Resilire: A Framework for Resilience Modelling in Electricity Networks

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Extreme weather can have a significant impact on the electricity network due to damage directly from the weather conditions or through second order effects such as flooding or falling trees. During extreme weather events this damage can be widespread, challenging the resilience of the network and the operational response, and leading to long interruptions to power supplies. Loss of power, especially over an extended period, has a significant impact on electricity customers, and this is only likely to become more so as reliance on electricity increases through decarbonisation. It is not possible to strengthen the entire network, so Resilire provides a means to assess the whole-system resilience to extreme weather, and to compare and target investment options to mitigate this risk into the future as effectively as possible.

1. Introduction

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During extreme weather events this damage can be widespread, challenging the resilience of the network and the operational response, and leading to long interruptions to power supplies. Loss of power, especially over an extended period, has a significant impact on electricity customers, and this is only likely to become more so as reliance on electricity increases through decarbonisation. Following an outage of five days caused by flooding of a 132kV substation in Lancaster, UK in 2015, a report by the Royal Academy of Engineering [1] highlighted that the loss of power over an extended period has significant impacts on a wide range of essential services. This includes utilities such as water and communications as well as payment services and the operability of public services such as health, education and transport.

In December 2021, Storm Arwen brought strong winds, heavy rain and snow to large parts of the UK and resulted in long power outages of over five days in cold conditions. A government review [2] following this storm found that '*Storm Arwen resulted in electricity disruption which* *went well beyond the expectations of both Government and society. Current resilience standards are solely defined as measures to be implemented rather than specific consumer outcomes. A principles-based outcomes-focused resilience standard would allow operators to plan and invest accordingly while setting Government and public expectations of the service they fund.'*

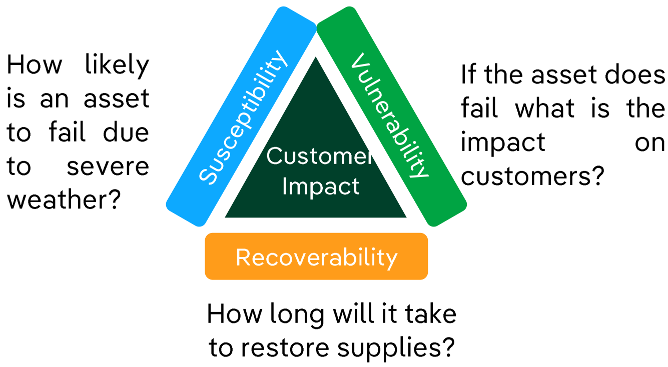
It is not possible to strengthen the entire network to withstand all possible severe weather events, so decisions must be made as to where on the network it is appropriate to invest in resilience, and to what extent, balancing the benefit of potentially avoiding the impact of long duration interruptions on customers against the cost of such interventions. Traditional approaches to this problem include defining design standards to improve the conditions an asset can withstand, combined with heuristic approaches to investment prioritisation, such as upgrading the 'main line' of an overhead circuit to modern standards on the basis that preventing faults here is likely to benefit the greatest number of customers. However, the benefits of these investments may be limited if the line's location makes modern standard upgrades inadequate, or if older standard lines are already sufficiently sheltered from severe weather. These network improvements must also consider alternative solutions such as increased network interconnection, mitigating the impact of asset failure, or investment in novel approaches such as embedded generation for islanded elements of network. A data-driven approach can help identify the highest-impact improvements and therefore maximise investment returns.

Resilire (pronounced *re-si-LEE-reh,* from the Latin root of the English word *Resilience,* meaning 'to bounce back') is a framework for resilience modelling in electricity networks which incorporates a whole system approach, and considers three elements of resilience:

- **Susceptibility**: How likely is each asset to fail due to severe weather? This considers the likely extreme wind conditions at the asset location based on long term weather modelling and local topography as compared to the design strength of the asset based on construction and condition, and the nature and proximity of vegetation.
- **Vulnerability**: If the asset does fail, what is the impact on customers? This considers the connectivity of the asset(s), network topology, sectionalisation, and switch automation by modelling network energisation and re-configuration.
- **Recoverability**: How long will it take to restore supplies? This considers the ability of the operational response to respond to the incident considering the scale, type, and geographic distribution of the network damage, and the resources available to conduct repairs and restore supplies.

Whilst these three factors define the scale, the impact of an incident is evaluated in terms of the effect it has on customers. This impact is fundamentally a function of the number of customers affected and the time each customer is off supply. However, the impact on each customer will depend on the customer characteristics (such as customer vulnerability), and may be non-linear with time, with additional costs present in longer interruptions which are not experienced in the shorter interruptions more normally experienced. In addition, where a given customer provides a community amenity (such as health services or grocery retail), there is a spill-over impact on people served by that service which may extend beyond the geographic extent of the actual outage.

On this basis, investments of different types can be compared. Reducing the susceptibility of the network to severe weather such that fewer failures occur undoubtably reduces the customer impact but equally reducing the number of customers affected by each failure through changes to network topology, and reducing the time taken to restore supplies would also reduce the customer impact. The use of the Resilire methodology allows the relative costs and benefits of such interventions to be evaluated.



2. Model Concept

Resilire models the impact of severe weather on the network in the following stages:

1. **Build a model of the network:** An initial model of the network is first built, representing the network in its normal configuration with no pre-existing failures. The model is built around a connectivity graph of the network but must be decorated with the geospatial location and details of assets which could be affected by severe weather.
2. **Apply damage:** Extreme weather conditions are applied to each asset based on the reasonable worst case weather condition at each asset location, and comparing this with the conditions to asset could be expected to withstand in its current state to determine whether the asset has failed. For example. This could involve comparing the 1/100-year flood depth at a site with the height of flood defences to determine whether the site could be expected to be flooded in that scenario. Each asset failure will result in a fault on the network, either directly or because it supports that network node (such as pole failure resulting in an overhead line fault). All damage is assumed to occur instantaneously at t =0.
3. **Apply Network Isolation:** Open the protected switch immediately upstream of each fault to simulate the action of protection.
4. **Determine Customers affected:** Using the network model, those customers no longer reachable from the network root can be deemed to be off supply.
5. **Apply automated restoration:** Close all tele-controlled switches, except where closing a switch would re-connect a fault to the network root
6. **Repair the network:** Simulate the restoration through dispatch of sources to identify the location of the fault, re-configure any non-tele controlled switches to reduce the zone of isolation around each fault and restore supplies to customers outside that zone where possible, repair damage, and finally re-energise the network. These activities are typically resource constrained due to the number of faults in a severe weather incident, so these tasks must be prioritised, and account taken of the time to travel between task locations.
7. **Calculate customer impact:** Calculate the cost of the interruption for each customer affected based on the time between the damage being applied and that customer being

restored. The total cost can then be calculated along with a normalised value calculated by dividing the total cost across the number of customers fed by the network.

3. Initial Implementation

The initial implementation of the framework has been to model the impact of a severe windstorm on the Medium Voltage (6.6kV/11kV) network operated SP Electricity North West in the UK.

3.1. Build a Model of the Network

The Resilire methodology uses a graph representation of an electricity network where each node is a network element such as a conductor, joint, switch or transformer, and the edges represent connections between these elements. For the initial MV implementation, customers can be assumed to be fed from an MV/LV transformer, and all HV/MV transformers can be connected to a single root node, such that the presence of a path between the root node and a given MV/LV transformer shows that the transformer is on supply. Switches can be represented as two nodes, and the edge between these added or removed to model the switch state. This approach allows graph analysis techniques, such as those implemented in the Python NetworkX library, to be applied.

3.2. Apply Damage

In the initial implementation, two failure modes related to wind damage are considered:

- Pole failure due to pole snap or overturn
- Trees falling to an overhead line.

During a windstorm, the predominate cause of damage to overhead electricity networks is the force exerted by wind pressure on structures or trees [2], causing either direct damage to those structures, or damage as a result of trees falling into lines. The magnitude of the wind pressure will necessarily be different at different locations within a network area, depending on factors such as topography and surface roughness, so a wood pole on exposed upland moor is likely to experience higher windspeeds (and therefore pressure) than a wood pole in a lowland urban setting within the same event. Similarly, the magnitude of wind pressure an asset could be exposed to may differ by direction due to shelter or channelling effect of topography. Within the Resilire model, the maximum expected windspeed considered is a 1 in 10-year return period, 3 second gust, at 5m above the ground.

Similarly, the wind pressure a pole structure can withstand is also affected by the design of the pole. Following the approach taken in ENA TS 43-40 [3], the critical moment a pole structure can withstand can be calculated by comparing the moment exerted on the structure due to the wind pressure on the cross-sectional area formed by the pole, conductors and any pole mounted equipment with the maximum bending stress of the woodpole, the maximum tensile strength of any stays and the bearing strength of the soil.

The risk of pole failure can be evaluated by comparing the critical moment the pole can withstand (as adjusted for any reduction in strength due to asset degradation) with the moment exerted by the wind pressure on the structure, adjusted for any additional cross section caused by ice accretion as shown in (1).

$$S = \min_{f \in F} \left(\frac{\frac{M_{crit,f}}{c}}{M_{wind,f}(P_{wind}, r_{ice})} \right) \quad (1)$$

Where:

S	Factor safety
F	The set of failure modes considered
$M_{crit,f}$	The critical moment that be sustained before a failure or mode, f
$M_{wind,f}(P_{wind}, r_{ice})$	The moment exerted by a wind pressure, P_{wind}, with a radius of rime ice r_{ice} in the context of failure mode, f
c	The health score factor for the pole as defined within CNAIM [4] Section 6.7

To assess the risk of failures that may occur because of trees or large branches falling during a windstorm, a model taking inspiration from Forest Research's ForestGALES software [5] is used, which is a hybrid-mechanistic model that assesses the risk of wind damage to forests in Britain. The model calculates a critical wind speed at which trees will be damaged, which varies based on tree and site information. Resilire follows a similar approach to Gardiner et al [6], and uses a combination of the National Forest Inventory [7] and Trees Outside of Woodland [8] datasets produced by the Forestry Commission to estimate the height, spacing and type (i.e. broadleaf or coniferous) of single trees, small groups or trees or woodland in the vicinity of the overhead line. Using an empirical regression relationship obtained from ForestGALES, the critical windspeed can be calculated for each area of woodland, and this can then be compared to the maximum expected windspeed in the woodland location.

For both the risk of pole damage and the risk of vegetation damage, the comparison between the critical and maximum expected windspeed can be converted to a probability failure using a logistic function as shown in (2) [6]

$$P_f = \frac{1}{1+e^{-\frac{v-c_w}{S}}} - \frac{1}{1+e^{-\frac{c_w}{S}}} \quad (2)$$

Where:

P_f	The likelihood of failure of a given asset
v	The maximum expected windspeed in m/s
c_w	The critical windspeed of a given asset
S	Slope parameter. Following Gardiner et al [6], this is set to 6

By selecting a threshold probability of failure, a set of assets predicted to be damaged either directly by wind or by treefall in the event of extreme wind speeds can be obtained. As such, the model does not attempt to predict which assets may fail in a specific scenario, but rather assesses which assets are most susceptible to failure in a storm event given the asset parameters and the location.

3.3. Apply Network Isolation and Determine Customers Affected

Within an electricity distribution network, safety is maintained through the use of protective devices which open (or 'break') when a fault occurs to minimise the damage caused by high current flows between phases or to earth. Within Resilire, the network is assumed to be radial, such that in the event of damage to the network, it can be assumed that the next protective device upstream of the fault location will open, and all customers downstream of that device will be off supply. By applying this across the network, all customer-supplying transformers affected by the damage can be identified.

3.4. Apply Automated Restoration

Most distribution networks apply some form of automated restoration such as Fault Location, Isolation, and Service Restoration (FLISR) [9]. Whilst the algorithms applied by these systems may differ, a simplified approach can be used to identify which customers can be restored using automated switching and can therefore be assumed to be restored within a short period of time. By opening the first telemetered switch upstream and downstream of each fault, and then closing all other telemetered switches, graph analysis functions can be used to identify which transformers can be reached from the root of the network (and are therefore on supply) and which are off supply. This in turn allows the transformers restored through automated switching to be identified.

3.5. Repair the Network

Whilst automated restoration is a function of network topology, restoring supplies to the remaining customers is a function of the interplay between network topology and the operational response.

A key factor in the duration of outages experienced by customers after a severe weather event is the ability of the operational response to deploy resources to identify the exact location and nature of damage, reconfigure the network using non-tele controlled switching devices to restore supplies where possible, and enact repairs. The scale of damage in a severe weather event is likely to exceed the capacity of the operational response to respond immediately, and so resources must be prioritised, meaning that some customers will experience much longer outage durations than would be expected under normal circumstances.

To account for this, the Resilire methodology simulates the operation response to the set of faults identified in Section 2.2. For each fault, the methodology simulates the following stages:

- **Identify the location of the fault:** before any restoration can be enacted the exact location of the damage within the protection zone must be ascertained through reconnaissance which requires a suitably authorised team to travel to the area of the fault and survey the line;
- **Conduct manual switching:** Once the location of the fault has been identified, manual switches either side of the fault can be opened, and the surrounding automated switches closed to restore customers not within the immediate isolated zone. It may also be possible to restore customers by closing manually operated open switches between circuits. This requires a suitably authorised team to travel to each switch to operate it;
- **Enact Repair:** A repair team can then be dispatched to repair the damage to the network. The type of team may vary depending on the damage type. For example, a snapped pole may require an overhead lines team, whereas fallen trees would require a suitably equipped tree cutting team.

The operational organisation will have a finite pool of resources to conduct these tasks for each fault, so the methodology simulates the prioritisation of tasks according to factors such as the number of customers affected by the fault, the distance from the depot and the likely time taken to conduct the task to determine which tasks to resource first. Lower priority tasks are then queued to be conducted once a suitable resource becomes available.

This approach allows the identification of the customers whose supply is likely to be interrupted by a severe weather event from Section 2.3 to be augmented with the likely duration of that interruption to provide a granular, localised view of the likely impact of the severe weather event.

3.6. Calculate Customer Impact

Regulatory approaches to quantifying the customer impact have generally used some form of Value of Lost Load (VoLL) [10]. VoLL approaches are grounded in customer research on willingness to pay and willingness to accept, and whilst this established approach provides a robust method to quantify the economic value attached to shorter duration outages experienced in normal times, they are unlikely to capture the full range of social costs experienced during a long duration interruption for the following reasons:

- Most customers are unlikely to have experienced a long duration interruption, so are less able to estimate the costs;
- The social cost of an interruption is non-linear over time with additional costs incurred as the outage persists as customers' organic resilience measures are exhausted;
- There may be significant spillover effects from extended loss of supply to community services such as healthcare facilities and grocery shops which may extend beyond the area direct impacted by the outage.

The Resilire methodology builds on the model of VoLL used by the GB energy regulator (Ofgem) [10] and augments this with additional costs related to long duration interruptions which are not captured within VoLL such as:

- Extended loss of lighting, heating and communications connectivity;
- Inability to prepare hot meals and spoiling of refrigerated or frozen goods;
- Disruption to work;
- Inability to use electric vehicles;
- Costs of alternative accommodation.

These additional costs can be estimated by determining the market cost of mitigating the loss of amenity. Some these costs may be higher for vulnerable customers, and in addition, where an outage affects a pharmacy or supermarket, the likely additional costs incurred by those who would otherwise use those facilities can be accounted for.

This approach enables the social cost of each customer outage to be quantified based on the length of the outage and customer characteristics. Figure 1 shows the application of this approach for a vulnerable customer with an electric vehicle. The baseline cumulative per customer VoLL defined in 2013 [10] and inflated to 2025 prices is shown by the dashed blue line. The estimated cumulative additional costs incurred by customers experiencing long duration interruptions but not incorporated in VoLL are shown by the dotted orange line, and the solid green line shows the combined value. Based estimates of these additional costs, the social cost of the interruption could three times that estimated by just extrapolating VoLL over a long duration outage.

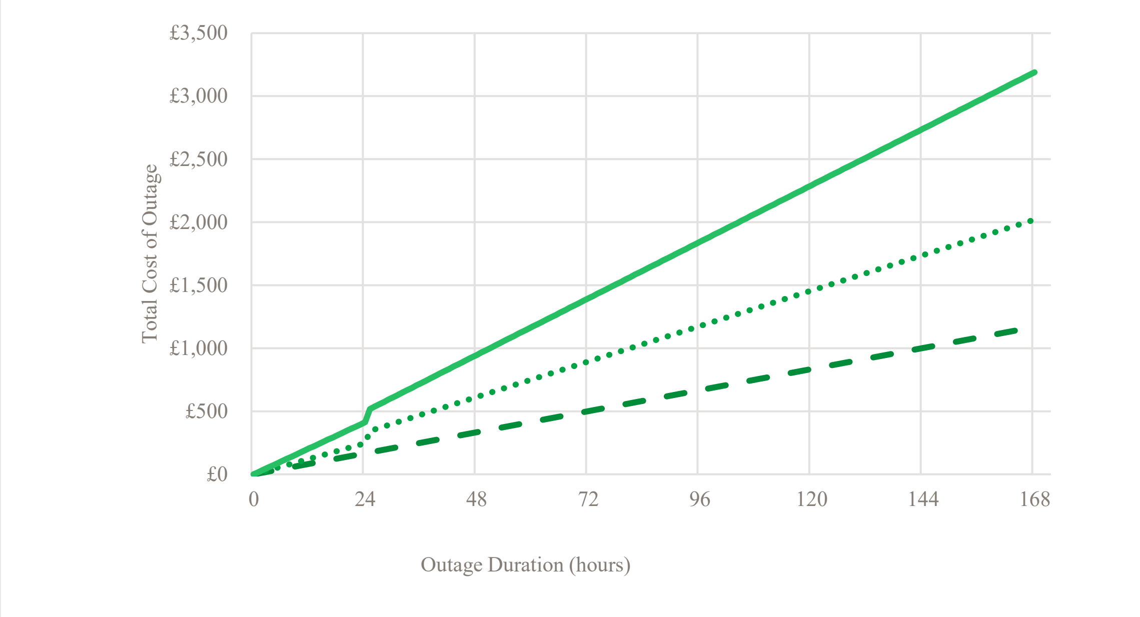


Fig. 1 Cost of outage over time for vulnerable customer within EV with blue (dashed) line showing the baseline VoLL, orange (dotted) line showing the additional costs and green (solid) line showing the total cost.

This approach to assessing the customer impact of outages also enables a network resilience metric to be derived. Summing the social cost across all customers and dividing by the total number of customers supplied by the network provides a measure of the social cost of an extreme weather event per supplied customer, allowing different networks to be compared, and the benefit of resilience investment options to be evaluated.

4. Discussion

The resilience of electricity networks has historically been difficult to quantify as severe weather is by nature uncertain, and large events are sufficiently infrequent that study of historic events does not give a full picture of the potential impact of future events. Whilst approaches such as fragility curves [11] provide useful high-level insight into the scale of impact from future events and can help translate future climate predictions into the impact on networks, they do not provide sufficient detail to enable the targeting of investment or enable to evaluation of investment options where the objective is the shift the fragility curve.

Similarly, resilience investment is often difficult to justify using standard cost-benefit analysis methodologies. Demonstrating the benefit from resilience investment is difficult, both because it is difficult to evaluate the counter-factual impact of an event had investment not taken place, and a rationally defined investment may avoid severe weather for a significant period due to the uncertainty of weather patterns. In addition, severe weather disproportionately impacts more remote communities due to both topography and the fact that they are more likely to be fed by overhead lines. Improving resilience for these customers often requires significant investment which will only directly benefit a relatively small number of people.

By taking a whole system approach based on susceptibility to severe weather damage rather than a specific scenario, the Resilire methodology enables a deterministic assessment of network resilience before and after intervention. By modelling the operational response, the methodology evaluates the second-order impact of investments which reduce the fault volume. An intervention which prevents a set of faults may have a modest local impact due to other faults upstream or downstream but freeing up the resources which would have been committed to identifying and repairing those faults can instead be used to fix other faults, marginally reducing the outage time over a large area. Given the non-linear increase in social cost over the duration of an outage, a relatively small reduction in the length of an outage over a large number of customers can result in a relatively significant reduction in the cost of the incident.

The methodology also enables the comparison of dissimilar investment approaches. For example, the benefit of asset-centric approaches such as upgrading overhead lines to modern standards or replacing exposed sections with underground cable can be compared with network-centric approaches such as installing additional telemetered switches to improve sectionalisation, or interconnecting circuits to enable the network to be re-configured around damage. Similarly, interventions to improve the operational response such as technology to locate damage and investments to improve community resilience can also be compared.

5. Conclusion

Resilire has been developed as a published methodology and as a design support tool software and is currently being used to target £20m of investment before 2028 as well as support the business case for continued investment into resilience into future regulatory periods. Resilire is allowing asset solutions, such as overhead line strengthening to be compared with network solutions such as interconnection to maximise the benefit to consumers from the committed investment.

Resilire has demonstrated the utility of a whole-system resilience model, and the framework can be easily adapted to other climate hazards.

6. References

[1] Royal Academy of Engineering, "Living without electricity: One city's experience of coping with loss of power," Royal Academy of Engineering, London, 2016.

[2] Department for Business, Energy & Industrial Strategy, "Energy Emergencies Executive Committee Storm Arwen Review: Final Report," London, 2022.

[3] Energy Networks Association, Technical Specification 43-40, "Specification for single circuit overhead pole lines for use at high voltage up to and including 33kV", Issue 4 2023.

[4] Energy Networks Association, DNO Common Network Asset Indices Methodology (CNAIM), v2.1, April 2021.

[5] Forest Research, "Tools and Resource - ForestGALES," 2025. [Online]. Available: https://www.forestresearch.gov.uk/tools-and-resources/fthr/forestgales/.

[6] B. Gardiner, R. Lorenz, M. Hanewinkel, B. Schmitz, F. Bott, S. Szymczak, A. Frick and U. Ulbrich, “Predicting the risk of tree fall onto railway lines,” Forest Ecology and Management, vol. 553, no. 121614, 2024.

[7] Forestry Commission, “National Forest Inventory GB 2022,” 14 November 2024. [Online]. Available: https://data-forestry.opendata.arcgis.com/datasets/25690ca444d54a588394d61a985006b5_0/about.

[8] Forestry Commission, “National Trees Outside Woodland Map,” 30 January 2025. [Online]. Available: https://data-forestry.opendata.arcgis.com/documents/01667a77c65f4fd9aaf6a45279373a25/about?path=.

[9] J. Estel, “Distribution resiliency through FLISR implementation,” in CIRED Chicago Workshop 2024: Resilience of Electric Distribution Systems, Chicago, 2024.

[10] London Economics, “The Value of Lost Load (VoLL) for Electricity in Great Britain,” 2013.

[11] S. Dunn, S. Wilkinson, D. Alderson, H. Fowler and C. Galasso, “Fragility Curves for Assessing the Resilience of Electricity Networks Constructed from an Extensive Fault Database,” Natural Hazards Review, vol. 19, no. 1, 2017.