very large.

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Contents

1 Introduction

The Scenarios for Extreme Events Strategic Innovation Fund project sets out to better understand how whole-energy system resilience can be impacted by extreme events, thereby enabling better identification of vulnerabilities, and informing future investment planning decisions. The improved understanding will result from the development of a model and resilience metrics that span electricity and gas networks, capturing the key linkages between these systems and other elements of essential UK infrastructure. These will provide insight into aspects of whole system vulnerability that would be missed through traditional siloed approaches to energy system resilience, which typically only considers each system in isolation.

This report describes the outcomes of Work Package 5, which estimates the potential benefits of developing such a model, investigating the potential savings through avoided costs that could be realised from making better informed investment decisions, and thereby reducing the size and impact of largescale energy system outage events.

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The approach to estimating benefits is based on applying analysis methods from the literature to a dataset of historical Scottish distribution network faults. The statistical parameters derived from this are then used to drive a series of Monte Carlo simulations of fault occurrence over a 25-year period. The simulations are conducted based on both current statistical parameters, and altered parameters that assume the implementation of enhanced resilience measures. In line with the Scottish dataset, the output from the Monte Carlo simulation is a change in the number of outages experienced by customers. Further assumptions map this to a monetary value for reduced unmet demand. The values for Scotland are extrapolated to give a value for avoided costs for the whole UK. This process is summarised in Figure 1.

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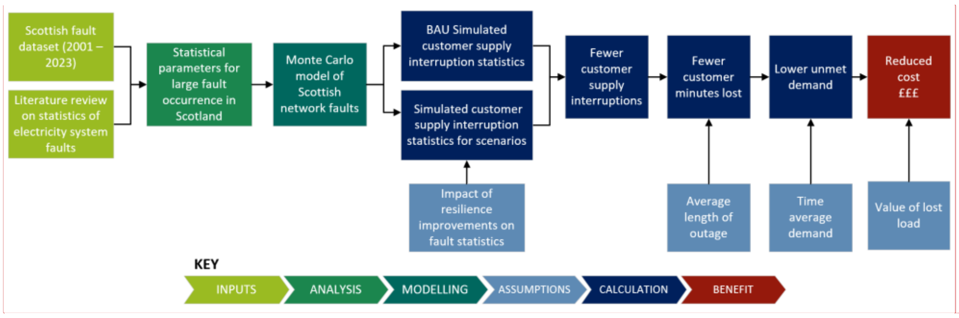

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Figure 1: A summary of the approach to estimating the benefits from improved resilience.

The report covers the following areas:

- The development of a benefits map that qualitatively charts the cascade of benefits that result from improving the resilience of key infrastructure (Section 2).
- A review of the literature that analyses the occurrence statistics for extreme energy network events (3).
- Statistical analysis of the Scottish electricity distribution fault data (Section 4).
- A description of the Monte Carlo benefits model and presentation of resulting estimates of project benefits (Section 5).
- Conclusions, discussion of results and suggestions for further work (Section 6).

2 Benefits mapping

The model and approach under development within this project has the potential to deliver considerable benefit to the UK through improvements in the resilience of national infrastructure, and the more efficient allocation of the resilience-building budget across several critical service industries. This is captured in Figure 2. The CBA valuation presented here does not attempt to capture this full cascade of benefits. As indicated, the metrics of reduction in electricity customer minutes lost (CML) and electricity customer supply interruptions are used to estimate a portion of the possible benefits. These are converted into monetary benefits through applying a fixed value of lost load (VoLL) conversion, and the resulting benefits captured are unlikely to reflect the full costs of a largescale supply interruption [1].

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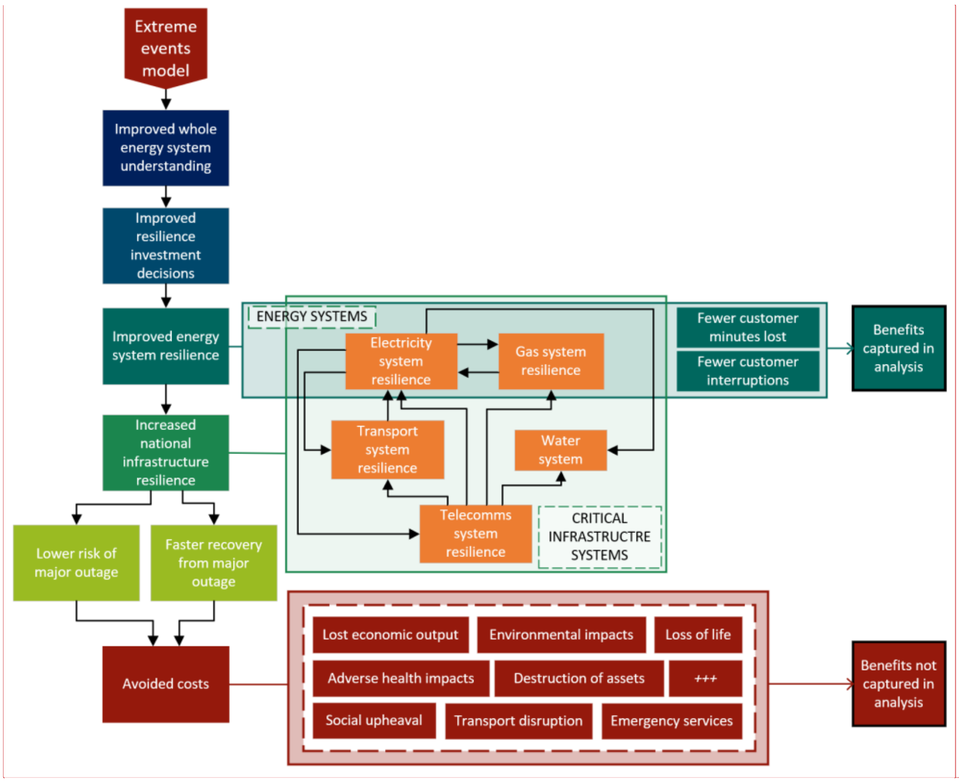

Figure 2: Benefits map illustrating the avoided costs that could result from the successful implementation of the extreme event modelling. The benefits model here seeks only to monetise the benefits obtained through reduction of the number of customer interruptions and customer minutes lost.

3 Literature on the statistics of extreme power outage events

A number of authors have collected and analysed data on large electricity system power outages. The following section presents a review of publications that examine and rationalise the statistics of these events, and some of the approaches to reducing the likelihood of occurrence.

Stankovski *et al.* [2], use both assembled data on severe blackout events across Europe and an Italian national dataset of transmission system events to identify cascading failure events. They define these as a series of sequential failures resulting from complex system interactions between components and/or human operators. The data is processed to produce plots of exceedance probability versus event size (demand not met) on logarithmic axes. These are observed to exhibit the straight-line behaviour characteristic of a power law process. Their detailed analysis identifies that:

- Cascade events are mostly commonly triggered by weather events.
- With sufficient data, it may be possible to spot the conditions that precede a cascade and potentially intervene to prevent it.
- Recovering failed assets within 13 hours could halve the level of unmet demand experienced within power systems.

As a probability distribution, the power law has been found to provide a way to model the occurrence of a wide range of natural phenomena, with its properties allowing it to inherently generate black swan behaviour, i.e. low probability high impact events [3]. Figure 3, taken from Hines *et al.* [4], shows an example of power law behaviour relating the size of an outage, S, (in terms of the loss of power), to the likelihood that a given outage is larger than S. The relationship is observed in data on large black outs in North America between 1984 and 2006.[1]

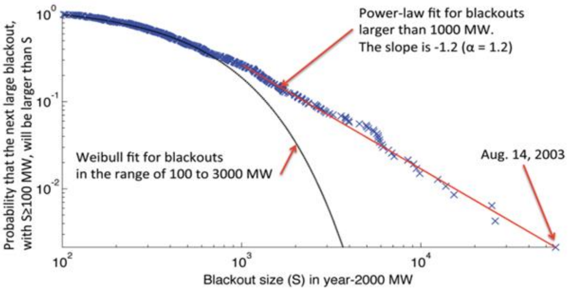

Figure 3: Probability that a large blackout will interrupt service by S or more MW. From [4]. The data is scaled to account for increases in whole system demand over the period, with power demand in 2000 acting as the baseline year.

Hines *et al.* [4] provide a rationale for the applicability of the power law to large electrical blackouts, noting that network faults do not occur independently of one another: a system in which one fault has already occurred is more likely to suffer additional failures through the increased stress placed on the remainder of the network. This exposes the system to the risk of cascading failures. In addition, Dobson *et al.* [5] suggest that there are aspects of the way in which power systems are designed and operated that are key to understanding the emergence of a power law

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[1] Further examples of this type of analysis may be found in the following references: [15], [24] and [23].

relationship. They point to economic pressures to operate power systems close to their maximum capacity, increases in the loads carried by the system and engineering responses to reliability and resilience as factors that combine to produce power law statistics.

In the UK, extreme wind speeds have the most significant impact on the electricity network [2, 6, 7], with climate change expected to produce more frequent occurrence of such destructive weather events [8, 9]. Additionally, the move to electrify an increased proportion of our energy needs in pursuit of net zero goals will dramatically increase the volumes of power transmitted [10]. Both of these factors point to a reinforcing of the mechanisms that generate power law statistics.

The literature contains insights into interventions that could lower the risk of cascading power system failures:

- **Reducing recovery times following failure.** This is mentioned by a range of authors (in addition to Stankovski *et al.* [2], mentioned above) as a way to mitigate some of the risk of large-scale outage (e.g. [11] [7] [12]) as it cuts the time during which the system is operating under increased stress.
- **Adding components to the system with the aim of 'buying time' and reducing the vulnerability of portions of networks that are downstream of faults.** For example, a number of authors (e.g. [11, 13, 8]) highlight the potential role that battery energy storage systems could play in building energy system resilience and reducing the risks of large, cascading failure events.

4 Analysis of Scottish distribution network fault data

The National Fault and Interruption Reporting System (NaFIRS) maintains statistical information on faults and interruptions for electricity DNOs in the UK. While the data held on NaFIRS is not generally publicly accessible, SSEN Distribution publishes the data that it uploads [14]. The data comprises a list of faults and outages recorded between April 2001 and August 2023, the cause of the outage, the number of customer disconnections and the number of CML. The following section describes the processing and analysis of this data so that it may be used to derive statistics that will allow an estimate of the occurrence and severity of large power blackout events within the SSEN region.

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The data considers each fault separately, and therefore does not make links between different faults associated with the same cause, for example, a large weather event. To account for this in a simple manner, the outages associated with faults occurring on the same day have been aggregated.

Section 4.1 analyses the frequency and occurrence of historical fault events and Section 4.2 covers the fault recovery times. In Section 4.3 we explain the assumptions and data sources that are used to extrapolate to UK-wide outage estimates.

4.1 Outage frequency and severity

Table 1 presents a summary of the occurrence, length and CML for outages above given thresholds of numbers of customers disconnected in a day.

Table 1: Summary of SSEN NaFIRS data [14], with aggregated daily outages. Days with > 10,000 affected customers are taken as the threshold for the power law analysis.

Customers affected in a day (S)	Number of days in sample with >S customers affected	Average number of days per year with > S customers affected	Average outage time per affected customer	Average CML (1000) per day with > S affected customers
1	7738	330.2	94	256
2000	1704	72.7	89	940
4000	555	23.7	121	2466
6000	292	12.5	155	4322
8000	176	7.5	194	6722
10000	129	5.5	225	8816
12000	96	4.1	249	11276

Adopting the approach used in the literature reviewed above (e.g. [15, 4, 2]) and exemplified in Figure 3, we plot the probability that daily outages impact more than S customers, against the number of customers affected, on logarithmic axes. This is shown in Figure 4. For days with a total of more than 10,000 customer disconnections (S > 10,000), this results in a power law relationship, with coefficient $\alpha = 1.7$ and R^2 coefficient of 0.998. The expected annual number of high disconnection days, according to this definition, is found to be 5.5.

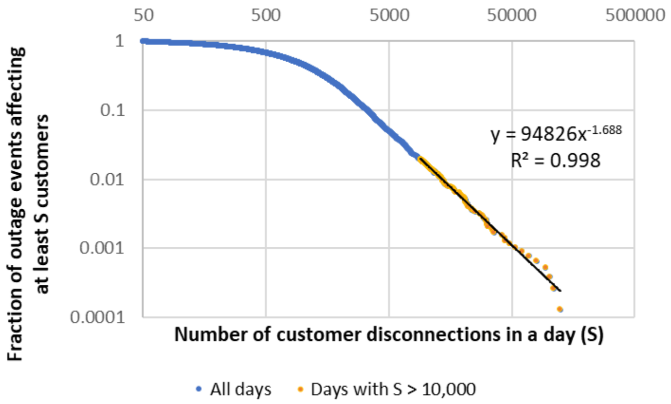

Figure 4: Exceedance distribution for the number of daily customer interruptions in Scotland between 2000 and 2023. The negative of the exponent in the power law line-of-best-fit gives the value of the alpha parameter used in later statistical modelling.

4.2 Fault recovery times and unmet demand

Data on the length of outage that results from individual faults (prior to aggregation into per-day customer disconnections) shows that the large outages are dealt with more quickly than the small ones but, within the category of 'large' outages, there is no correlation with size. This is consistent with findings reported in the literature [6]. However, examining the daily aggregated data (Figure 5), it is found that faults take longer to clear on days with many customer disconnections. For days with > 10,000 outages, the average fault duration is 225 minutes. As a simplification, this single value is used in the analysis. It will lead to an underestimation of the number of CML in very large events.

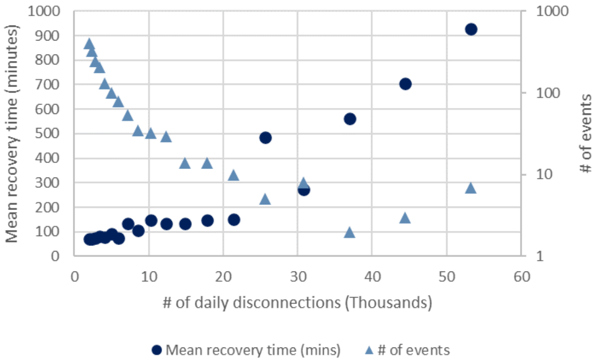

Figure 5: Plot showing the mean recovery time for daily events of size S (dark blue circles, left hand y-axis), together with the number of events in the dataset that were of that size (light blue triangles, right hand y-axis – note the log scale)

The data in Table 2 was used to estimate the unmet demand resulting from CML, by using an assumed energy consumption across both domestic and non-domestic meters of 8.21 MWh per year.

Table 2: Data sources and assumptions for calculating the average energy consumption per electricity meter in Scotland.

Quantity		Unit	Notes
Total Annual demand in Scotland	22.71	TWh	[16]
Number of domestic meters in Scotland	2.55	Million	Assumed equal to the number of households and dwellings [17]
# domestic and non-domestic meters in Scotland	2.765	Million	Estimated by scaling from total number of domestic [18] and non-domestic [19] meters in England.
Average demand per meter	8.21	MWh/year	Annual demand / # meters

4.3 Value of unmet demand and extrapolation to the UK

The study assumes a Value of Lost Load (VoLL) of £6,000 per MWh [20].

The values for the impacts of extreme events within the SSEN region are extended to the whole UK via the following assumptions:

- ~26.9 million electricity meters in England (comprising ~24.8 million domestic [18] and ~2.1 million non-domestic [19] electricity meters).
- English electricity consumption comprises 81.1% of UK consumption [21], assuming that meter numbers scale with overall demand, this implies ~ 33.2 million UK electricity meters.
- ~800,000 electricity meters within the SSEN region[2] therefore the SSEN region contains ~ 2.4% of the UK's electricity meters.
- Assuming that outage statistics are uniform across the UK, multiplying the SSEN benefits by a factor of 41.5 will give an estimate of UK-wide benefits from improvements in resilience.

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[2] Information from ESO

5 Benefits Modelling: Approach and Results

This section describes the approach to modelling the benefits of the extreme events energy system model, expanding on the basic outline from Figure 1.

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Figure 2 gave a non-exhaustive list of the areas where large-scale outages bring economic, social and environmental costs: costs that might be reduced if the whole system could be made more resilient to the events that cause the outages. The monetised benefit assessment presented here focusses on the electricity system only: this enables an analysis to be performed on the basis of UK data, backed by credible peer-reviewed publications that follow the same methodology. The resulting estimate of potential avoided costs will (potentially greatly) underestimate the full potential costs of a large event that spans multiple networks.

The route to monetising the benefits is by estimating the reduction in customer outages that will result from:

- A decrease in the number of outages that occur.
- A reduction in the likelihood that an outage is severe – i.e. an increase in power law parameter α
- Both of the above in combination.

Section 3 provided justification for adopting a power law distribution to describe the occurrence and size of large outages in Scotland. We use a Monte Carlo model to assess how altering both the frequency of occurrence of extreme outage events and changing the power law α-parameter (to impact the probability that the next large event will be above a certain size) alters the number of customer disconnections.

The modelling is based around the analysis of SSEN data presented in Section 4. Days with over 10,000 customer disconnections are assumed to occur randomly, following a Poisson distribution. Given that an event has occurred, its severity is selected from a power law distribution. The simulation covers 25 years, and the total number of customer disconnected over this period is recorded and discounted at the social annual discount rate of 3.5%[3], to give a total discounted number of customer interruptions.

The power law produces highly variable statistics [3], a characteristic that makes it suitable for use in describing the statistics of impact low probability, but which means that the Monte Carlo simulation needs to be iterated a very large number of times to ensure confidence in the outputs. Here we use 250,000 iterations to ensure confidence in the findings, generating stable statistics for the mean, P10 and P90 statistics. We have also examined the size of events with differing return periods, though these become less reliable where the return period is over 100 years.

A counterfactual case is used that is consistent with the data in Section 4.1. The parameters are shown in Table 3.

Table 3: Counterfactual case parameters

Model parameter	Value
Expected annual number of days with total outages affecting > 10,000 customers (Poisson λ)	5.5
Power law α parameter	1.7
Average disconnection time for outages on days with > 10,000 disconnections	125 minutes
# years	25
Discount rate	3.5%

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[3] The social discount rate suggested by [22].

Average annual demand per meter (domestic and non-domestic)	8.21 MWh/year

It should be noted that the modelling presents a theoretical estimate of how changing fault rates and the chances of a large outage event can bring savings through reductions in CML. There are two key messages:

- Any resilience intervention will only yield a benefit if an event occurs that allows it to make an impact and it is likely to be difficult to identify in many instances the extent of the saved costs that interventions may have delivered.
- The alpha parameter is empirically derived from a large dataset collected over many years and it is unlikely to be possible to know in advance how a particular set of resilience measures might reduce this. However, improved understanding of what network characteristics make cascade events more probable could deliver insights into design features that will reduce their likelihood.

5.1 Results

56 Monte Carlo simulations were run using different combinations of event likelihood and alpha, each with 250,000 iterations of a 25-year period. The following key scenarios are defined relative to the counterfactual in:

- SCENARIO 1: Event occurrence is unchanged; Alpha increases by 10%.
- SCENARIO 2: Event occurrence is reduced by 10%; Alpha is unchanged.
- SCENARIO 3: Event occurrence is reduced by 10% and Alpha increases by 10%.

Table 4 shows a comparison of headline statistics for the data and the Monte Carlo output for the counterfactual case. The 'average number of disconnections per high disconnection day' is higher in the modelled case because it is derived from 200,000 samples from the power law distribution and therefore includes some very large events, as illustrated in Figure 6.

Table 4: Comparison of Monte Carlo simulated event statistics with those of the SSEN data.

Parameter	Data	Model
alpha	1.7	1.7
Expected number of days with > S disconnections in a year	5.51	5.51
average number of disconnections per high disconnection day	21,819	24,278
Sample size	129	200,000

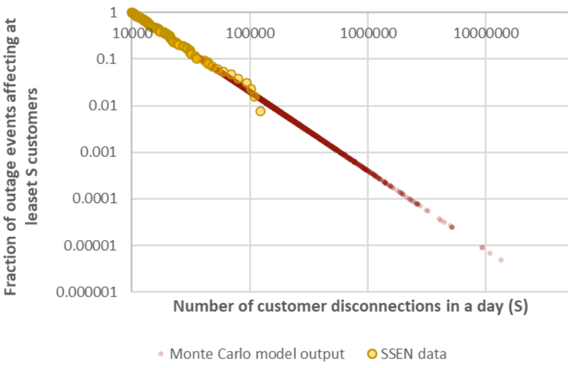

Figure 6: Comparison of modelled event occurrence with the data.

Table 5 shows the key results for the scenarios and counterfactual case, showing the discounted 25-year mean number of customer disconnections occurring on high disconnection days, and the sizes of individual daily events with return times of 10, 50, 100, 500 and 1,000 years. The probability that over 25 years a given scenario will deliver fewer customer disconnections is also presented.

Table 5: Model results comparing the three scenarios for changing the likelihood of extreme outage days and the severity of the extreme outages: mean number of customers disconnections (discounted total over 25 years), the size of events with different return times, and the probability that the scenario will deliver few large customer disconnections over a 25-year period.

Scenario	Alpha	Expected # high interruption days per year	Statistic	Customer disconnections (thousands)						Prob of reduction in total interruptions over 25 years
				Mean (25-yr)	Event return time (years)					
					10	50	100	500	1000	
CF	1.70	5.51	P10	1852.3	23.9	103.6	260.2	384.4	910.2	-
			mean	**2337.2**	**24.3**	**105.6**	**272.1**	**408.9**	**1050.5**	-
			P90	1852.3	24.7	107.7	284.4	434.5	1200.2	-
1	1.70	4.95	P10	1650.2	23.9	103.5	260.2	383.8	909.6	69%
			mean	**2101.0**	**24.3**	**105.7**	**272.0**	**408.6**	**1045.8**	**71%**
			P90	1650.2	24.7	107.8	284.3	434.5	1200.1	74%
2	1.87	5.51	P10	1697.9	21.3	83.9	193.2	274.9	605.1	70%
			mean	**2067.6**	**21.5**	**85.2**	**201.3**	**292.1**	**689.2**	**73%**
			P90	1697.9	21.7	86.7	209.0	309.8	778.5	75%
3	1.87	4.95	P10	1515.8	21.3	83.8	194.0	274.8	595.7	86%
			mean	**1862.5**	**21.5**	**85.4**	**201.8**	**292.2**	**685.4**	**88%**
			P90	1515.8	21.7	87.0	209.8	310.7	775.4	90%

Scenario 1 and Scenario 2 give similar 25-year total numbers of disconnections: Scenario 1 through reducing the probability of a high interruption day; Scenario 2 through reducing the chance that an event is severe. It is notable that the impact of reduced event probability on the size of significant individual events of differing return times is negligible, indicating that improving everyday reliability/resilience will give little protection against the occurrence of a very large event.

Figure 7 shows the results of an investigation of the impact of changing alpha and event probability over a wider range of values. Moving upwards corresponds to more frequent high-impact events, such as might be expected due to increases in occurrence of extreme weather events due to climate change. Moving leftwards corresponds to decreasing alpha[4]. This might occur due to the increasing interconnectedness of different infrastructure networks and the increasing complexity of the electricity networks as they develop to accommodate net zero ambitions.

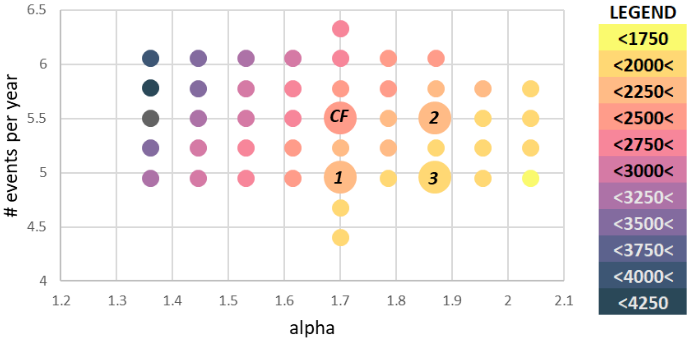

Figure 7: Scatter plot showing the 25-year average discounted number of customer interruptions (thousands) that result from different assumptions on the # large events per year and the alpha parameter for the log law. The larger circles correspond to the scenario assumptions from Table 5.

Figure 8 shows the cumulative distribution function for the difference in total discounted number of customers disconnected over 25 years between the counterfactual and the scenario. Negative values indicate a saving; the cumulative probability is the chance that the saving will be at least as large as the x-axis value. Comparing the curves for Scenario 1 and Scenario 2, it is evident that increasing the alpha parameter is driving a reduction in the number of very severe events, as was also noted above in relation to the results in Table 5.

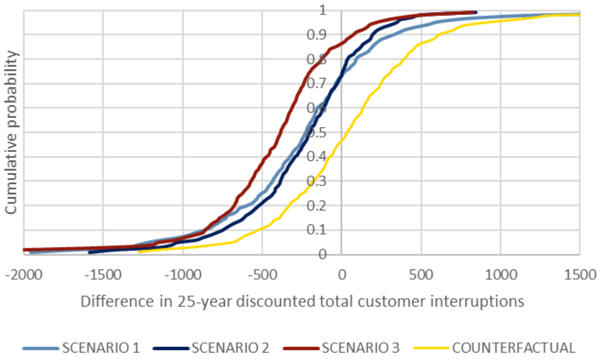

Figure 8: the cumulative distribution function for the difference in total discounted number of customers disconnected over 25 years between the counterfactual and the scenario.

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[4] With reference to Figure 4, a reduction in alpha makes the gradient shallower, implying a greater probability that the next extreme event will be large.

Figure 9 shows that the influence of lower event severity starts to become apparent for event sizes in which more than 150,000 customers are disconnected. From Table 5, it can be seen that an event of this size has a modelled return time of roughly 50 years.

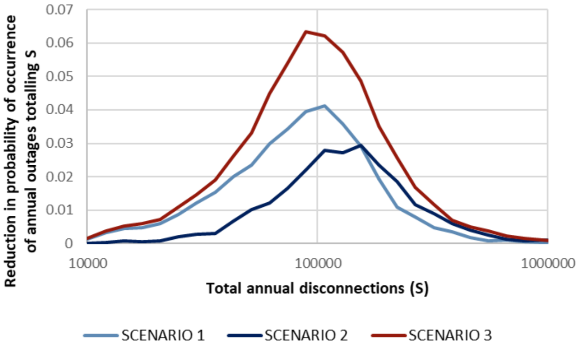

Figure 9: Plot showing how changes in the event frequency and probability of severity impact on the probabilities of different sized events. Differences show **reductions** in probability of events of a particular size.

Table 6 steps through the calculation to derive an estimate for the reduction in overall costs due to outages that results from the changes made in each Scenario. The values given are discounted 25-year estimates of the mean, P10, P50 and P90 amounts. The SSEN region is estimated to contain around 800,000 electricity meters[5], both residential and non-residential. Scaling the results to the UK, with an estimated 33 million[6] electricity meters, gives the following UK-wide potential avoided costs.

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[6] Estimated from the ratio of domestic:non-domestic meters for England and scaling according to 81% of electricity consumption being in England.

SCOTTISH DATASET																
	25-year discounted customer interruptions (thousands)				Estimated CML (millions)				Estimated unmet demand (MWh)				25-year discounted cost of unmet demand (£m)			
CF	**2337**				**525**				**8208**				**£49.25**			
	Reduction in 25-year discounted customer interruptions (thousands)				**Reduction in Estimated CML (millions)**				**Reduction in estimated unmet demand (MWh)**				**Reduction in 25-year discounted cost of unmet demand (£m)**			
Scenario	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**
1	-239	-816	-224	338	-54	-183	-50	76	-841	-2867	-787	1188	-£5.04	-£17.20	-£4.72	£7.13
2	-271	-783	-213	245	-61	-176	-48	55	-950	-2749	-748	862	-£5.70	-£16.49	-£4.49	£5.17
3	-472	-985	-413	31	-106	-221	-93	7	-1659	-3461	-1450	110	-£9.96	-£20.76	-£8.70	£0.66
UK-WIDE EXTRAPOLATION																
	25-year discounted customer interruptions (thousands)				Estimated CML (millions)				Estimated unmet demand (MWh)				25-year discounted cost of unmet demand (£m)			
CF	**96961**				**21793**				**340533**				**£2,043**			
	Reduction in 25-year discounted customer interruptions (thousands)				**Reduction in Estimated CML (millions)**				**Reduction in estimated unmet demand (MWh)**				**Reduction in 25-year discounted cost of unmet demand (£m)**			
Scenario	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**	**mean**	**P10**	**P50**	**P90**
1	-9932	-33866	-9297	14035	-2232	-7612	-2090	3155	-34882	-118939	-32651	49293	-£209	-£714	-£196	£296
2	-11224	-32468	-8839	10185	-2523	-7298	-1987	2289	-39420	-114031	-31043	35769	-£237	-£684	-£186	£215
3	-19602	-40879	-17129	1296	-4406	-9188	-3850	291	-68843	-143570	-60159	4551	-£413	-£861	-£361	£27

Table 6: Estimate of the 25-year discounted value (£m) of the reduction in unmet demand resulting from the reduced risk of major outage events. Values are based on analysis for the SSEN region and extrapolated to the whole UK. Negative values imply a saving or cost reduction over the counterfactual case.

6 Conclusions

The following section draws together the main conclusions of this benefit assessment and suggests areas for further investigation.

- **Monte-Carlo modelling based on the faults observed within the SSEN region over 23 years suggests that improving electricity system resilience through cutting fault occurrence and fault severity could save of the order of hundreds of millions of pounds over 25 years (**Table 6**).**

  The link between this notional saving and the energy system model currently under development is premised on the model being able to identify both new areas of network vulnerability, and capture characteristics of the whole network that allow the development of effective interventions to reduce the chances and minimise the impact of large cascade failure events.

- **Improving everyday reliability and resilience will give little protection against the occurrence of a very large event (**Table 5**).**

  Scenario 1 and Scenario 2 give similar 25-year total numbers of disconnections: Scenario 1 through reducing the probability of a high interruption day; Scenario 2 through reducing the chance that an event is severe. The impact of reduced event probability on the size of significant individual events of differing return times is negligible. This indicates considerable benefit could be derived from understanding how to lessen the chances of the very largest events.

- **The most impactful resilience improving approach is likely to combine 'traditional' resilience measures, that aim to cut failure rates, with interventions that reduce the likelihood of failure cascades (Section 3**).

  For example, improving fault response times, and thereby reducing the length of time for which the system is under stress, could cut the chances of a cascade event [2]. And developing 'fire breaks' within and between networks, for instance, strategically positioned battery storage that could deliver back up power for long enough to prevent the cascade of failures between systems.

The study presented here could be usefully extended through:

- Analysis of UK-wide distribution and transmission fault data for both the electricity and gas networks, to include comparison between the statistics of different regions to see if it is possible to draw out intrinsic network characteristics that influence events that bring large numbers of outages.
- Deeper analysis of outage times in relation to the number of customers affected.
- A more sophisticated analysis of linked faults than aggregating total daily outages.

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