SP Electricity
North West

Resilire

A Framework for Resilience Modelling in Electricity Networks

Technical Methodology Document

Version 1.0

2025-10-28

Asset Management

Version Control

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1. Introduction

1.1. Context and Background

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 an extreme weather event, this damage can be widespread, challenging the resilience of the network and the operational response, 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 Storm Arwen in December 2021, a need for a Storm Resilience Model (Resilire) was identified to allow SP Electricity North West to identify and target areas of the network which are most susceptible to extreme weather conditions, and where such damage is most likely to lead to severe disruption to customer supplies over an extended period. The aim of this model is to provide outputs which allow investment to be targeted where the customer benefits is greatest, and to compare the likely benefit from alternate options.

Resilire is a whole system modelling framework around the concept of network resilience to extreme weather events considering the risk of damage, the impact of that damage on the ability of the network to maintain supplies, and the response of the network operator in an extreme weather scenario to effect repairs and restore supplies. As such Resilire allows different forms of interventions to be evaluated against a common metric, ranging from asset-level interventions to strengthen specific assets, to network-level interventions to lessen the impact of asset failure, to operational changes to improve the operational response.

Importantly, Resilire does not aim to evaluate the impact of historic storms, but rather to assess the potential impact of future events based on the plausible extreme conditions at each asset location, the current state of the network, and the operational resources available to respond to major incidents. As such, Resilire assesses the resilience of the network and supporting organisation to future events, rather than predicting the impact of a specific event.

1.2. Model Scope and Assumptions

Resilire is a modelling framework designed to be sufficiently flexible to assess the resilience of different networks to different environmental risks. However, this initial version of the methodology is limited to resilience of the High Voltage (6.6kV, 11kV or 20kV) networks to windstorms, including associated icing. The modelling framework could be extended to other risks such as flooding, wildfires or extreme heat, and this is discussed in Section 9.

Resilire models the resilience of individual storm events, and a key modelling assumption is that the network is undamaged at the start of the event. Similarly, Resilire does not consider chronic impacts of climate change, or long-term degradation of assets. Finally, the current version of Resilire assumes the network restoration through re-configuration is not capacity constrained.

2. Conceptual Foundations

2.1. Definition of Resilience in Electricity Networks

Resilience can be defined as a network's ability to withstand an external disturbance without degradation in service and return to its stable state after that disturbance. In the context of an electricity network, this can be understood as the ability to minimise the impact of an event on customer supply, and restore supplies to all customers following an event, in the case of the Resilire framework, a severe weather event.

Resilience is comprised of three elements as shown in Figure 1.:

1. **Susceptibility** – How likely is an asset to fail due to severe weather?
    - This is a function of the design of the asset in terms of the conditions it should be able to withstand, and the plausible extreme conditions in the asset location.
    - In a given location a heavier duty pole with stay supports will be less likely to fail than a lighter duty pole, but equally a pole in a more exposed location is more likely than an equivalent specification pole in a more sheltered location.
2. **Vulnerability** – If the asset does fail, what is the impact on customers?
    - This is a function of the network topology and defines which customers would be de-energised by a given set of failures.
    - Which customers can be restored through restorative network switching, and which would require the intervention at the failed asset?
    - A network with many interconnects between circuits has a lower vulnerability than a fully radial network.
3. **Recoverability** – How long will it take to restore supplies?:
    - This is a function of the scale of the damage, and the capacity for operational response.
    - The operational response will be affected by the number and type of resources available to identify the location of damage, conduct manual switching operations, and effect repairs, as well as by the geographical disposition of those resources which affects the time taken to get to the site of these activities.
    - Where the scale of the damage overwhelms the ability of the resource available, these tasks may also need to be queued, so some activities can be only be started once others have been completed.
    - Together these factors define the length of time each customer will expect to be off supply.

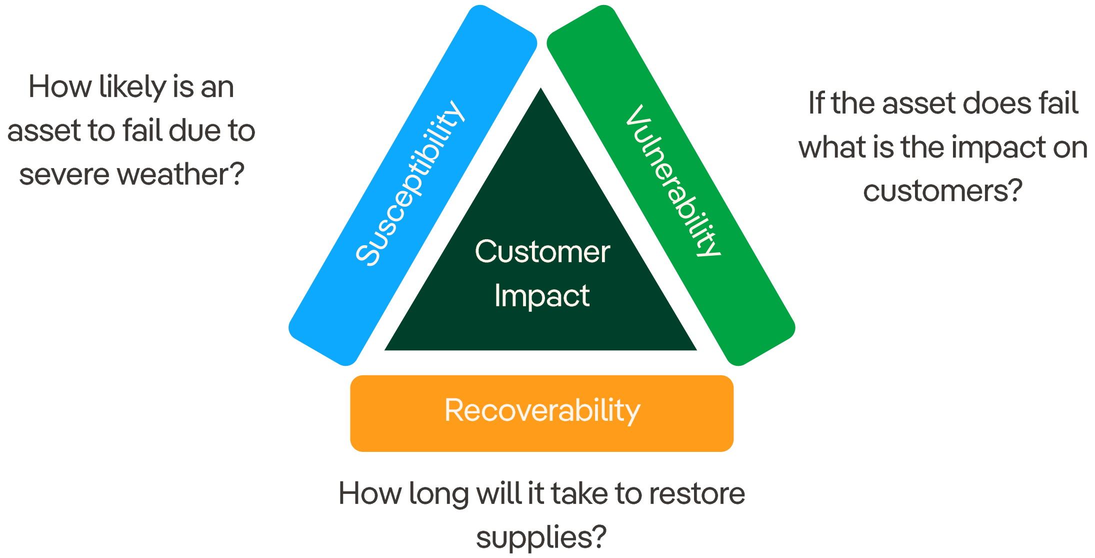

Figure 1: Elements of Resilience

Whilst these three factors define the scale of the impact, the impact an incident is evaluated in terms of the impact on customers. This impact is fundamentally a function of the number of customers affected, and the time each customer is off supply, but the impact on each customer will depend on the customer characteristics (such as customer vulnerability), and be non-linear with time, with longer interruptions being more impactful than shorter duration interruptions. In addition, where a given customer provides a community amenity (such as a 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.

By summing the impact across all customers affected, directly and indirectly, the overall impact of the incident can be evaluated, and therefore the likely benefit of any investment to improve Susceptibility, Vulnerability or Recoverability.

2.2. Uncertainty

The impact of a severe weather event is intrinsically uncertain due a combination of uncertainty as to weather conditions experienced, uncertainty regarding the condition of the network and component assets before the event, and the exact behaviour and strategy adopted in the operational response.

The objective of the Resilire methodology is to assess the likely impact of future events, rather than predict the impact of a specific event, and as such the methodology is designed to be deterministic rather than stochastic. This is on the basis that across a number of events, any uncertainty around the conditions in a given location can be assumed to average out, and to assess the vulnerability and recoverability elements, it is necessary to assess a defined set of failures. The deterministic nature of the methodology allows the effect of interventions to be isolated from any random variation between model runs, and ensures results are repeatable.

One area in which uncertainty may be accounted for is in the likely correlation between extreme conditions experienced by given locations in a given event. For example, a windstorm typified by strong south westerly winds is likely to result in co-incident failure in assets exposed to winds from this direction, and these may be different to failure experienced due to strong north-easterly winds. In this case, the methodology may be run for multiple weather scenarios, with the results weighted according to the relevant likelihood of those scenarios occurring.

This deterministic approach ensures consistent results, and therefore ensures that different runs are comparable, allowing the effect of a given set of interventions to be evaluated.

3. Susceptibility

3.1. Overview

The purpose of the susceptibility portion of the framework is to determine which assets in a network are most susceptible to failing during the selected scenario. A schematic of the high-level processes is presented in Figure 2.

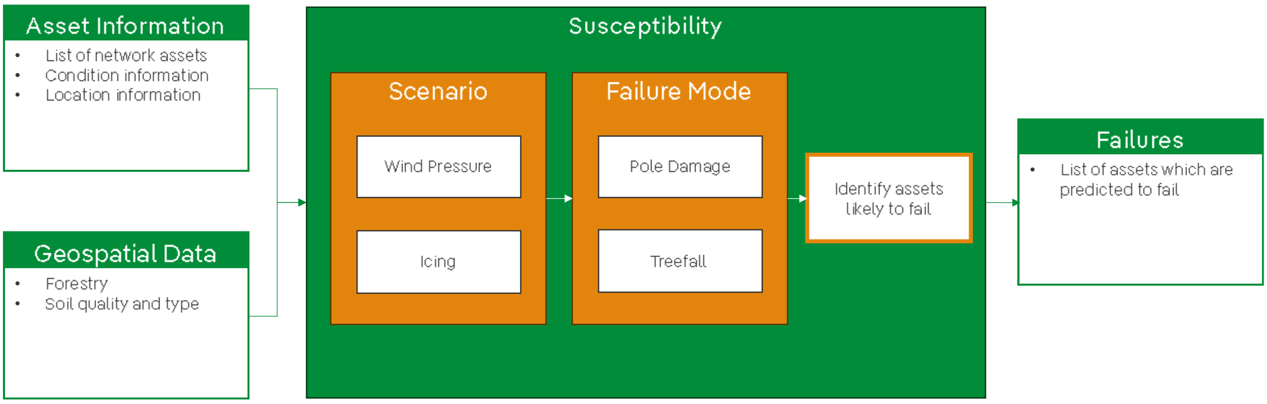

Figure 2: Overview of the susceptibility methodology's key processes, inputs, and outputs. Two groups of data inputs are required: asset information and geospatial data, and the methodology returns a list of assets estimated to fail under based on the represented scenario data.

The resilience methodology can consider multiple failure modes when determining likelihood of failure. Currently two failure modes are defined, which are described in more detail in this section:

- Pole damage from windstorms.
- Conductor damage from treefall during windstorms.

In all cases, the susceptibility is a function of the likely extreme conditions at each asset location, and the critical conditions that can be withstood by the asset to provide a likelihood of failure between 0 and 1 for each asset, where 0 indicates the asset will not fail (through this mode) and 1 reflects a very high likelihood of failure under these conditions.

A failure threshold is defined for each mode, above which the asset is assumed to have failed. This threshold may be adjusted based on the level of uncertainty within the damage model to calibrate the scale of failures predicted with the level of failure historically experienced.

The entire resilience methodology shall be calculated for each scenario independently, and the customer impact (Section 6) resulting from each scenario calculated.

The susceptibility module is made up of two sub-processes: Scenario Modelling, and Failure Modelling.

3.2. Scenario Modelling

Scenario modelling is used to define the extreme weather conditions that an asset at a given location is likely to experience. Within the current version of Resilire, this is limited to the combination of wind pressure and icing.

3.2.1. Wind Pressure

During a windstorm, the predominate cause of damage to overhead electricity networks is the force exerted by wind pressure on structures or trees, 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 with 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 methodology, the extreme wind speed is calculated for each asset location based on the parameters in Table 1.

Table 1: Extreme Wind speed Parameters

Parameter	Value
Return period	1 in 10 years
Sampling frequency	3 second gust
Height above ground	5m

Extreme wind speeds may be calculated as omnidirectional extreme values, or as extreme values for each compass point. Conventionally, wind in the UK is considered in terms of South-west, North-west, North-east and South-east directions due to the prevailing south-westerly airflow.

The extreme wind speed is then converted to an extreme wind pressure using Equation 1.

Equation 1: Dynamic Pressure

$$P = \frac{1}{2}\rho v^2,$$

Where:

P	Dynamic pressure (N/m^2)
ρ	Air density (kg/m^3). This may be forecast from weather models, or a standard value of 1.225kg/m^2 [1] may be used.
v	Windspeed (m/s)

3.2.2. Icing

Within a windstorm, high wind speed may coincide with the accretion of icing on conductors and structures. This ice accretion increases the load in two ways:

- The mass of the ice increases the mass on the conductor, and therefore the conductor tension;

- The volume of ice increases the cross-sectional area of the conductor, and potentially the pole, and therefore increases the force applied by a given wind pressure.

Within the Resilire methodology, icing is considered to be rime ice with a consistent radius around the conductor or structure. The 1 in 10-year extent of icing may be predicted from weather modelling, either as an omni-directional value, or as a function of the wind direction.

Where modelling is not available, an icing radius of 6mm can be assumed [2].

Where wind pressure and/or icing is defined per compass point as opposed to omni-directionally, the extreme wind pressure and icing on each asset for a given wind direction shall be considered to be a scenario. The relative likelihood of extreme winds of each compass direction shall be defined, based on the historic frequency of extreme winds from each direction.

3.3. Failure Modelling

3.3.1. Wind – Pole Strength

3.3.1.1. Overview

The wood pole wind damage model predicts the failure of poles due to wind in terms of three failure modes mechanisms are:

1. Failure of the pole in bending due to horizontal loads
2. Failure of the soil around the pole anchorage, causing the pole to tip due to horizontal loads
3. Failure of a pole stays in tension.

In each case, it is possible to calculate the moment induced by the wind, M_{wind}, and the critical moment the structure can withstand, M_{crit}, and the factor of safety, S, is then the minimum ratio between these moments as shown in Equation 2.

As a pole degrades, the strength of the pole will reduce, as will the critical moment the structure can withstand. To account for this, the calculated critical moment is factored down by Health Score Factor calculated as part of the Common Network Asset Indices Methodology (CNAIM) [3] which is based on observed and measured condition data. It is judged that the health score factor is applicable to all three failure mechanisms, as an approximate measure of degradation in the wooden pole, the state of the pole foundation, and stay arrangements. This is consistent with the 'Functional Failure Definitions' listed in Table 19 of CNAIM.

Equation 2: Wind Damage - Factor of Safety

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

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 Section 6.7

For poles without stays, only the failure of the pole in bending and the failure of the soil around the pole anchorage are considered.

Wherever appropriate throughout, the methods retain consistency with the primary ENA Technical Specification 43-4 [2] and the associated method for assessing pole performance during design, ‘WOODPOLE’.

3.3.1.2. Moment exerted by wind

In the general case, the moment exerted by the wind is given by Equation 3.

Equation 3: Wind induced moments

$$M_{wind} = Design\ Wind\ Pressure \times \sum_{source}^{\substack{pole,\\ conductor,\\ insulator,\\ plant,}} [Line\ of\ action \times projected\ area]$$

The different pole features are subject to wind loads depending on their projected area into the wind. The bending moment contributing to the relevant pole failure modes depends on their height above the ground. For the failure mechanisms assessed, the loads are all resolved into the chosen wind direction. For conductor loads, this utilises relative angles between spans (whose angles are defined relative to North) and the input wind direction into the model. This is defined in detail in Section 3.3.1.2.4.

Where the wind direction is not known, M_{wind} is calculated across 8 compass points[1], and the worst case (maximum) value taken/

Each of the loads below are defined by having a horizontal magnitude and a height of action from ground level. Horizontal magnitudes are expressed as their projected area under wind pressure.

3.3.1.2.1. Wind load on pole

The pole’s diameter and taper information allows for the loaded area and moment arm to be calculated. This load is assumed to be the same for any wind direction, i.e. ignoring any shielding effects specific to the pole location, or to the relative position of the two poles in an H-pole structure.

Equation 4: Pole Projected Area

$$A_{pole} = n_{poles} * 0.5 * \left(D_{base} + D_{top}\right) * H_{pole}$$

Where A_{pole}	Pole projected area (m²)
n_{poles}	Number of poles
D_{base}	Critical (ground level) diameter (m)
D_{top}	Pole top diameter (m)
H_{pole}	Pole height above ground (m)

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[1] *North, North-west, West, South-west, South, South-east, East and North-east*

Equation 5: Pole Line of Action

$$L_{pole} = 0.5 * H_{pole}$$

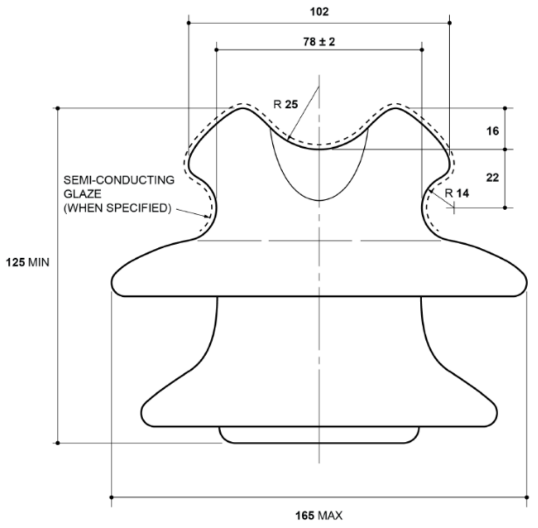
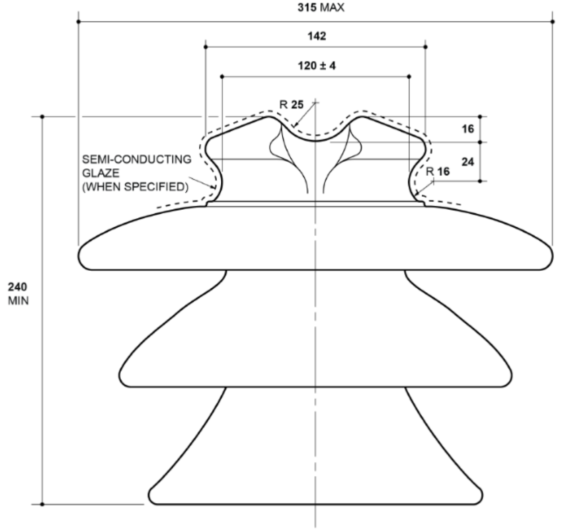
Where:

H_{pole}	Pole height above ground (m)
L_{pole}	Pole line of action (m)

3.3.1.2.2. Wind load on insulators

The profile of the insulators is assumed for the different pole types (Intermediate, Section, and Terminal). For all Inter poles, 11kV pin mounted insulators (specified in ENWL drawing I-40014-INS-001) are assumed. For Section and Terminal poles, 11kV/33kV section pin mounted insulators (specified in ENWL drawing I-40014-INS-002 in [4]) are assumed. The area loaded by wind is estimated, and the moment arm of this load is calculated based on the insulator size and the standard height of lines above the top of poles, as defined in ENA TS 43-40 Section 4.5 and Table A4 [5] as shown in Table 2.

Table 2: Insulator Parameters

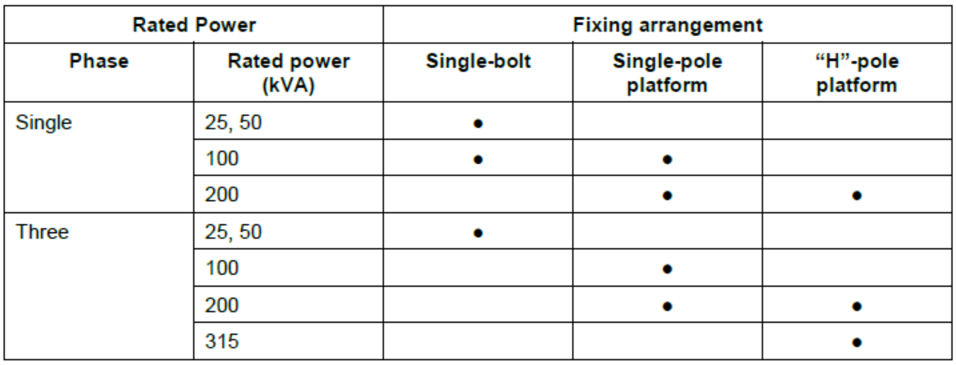
11kV Pin Mounted Insulator [4]	**11/ 33kV Section Pin Insulators [4]**
	
Assumed for Inter poles	Assumed for Section and Terminal Poles
$\boldsymbol{A_{insulators} = n_{phases} \times \frac{0.125 \times 0.165}{2} = 10.3 \times 10^{-3} \times n_{phases}}$	$A_{insulators} = n_{phases} \times \frac{0.240 \times 0.315}{2} = 37.8 \times 10^{-3} \times n_{phases}$
Assumed line of action (from ground level), $\boldsymbol{L_{insulators} = \text{Centre of insulator} + (\text{height of insulators above supports} - \text{height of supports below top of pole}) + \text{pole height}}$ Where: • The height of insulators above support is obtained from SP Electricity North West specification ES 40014 [4] • The height of supports below top of the pole is obtained from ENA Technical Specification 43-40 [5]	

$L_{insulators} = \frac{\mathbf{0.125}}{\mathbf{2}} + (\mathbf{0.260} - \mathbf{0.100}) + h_{pole}$	$L_{insulators} = \frac{0.240}{2} + (0.450 - 0.100) + h_{pole}$

3.3.1.2.3. Wind load on pole-mounted plant

Pole mounted plant, such as transformers and switchgear, are likely to contribute significantly to pole loading due to their height above ground and moderate profile. For each pole asset, the type and MVA rating of any pole mounted transformer is known. The MVA rating corresponds to a set of maximum dimensions in ENA TS 35-1 Part 4 [6], based on the allowed fixing arrangements:

Table 3: Fixing arrangements by rated power of pole mounted transformers (reproduced from Table 1 of [6])



Rated Power		Fixing arrangement		
Phase	**Rated power (kVA)**	**Single-bolt**	**Single-pole platform**	**“H”-pole platform**
Single	25, 50	•		
	100	•	•	
	200		•	•
Three	25, 50	•		
	100		•	
	200		•	•
	315			•

Figure 3 shows how each fixing arrangement has a specified set of maximum dimensions. The woodpole model uses the values of maximum height and total width to calculate an upper bound profile of a pole’s mounted plant. Where a rated power value has several fixing arrangement options (i.e. 200kVA transformers), the larger of the two options is assumed. The relevant dimensions are reproduced in Table 4. Where a transformer has a rating which is not listed, the next higher value shall be used.

Table 4: Assumed Pole Mounted Transformer Dimensions

Transformer Rating (MVA)	Maximum Height (h) (mm)	Vertical centreline of tanks fixing[2] (d) (mm)	Total Width (w) (mm)
0.025	1270	225	760
0.05	1270	225	760
0.1	1320	460	1320
0.2	1500	535	1380
0.315	1500	535	1380

The transformer projected area is therefore given by:

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[2] *The fixing is based on the position of the LV bushing or the radiator, whichever gives the greatest distance to the vertical centreline,*

Equation 6: Projected Area of Transformer

$$A_{transformer} = h \times w$$

(defined in m²)

For smaller pole mounted plant, such as switchgear, there is a much greater variety of equipment types and mounting arrangements, which is not well documented for all HV pole assets. As such, the model uses an assumed projected area of switchgear assets of 500 mm x 500 mm, judged to be an appropriate upper bound.

Equation 7: Projected Area of Switchgear

$$A_{switchgear} = 0.5 \times 0.5 = 0.25$$

(defined in m²)

SP Electricity North West Code of Practice (CP) 420, Chapter 15A specifies the clearances required for pole structures for overhead lines [7]. The allowable clearance between overhead line and plant equipment is 1.2m to 2.0m, as shown in Figure 4. Pessimistically, the model assumes a minimum clearance of 1.2 m; to give an upper bound of the moment arm of the equipment's wind load relative to ground level. This value is used for both pole mounted transformers and switchgear to give the Plant wind load line of action, L_{plant}:

Equation 8: Plant wind load line of action

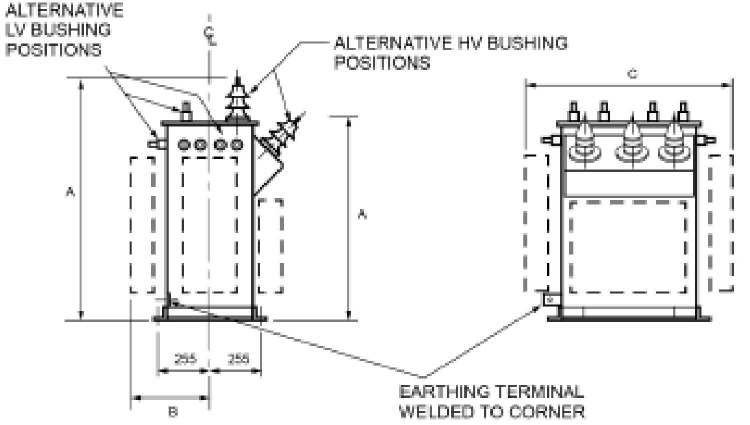
$$L_{plant} = h_{conductor} - 1.2$$

Where:

$h_{conductor}$	The height of the conductor above ground at the pole in metres

Third Angle Projection

THREE PHASE TRANSFORMER
SHOWN AS EXAMPLE ONLY



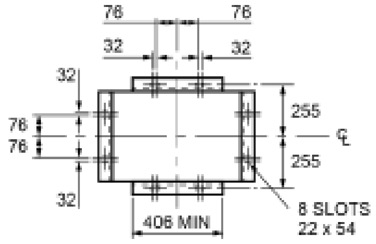
DO NOT SCALE

IF IN DOUBT ASK

DIMENSION 'A' IS OVERALL HEIGHT i.e. TO TOP FACE OF LID OR TOP OF BUSHING WHICHEVER IS GREATER

DIMENSION 'B' IS ℄ OF TANK TO LV BUSHING OR RADIATOR WHICHEVER IS GREATER

DIMENSION 'C' IS OVERALL WIDTH i.e. BUSHING TO BUSHING OR RADIATOR TO RADIATOR WHICHEVER IS GREATER



FIXING HOLE POSITIONS

DIMENSION	MAX. FOR H-POLE PLATFORM (FIG. 4(B))
A	1500
B	535
C	1380

NOTES:
1. FOR ARRANGEMENT ON POLE SEE FIG. 4
2. ACCEPTED POSITIONS FOR OPTIONAL RADIATORS ARE INDICATED BY CHAIN DOT
3. ALL DIMENSIONS ARE IN mm AND ARE SUBJECT TO NORMAL MANUFACTURING TOLERANCES U.O.S.
4. FOR PHASE AND EARTH CLEARANCE – SEE TABLE 2
5. ALTERNATIVE LV BUSHING POSITIONS INDICATED FOR INFORMATION ONLY. ACTUAL LOCATION SHALL BE AGREED WITH PURCHASER (SEE CLAUSE 4.4)

Figure 3: Example of assumed dimensions for pole mounted transformers (reproduced from Figure 3 of [6])

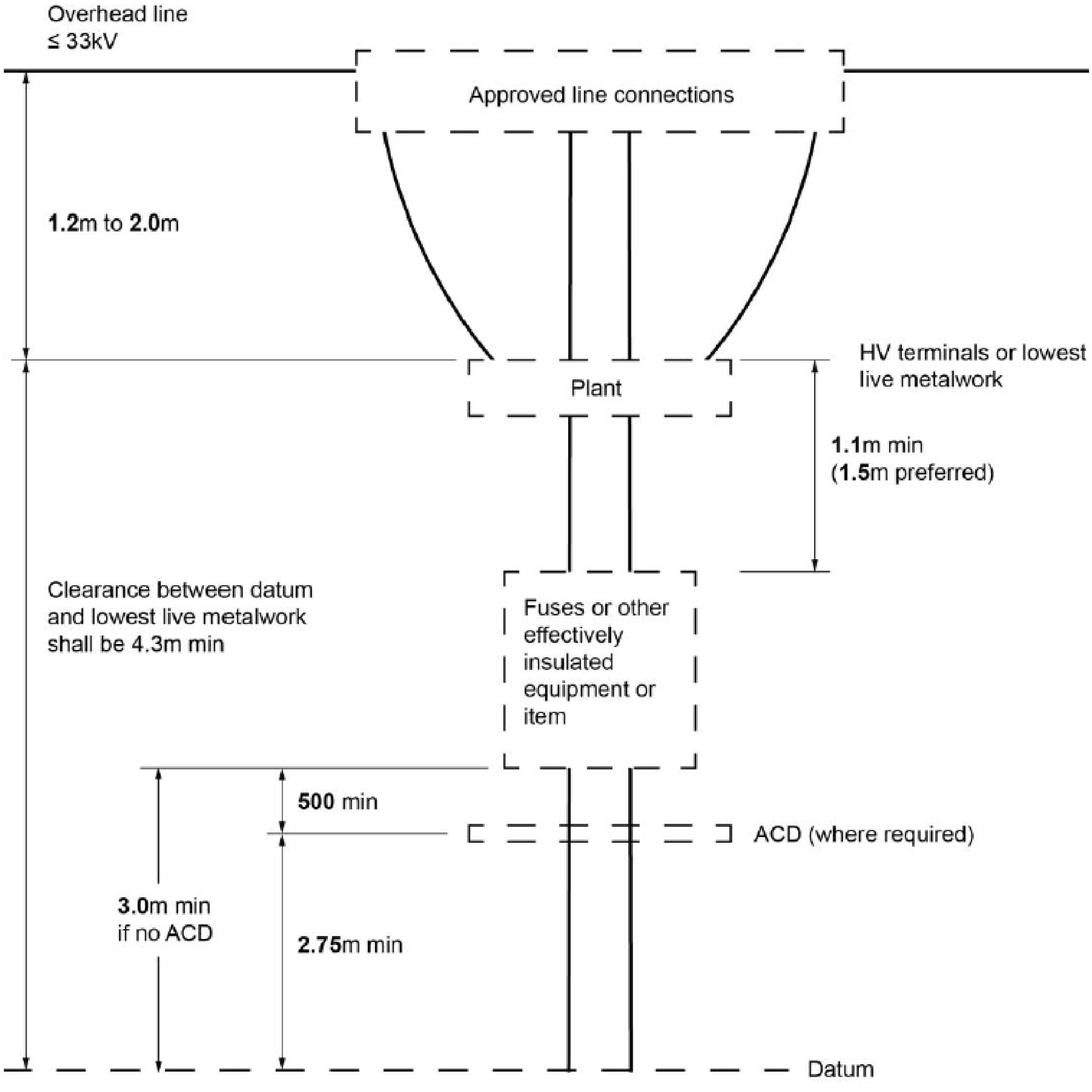


Figure 4: Specified clearances of pole mounted equipment as per [8] . Pole mounted plant is modelled at 1.2m from the overhead lines (conservatively assuming the longest moment arm for the wind loading).

3.3.1.2.4. Wind load on conductors and their attachments

The wind loading on the conductors results in a horizontal force on the top of the pole. This is denoted as the conductor pressure by ENA TS 43-40 (Maximum Conductor Pressure (MCP) for the empirical design approach [2]). The area experiencing wind pressure is increased by conductor icing and by any attachments such as bird flight diverters (BFDs).

The magnitude of the conductor pressure is dependent on the relative angle of the spans and the wind direction. The projected area of the conductor into the wind is the relevant area, governed by the span length and the relative angle of each span. This is illustrated for the range of possible relative span angles in Figure 4, confirming that the expression below is applicable for the full range.

It is assumed that the pressure exerted on each span is distributed evenly between the two poles supporting it, such that the conductor projected area calculation uses half of the span length provided by a pole's asset data:

Equation 9: Conductor Projected Area

$$A_{conductor} = \left(\left(\frac{l_{span}}{2} \times \left(d_{conductor} + d_{icing}\right)\right) + A_{BFD}\right) \times \text{abs}\left(\sin\left(\theta_{span,relative}\right)\right)$$

Where:

$A_{conductor}$	The projected area of the conductor (m²)
l_{span}	Conductor span length (m)
$d_{conductor}$	Diameter of the conductor (m)
d_{icing}	Diameter of icing on the conductor (m)
$\theta_{span,relative}$	Relative angle of the span to the wind direction
A_{BFD}	The area of bird flight diverters (m²), as given by Equation 10.

Where a conductor is fitted with bird flight diverters (BFDs), these increase the projected area of the conductor, so should also be considered. Bird flight diverters are assumed to be circular plates attached at intervals along the conductor, with each pole supporting those on half the span length.

Equation 10: Area of bird flight diverters

$$A_{BFD} = \pi\left(\frac{d_{BFD}}{2}\right)^2 \times \frac{l_{span}}{2 \times i_{BFD}}$$

Where:

A_{BFD}	The area of bird flight diverters (m²)
d_{BFD}	Diameter of a bird flight diverter, assumed to be 0.1m
l_{span}	Conductor span length (m)
i_{BFD}	The interval of bird flight diverter along the span, assumed to be 10m

The conductor line of action, $L_{conductors}$, is assumed to be at the same height above the ground as the insulators defined in Table 2

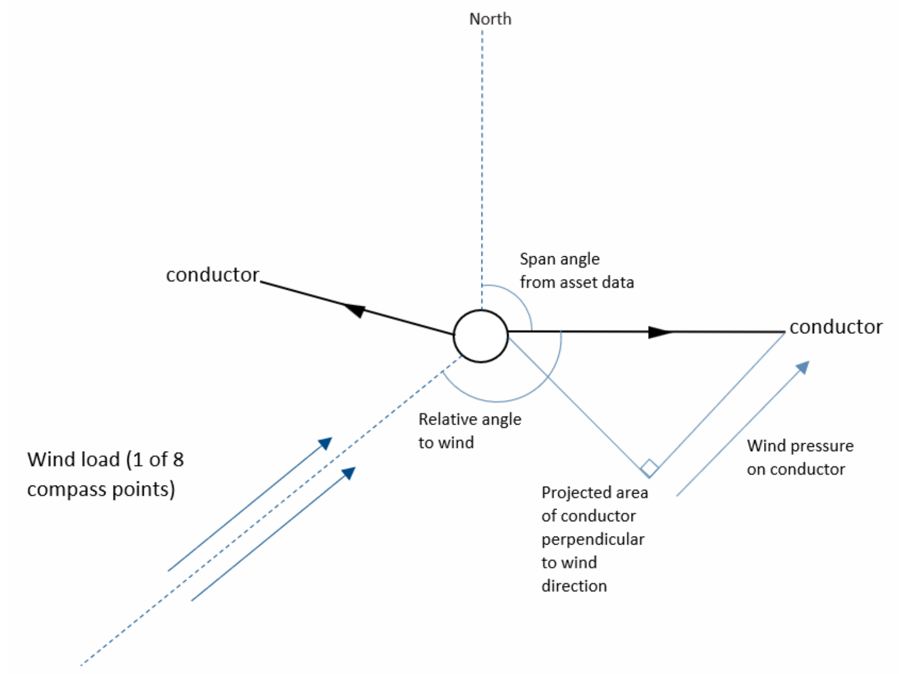


Figure 5: Resolving conductor pressures into the direction of the wind

3.3.1.2.5. Tension in conductors

The ENA TS 43-40 empirical design checks on pole strength assume that conductor tensions are balanced such that the top of the pole sees no resultant force from this source [5]. In the case of Intermediate poles, this results from the two spans being aligned, and an assumption that tensions of conductors upon assembly are equal. Likewise, for Section and Terminal poles, it is assumed that conductor tension is balanced by the use of appropriate stays. As such, the ENA TS 43-40 WOODPOLE calculations ignore conductor and stay tension as a contributor to the two failure mechanisms [5]. This allows the empirical process to treat the pole structure as statically determinate.

In reality, conductor tension may vary due to temperature, ice loading, and wind loading, all of which can also change the angle of the conductor to the horizontal. The SAGNTEN method in ENA TS 43-40 [5] explores the interaction between conductor wind pressure, conductor tension, and ice loading; the design calculation route assumes a design wind pressure and iterates through solutions of cable sag angles to estimate conductor tension. Such an approach is not possible in the structure of this methodology, due to its independence from an input wind pressure. Likewise, the weight of any icing on conductors is not considered as its impact on the bending load on the pole depends on this interaction between conductor tension, weight, and wind.

The woodpole damage model retains the assumptions in the ENA TS 43-40 WOODPOLE method – both for consistency and to preserve the loading as a statically determinate problem, such that the wind pressure can be back-calculated.

3.3.1.2.6. Additional resistance provided by stays

The empirical design process assumes that tension in stays balances any resultant conductor tension due to the angle of line deviation – allowing the WOODPOLE method to ignore both contributions, as noted in Section 3.3.1.2.5 [5]. The stays themselves are designed on this assumption, in the S STAY and H STAY methods in [5]; the azimuthal angle of the stays are chosen to match the angle of line deviation of the spans, and the required stay strength is calculated assuming the design wind pressure is in the same direction as the resultant conductor tension.

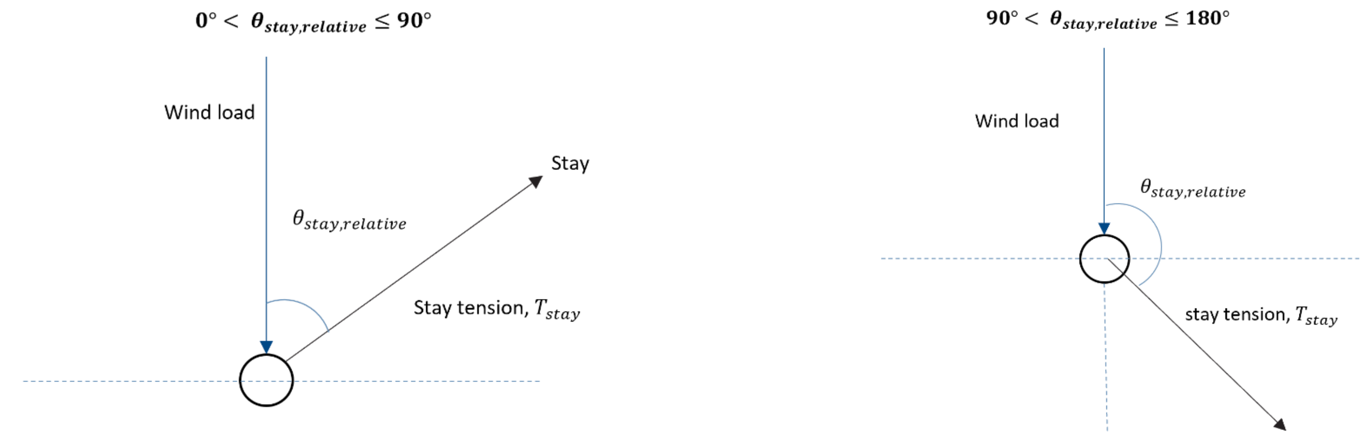
As this model considers multiple wind directions, the stay tensions cannot be calculated in as simple a manner, especially if multiple stays are present. As noted above, contributions from stays and conductors alongside any reaction force from the soil makes the pole a statically indeterminate structure. Likewise, the wind load on the stays is carried by both of its attachments (to the ground and to the pole) in an unknown distribution.

Therefore, a simplified approach is used to account for the benefit of stay tension. An ‘unstayed’ design wind pressure is calculated by ignoring tension from stays (see Section 3.3.1.3.1 and 3.3.1.3.2, where only pole bending and soil bearing resistances are considered). Then, a ‘stayed’ design wind pressure is calculated with assumptions about stay tension, ignoring any resistance from the pole or the soil.

To back-calculate this stayed design wind pressure, all stay tensions are set at the maximum Safe Working Load (SWL) of 40.4 kN. This is the value given in paragraph 5.2.2 of SP Electricity North West Code of Practice (CP) 420 Part 1 [7] for heavy duty stays, applicable to 11kV and 33kV overhead line structures. All stays are assumed to have the recommended slope of 45°C to the pole (paragraph 6.1 of CP 420 Part 1). This angle is used to calculate the horizontal component of the force acting on the pole from the stay.

This horizontal component of stay tension is resolved in the direction of the wind, using a similar approach to that of the conductor wind loaded area. This is illustrated in Figure 6. For relative angles between 90° and 270°, any stay tension would act in the same direction as the wind. This is not credible, and therefore tension is assumed to be zero for such stays – no benefit is assumed, but neither is the asset’s resilience compromised unrealistically.

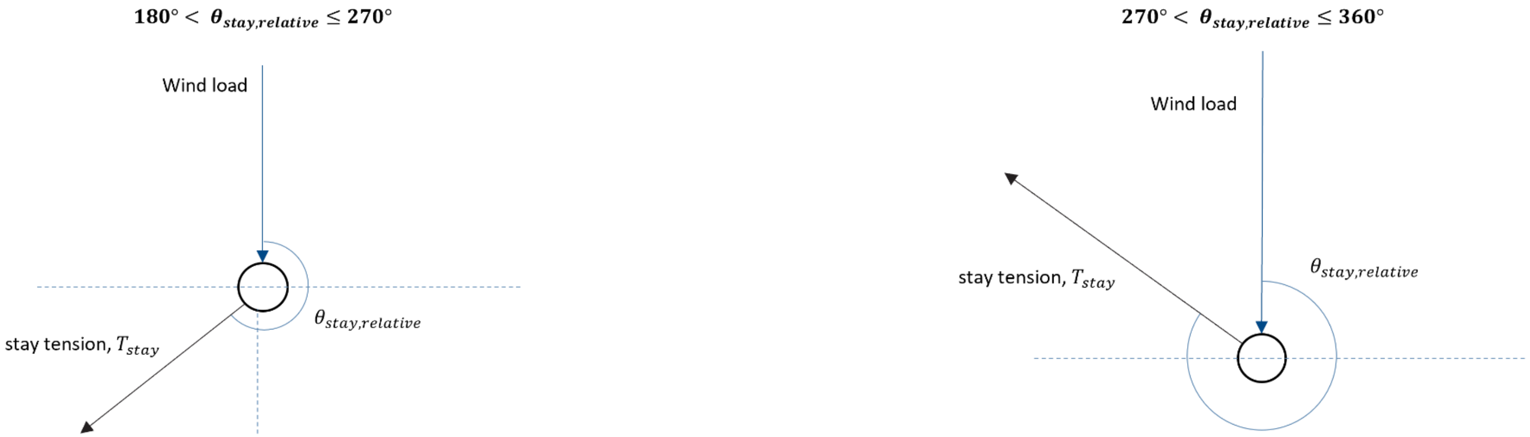
As will be discussed in Section 3.3.1.3.3, the critical wind pressure to cause the stays to be in maximum tension is back-calculated on the assumption that the stays fully balance the wind loading forces (ignoring the unknown contributions from conductor tensions). Stay tensions perpendicular to the wind are neglected, assumed to simply balance resultant conductor tension in this direction as per the design code. Wind pressure loading on the stays themselves is also ignored. This simplified approach means that the benefit of stays can be accounted for.



Component of tension in wind direction, $F_{conductors} = -1 \times T_{stay} \times \cos(\theta_{stay,relative})$

Component of tension in wind direction, $F_{conductors} = T_{stay} \times \cos(180° - \theta_{stay,relative})$

$= -1 \times T_{stay} \times \cos(\theta_{stay,relative})$



Component of tension in wind direction, $F_{conductors} = T_{stay} \times \cos(\theta_{stay,relative} - 180°)$

$= -1 \times T_{stay} \times \cos(\theta_{stay,relative})$

Component of tension in wind direction, $F_{conductors} = -1 \times T_{stay} \times \cos(360° - \theta_{stay,relative})$

$= -1 \times T_{stay} \times \cos(\theta_{stay,relative})$

Figure 6: Illustration of how stay tension is resolved into the wind direction for different values of relative stay angle

3.3.1.3. *Modelled failure mechanisms*

3.3.1.3.1. Failure by maximum fibre stress in pole

The modelled pole fails in bending when the reaction moment at ground level reaches a critical value, defined as:

Equation 11: Critical pole bending moment

$$\sigma_{crit,pole} = Wood\ Fibre\ Stress \times Elastic\ Section\ Modulus$$

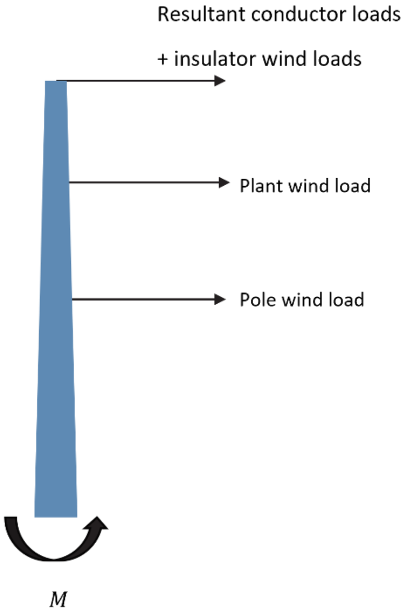


Figure 7: Free-body diagram of the pole under bending, idealised as a cantilever fixed at ground level.

The start-of-life critical fibre stress of a pole is assumed to be 53.8 N/mm^2, in line with the guidance in the WOODPOLE calculation sheet of the ENA TS 43-40 method [5]. However it can be expected that there is some age-related degradation in strength, so the strength is assumed to be reduced to 52.4 N/mm^2 at the expected life of 55 years (the Normal Expected Life of a wood pole in CNAIM v2.1, Table 20 [3]). For poles younger than 55 years, the critical fibre stress is linearly interpolated between these two values, as shown in Equation 12 and Figure 8.

Equation 12: Pole Critical Fibre Stress

$$\sigma_{crit,pole} = \begin{cases} 53.8 - 0.0225 \times Age_{pole}\ where\ Age_{pole} < 55\ years \\ 52.4\ where\ Age_{pole} \geq 55\ years \end{cases}$$

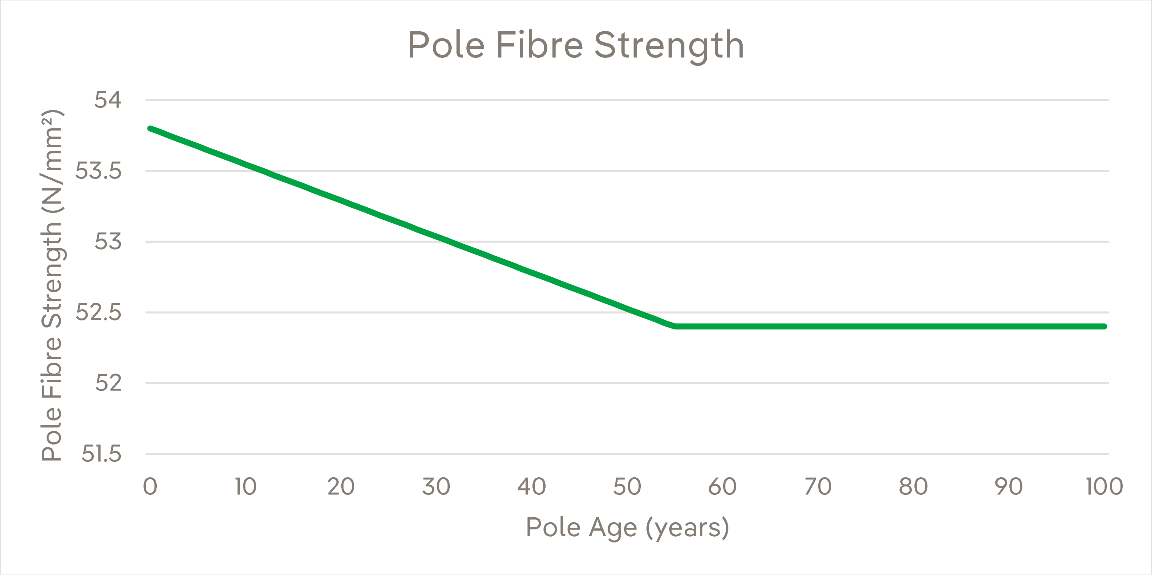


Figure 8: Pole Critical Fibre Stress

Equation 13: Pole ultimate bending moment

$$M_{crit,pole} = \sigma_{crit,pole} \times \frac{D_{top} + D_{base}}{2} \times H_{pole}$$

Where:

$M_{crit,pole}$	Pole ultimate bending moment (Nm)
$\sigma_{crit,pole}$	Pole critical fibre stress (N/m²)
D_{base}	Critical (ground level) diameter (m)
D_{top}	Pole top diameter (m)
H_{pole}	Pole height above ground (m)

The bending moment exerted by the wind on the pole is equated to the resultant moments from the loads defined in the previous section. This is consistent with ENA TS 43-40 calculations of maximum allowable span, in its WOODPOLE method.

Equation 14: Bending Moment due to wind

$$M_{wind,pole} = \mathit{Design\ Wind\ Pressure} \times \begin{Bmatrix} A_{pole}L_{pole} \\ +A_{insulators}L_{insulators} \\ +A_{transformers}L_{plant} \\ +A_{switchgear}L_{plant} \\ +A_{conductors}L_{conductors} \end{Bmatrix}$$

3.3.1.3.2. Failure by maximum bearing stress in soil

The ENA TS 43-40 WOODPOLE model also calculates a maximum allowable conductor span limited by soil bearing resistance, before choosing the minimum of the pole-limited and soil-limited allowable spans. This is based on a calculation of the critical soil moment. While a range of solutions exist in foundation design for structural piles, based on a number of variable soil properties, the expression used in the ENA TS 43-40 WOODPOLE method is as follows:

Equation 15: Maximum Soil Bearing Stress

$$M_{crit,soil} = K \times D_{avg,buried} \times \frac{d^3}{12}$$

Where:

$M_{crit,soil}$	Maximum Soil Bearing Stress (kNm)
K	Soil bearing strength (kN/m³)
$D_{avg,buried}$	The average pole diameter below ground level (m)
d	The planting depth (m)

Where d is the planting depth, $D_{avg,buried}$ is the average pole diameter below ground level, and the K value is defined value of soil bearing strength as per ENA TS 43-40, which defines three levels of soil strength, in kN/m^2 per unit depth:

Table 5: Soil Bearing Strength

Soil	K value
Good	628 kN/m³
Average	471 kN/m³
Poor	314 kN/m³

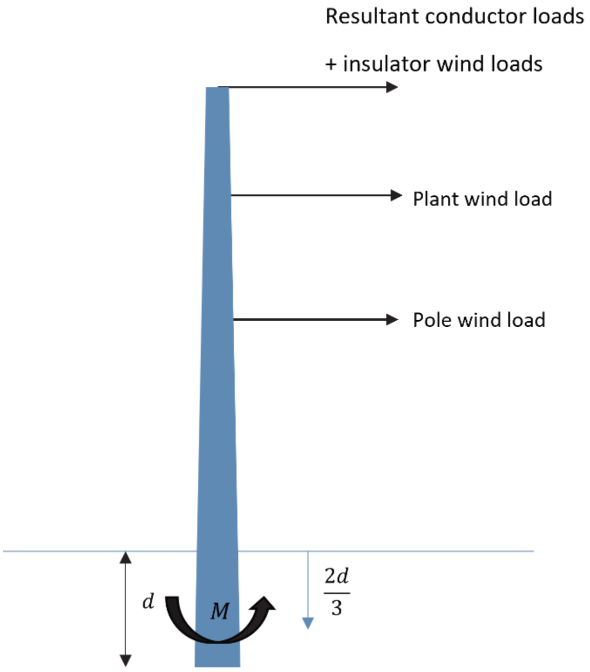


Figure 9: Free body diagram the pole's loading and the assumed location of the soil reaction.

The expression above assumes parabolic ground loading, corresponding to the fulcrum of the resultant moment on the soil occurring at two thirds of the planting depth. The ENA TS 43-40 WOODPOLE method also considers linear ground loading but, with no blocks included in the foundation, the parabolic loading solution is always bounding so the linear ground loading can be ignored.

As such, the moment exerted by wind applicable to soil failure uses the following expression:

Equation 16: Soil Bearing Stress due to wind

$$M_{wind,soil} = Design\ Wind\ Pressure \times \left\{ \begin{array}{c} A_{pole}(L_{pole} + \frac{2d}{3}) \\ +A_{insulators}(L_{insulators} + \frac{2d}{3}) \\ +A_{transformers}(L_{plant} + \frac{2d}{3}) \\ +A_{switchgear}(L_{plant} + \frac{2d}{3}) \\ +A_{conductors}(L_{conductors} + \frac{2d}{3}) \end{array} \right\}$$

3.3.1.3.3. Failure by maximum tensile load in stays

Poles with stays have significantly more resilience to wind loads. In this model it is assumed that, while the pole's stays survive, failure is not credible by the two mechanisms above. To calculate a critical value for stay failure to use in a back-calculation of wind pressure like those above, it is assumed that the contribution of the stay tension fully balances the wind loads such that the bending moment in the pole at ground level is zero. This is illustrated in Figure 10 below.

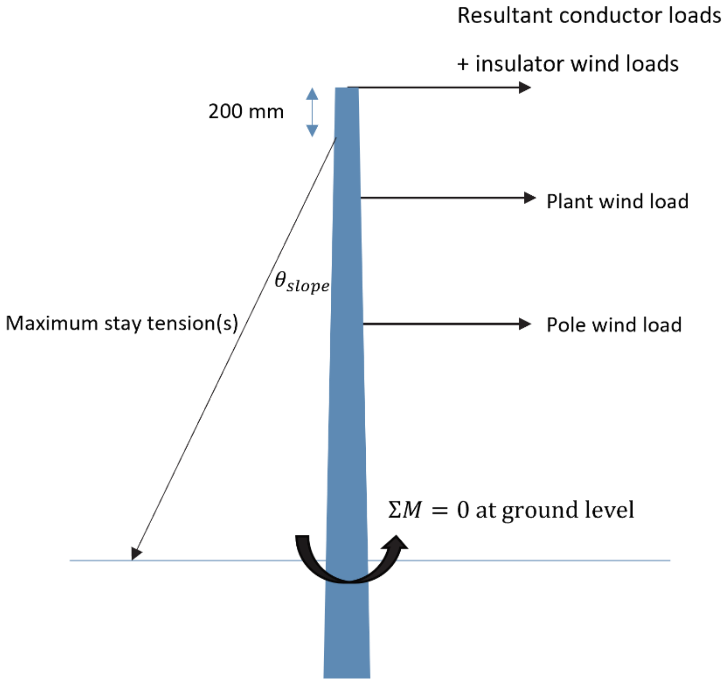


Figure 10: Free-body diagram of a pole's wind loading and the assumed resistance from stay tension.

Equation 17: Critical moment for tensile stays

$$M_{crit,stay} = L_{stay} \times T_{stay} \times cos(\theta_{stay,relative}) \times sin(\theta_{slope})$$

Where:

$M_{crit,stay}$	Maximum stay tensile moment (kNm)
L_{stay}	the distance from the stay attachment to the ground (m) (assumed to be 200 mm below the pole top, matching the locations of stay attachments in Figures 6-7 of ENA TS 43-40 [5])
T_{stay}	The maximum Safe Working Load (SWL) of the stay (assumed to be 40.4 kN from Section 5.2.2 of Code of Practice (CP) 420 Part 1 [7]).
$\theta_{stay,relative}$	The relative angle between the stay and the wind direction
θ_{slope}	The vertical slope of the stay (assumed to be 45°)

Similar to the other two mechanisms, a stayed design wind pressure is calculated based on the above critical stay loading:

Equation 18: Stay stress due to wind

$$M_{wind,stay} = Design\ Wind\ Pressure \times \left\{ \begin{matrix} A_{pole}L_{pole} \\ +A_{insulators}L_{insulators} \\ +A_{transformers}L_{plant} \\ +A_{switchgear}L_{plant} \\ +A_{conductors}L_{conductors} \end{matrix} \right\}$$

3.3.1.4. Assumptions and judgements log

The assumptions and judgements made in the above methods are collated as follows:

- The benefit of components shielding each other from the wind (such as the two poles of an H pole) is not accounted for – therefore the calculated areas for wind loading are an upper bound
- The sizes of plant equipment are based on the known limits on equipment size for different mounting arrangements.
- For calculating the unstayed design wind pressure, conductor and stay tensions are balanced such that the pole sees no resultant force. Hence the effect of conductor and stay tensions can be ignored in the first two failure calculations (pole and soil failure), to keep the modelled pole statically determinate.
- The following insulator types are assumed based on pole type:
    - Inter: 11kV pin insulators
    - Section and Terminal: 11/33kV pin insulators
- For the range of poles in the HV asset data, they are grouped into single and H poles for modelling:
    - H pole: H pole, 3 Supports, Stub, Strut, and A pole
    - Single pole: all other pole types

  It is noted that these assumptions may be highly conservative for some pole types (e.g. for stub poles).

- The pole foundation is assumed to have no blocks to support the pole's resistance to failure by soil bearing.
- The mass of mounted plant is discounted due to the very small moment arm for the failure mechanisms considered.

- The critical moment in the soil uses the same assumed expression as in the ENA TS 43-40 calculations for soil-limited maximum span.
- The critical tensile load in stays is assumed to be 40.4 kN in line with the Safe Working Load (SWL) in Code of Practice 420 Part 1 Chapter 07 [7].
- The slope of all stays is assumed to be 45° [7], and their attachment is assumed to be 200 mm below the top of the pole [5].
- Only stays whose tension would counteract the wind in the wind direction are considered. Stays where any assumed tension would exacerbate the pole loading are assumed to have no tension.
- All failure mechanisms use the health score factor as an indicator of the asset's degraded resistance to failure.

3.3.2. Vegetation – Conductor Damage

The purpose of the vegetation damage model is to account for failures that may occur because of trees or large branches falling during a windstorm. The model takes inspiration from Forest Research's ForestGALES software [9], which contains a hybrid-mechanistic model that assesses the risk of wind damage to forests in Britain.

Applying a similar concept to the pole damage model discussed Section 3.3.1, the ForestGALES model calculates a critical wind speed at which trees will be damaged, which varies based on detailed tree and site information. This information is listed in Table 6, of which a limited amount of data is available publicly.

Table 6: Tree and site information used by Forest Research to determine critical wind speeds.

Tree Information	Site Information
• Species • Height • Stem diameter • Age	• Soil type • Rooting depth • Spacing between trees • Thinning • Type of forest edge

For the resilience model, instead of estimating critical wind speeds for each individual tree a risk of failure of a conductor due to treefall is calculated based on a global critical wind speed and proportion of at risk trees in the vicinity of the asset (Equation 19).

Equation 19: Likelihood of failure from treefall

$$P_{fi} = \begin{cases} e^{x_i} - 1 & if\ w_i \leq w_c \\ 0 & otherwise \end{cases},$$

Where:

P_{fi}	The likelihood of failure of individual span, i
x_i	is the proportion of the span's surrounding area that contains at risk trees (as calculated using the method in Figure 11)
w_i	The wind speed at the span location
w_c	The critical wind speed for a treefall[3].

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[3] *Critical wind speed for treefall is currently set as a global value of 20.8 m/s based on the Beaufort wind scale for a 'strong gale' [20].*

The proportion of trees near the conductor is calculated using the method outlined in Figure 11 and is used as an indicator of how at risk a conductor is to treefall damage where 0% represents very low risk and 100% represents very high risk.

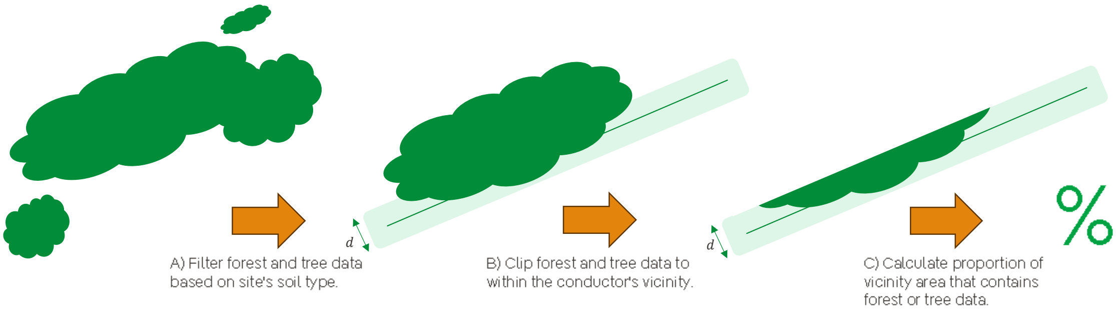

Figure 11: Approach to estimating assets at highest risk of treefall damage. A) Forest inventory [10] and trees outside woodland [11] data are filtered according to the site's soil type [12]. B) The forest and tree data is clipped to only reflect trees within a buffer (d metres) of the network's conductor assets. C) The proportion of the conductor's surrounding area that contains trees is calculated.

4. Vulnerability

4.1. Overview

The purpose of the vulnerability methodology is to determine which customers may be affected by an asset failure, when considering the complexity of the network connections. The diagram below provides a high-level description of the key inputs and outputs.

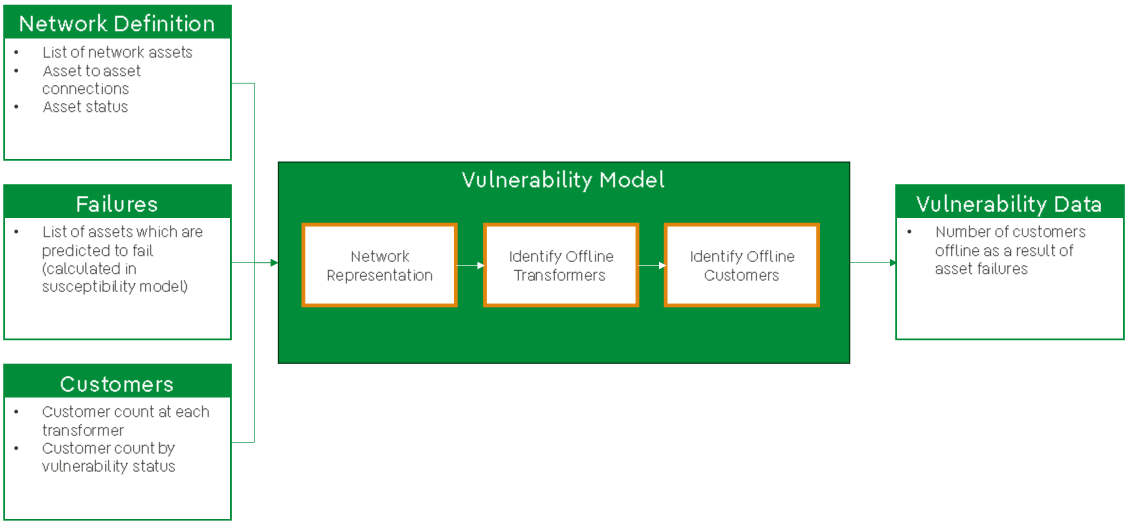

Figure 12: Overview of the vulnerability model key processes, inputs, and outputs. The model requires three data inputs: network definition, customer counts, and the list of failed assets identified by the damage model and returns information on how many customers would be off supply given these failures.

The vulnerability model also provides the mechanism to evaluate the restoration impact of post-fault activities, such as switching and repair, conducted as part of the Operational Response Model described in Section 5.

4.2. Network Representation

The vulnerability methodology considers the network as a graph with nodes representing any component and edges representing the connection between the two (Figure 13 provides an abstract visualisation). While any network components can be captured in the graph, the following are essential for this approach:

Table 7: Network Component Types

Component Type	Description
Root node	This is the 'source' on the network and represents the Extra High Voltage network, or other connected networks where interconnects exist.
Transformer	Transformers act as the 'sinks' on the network. These are the final point before customers and are used when determining whether customers are impacted by a failure in the network. Whilst termed 'transformer', this may also represent the connection point of a HV customer where the transformer is owned and operated by a customer.
Feeder	All the nodes of type 'feeder' are connected to the single master root node, and may represent the secondary side of a primary transformer[4] feeding the network, an interconnect to another network (such as that operated by another DNO) or a generator able to supply the network in an 'islanded' mode. The feeder is assumed to be always energised for the purposes of resilience modelling.
Switch	Switches represent devices on the network which may be used to energise or de-energise a part of the network, and many be normally open or normally closed. Three types of switches are considered: 1. Protected Switches: These are devices which automatically open (or 'trip') when a fault occurs downstream. Examples may include circuit breakers, pole-mounted reclosers and fuse switches. Protected switches are assumed to be telemetered so the state of switch can be observed by the network control system, but not necessarily tele controlled. 2. Tele controlled switches: These are devices which can be remotely operated by a network control system, so can be operated immediately after a fault and before resource arrive on site. 3. Manual switches: These are devices which must be locally operated, so can only be operated once resources arrive on site. Switches are considered as two nodes which are joined by an edge if the switch is closed and not connected if the switch is open.
Conductor	Overhead lines or undergrounded cables.

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[4] *For example, a 33kV/11kV transformer*

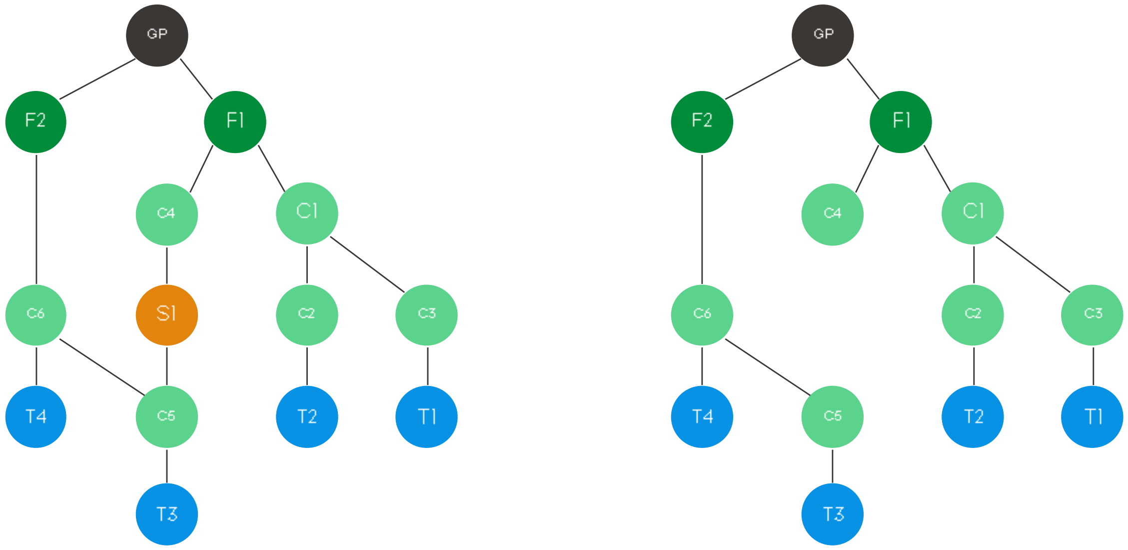

Figure 13: Abstract representation of a portion of a network, using graph structures. Circles represent nodes, which are the network components, and lines represent edges connecting these nodes. Black ('GP') nodes are the root 'supply' point of the graph, dark green ('FX') nodes are feeders, light green ('CX') nodes are conductors, orange ('SX') nodes are switches, and blue ('TX') nodes are transformers. The left image shows the network with a closed switch, and the right image shows the same network, but with the switch opened.

4.3. Network Restoration Process

The vulnerability methodology considers the network in five stages shown in Figure 14.

Figure 14: Network restoration process

All faults are assumed to occur at time =0 as opposed to occurring progressively through an incident. The methodology does not attempt to calculate load flow, so assumes that network re-configuration to restore supplies is not capacity constrained and does not consider the impact of network configuration on circulating currents or fault level. As such, the methodology only considers switching operations required to isolate faults and restore supplies, and not those required to avoid parallel circuits.

4.3.1. Apply Damage to the Network

The susceptibility model described in Section 3 identifies a number of network failures across the network referred to within this methodology as 'faults'. Each fault can be inserted into the network at the location at which it occurred. For example, a pole failure would be applied to the conductor(s) the pole supports, or to the conductor and next electrical element.

4.3.2. De-energise Faults

To apply the effect of the faults, it is necessary to ensure there is no network path between the root node of the network and the fault. To achieve this, it is assumed that the first protected switch on the path from the fault to the root node opens (or 'trips') to de-energise the fault. This simulates the operation of protection on the network.

This may also disconnect transformers from the root node, so these transformers can now be identified as being de-energised, or offline. An example of this is shown in Figure 15 with de-energised network coloured red.

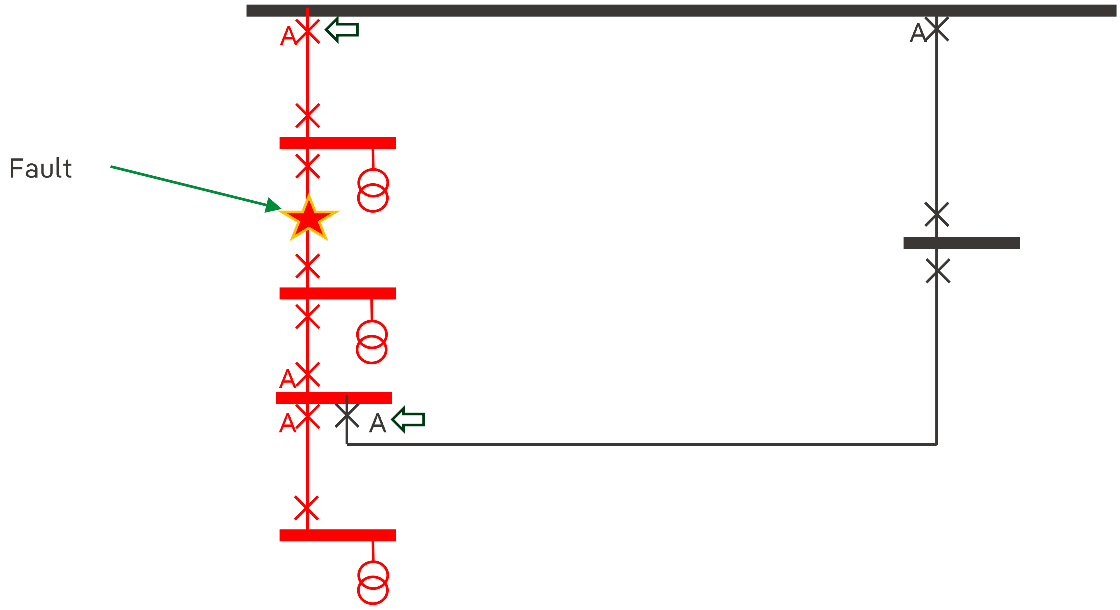

Figure 15: Example network following fault de-energisation ('A' alongside a swich indicates the switch is protected, and an open arrow indicates the switch is open)

4.3.3. Restore supplies through automated switching

The next phase is to simulate the action of automated restoration through Fault Location, Isolation and Service Restoration (FLISR) systems. The methodology does not seek to simulate the entire routine but rather identify the elements of the network which could be re-energised through automated switching subject to the constraint that there can be no path between the root node and any fault. This is achieved by closing all tele-controlled switches and opening the first tele-controlled switch on any path from a fault to the root node.

Automated switching is assumed to happen instantaneously following the fault. In reality, switching would be expected to occur within 3 minutes of the start of the outage but this time period is considered insignificant in the context of the overall recovery period.

The network positions after automated switching is shown in Figure 16, with de-energised network shown in red, and network energised by automated switching shown in green.

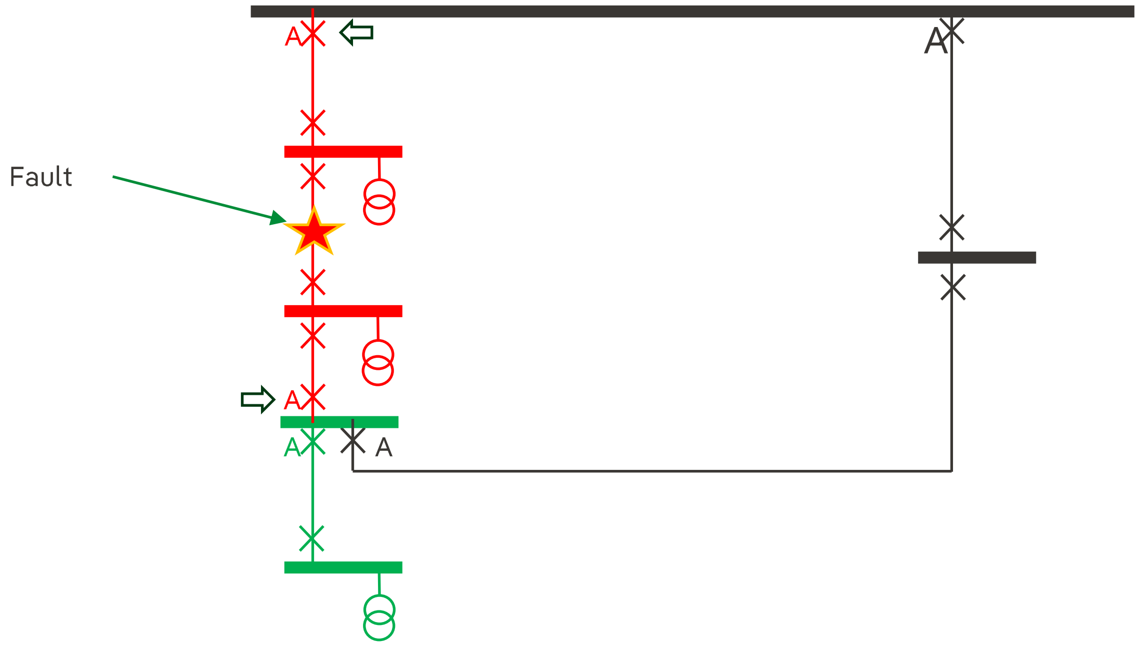

Figure 16: Example network following automated switching

4.3.4. Restore supplies through manual switching

Following automated switching, manual switching is conducted to reduce the area of the network de-energised by further isolating the fault, and/or close open manual switches to re-energise parts of the network which do not contain a fault. Operating a manual switch requires a suitably authorised person to attend the switch location, so the timing of these operations is governed by the Operational Response model described in Section 5.

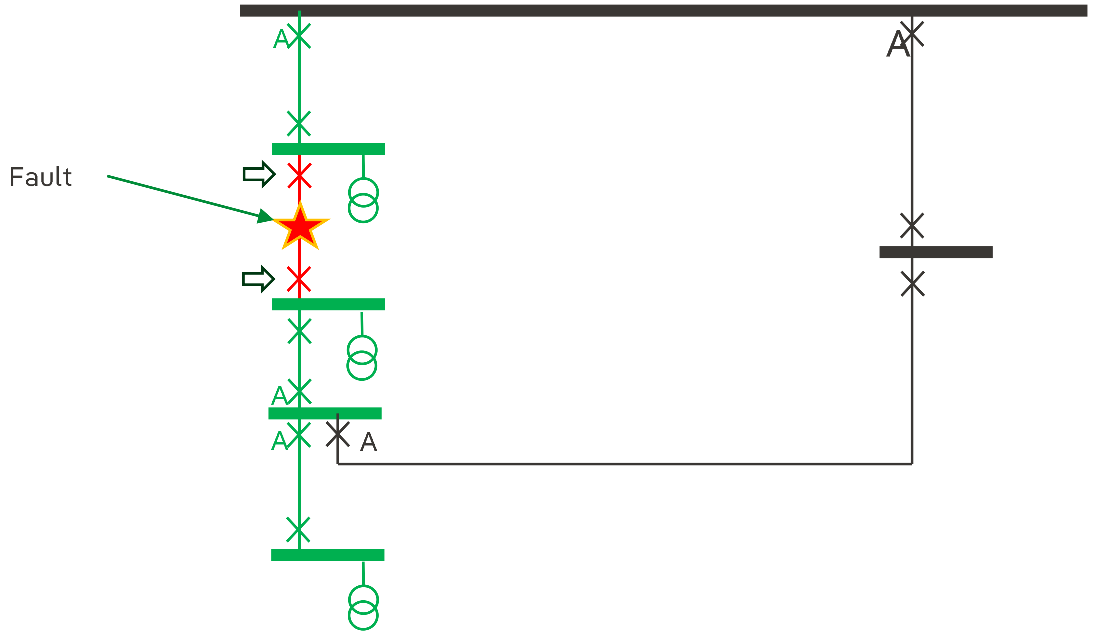

Figure 17: Example network following manual switching

4.3.5. Re-energise following repair

The final stage is to conduct a repair to remove the fault (as described in Section 5), and then close switches separating the fault from the rest of the network. Tele controlled switches are assumed to be closed instantaneously after the fault is removed, whereas manual switch required an authorised person to attend the switch location.

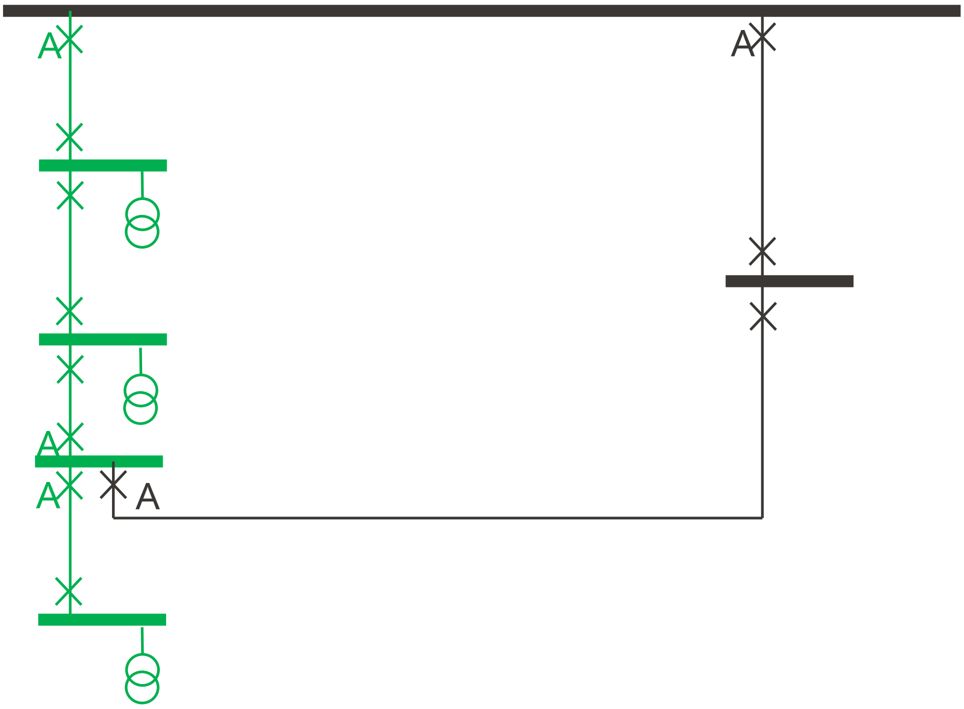

Figure 18: Example network following fault repair

4.3.6. Multiple faults

The examples in this section consider a single fault for simplicity, whereas in reality it is likely there would be multiple faults in the same area of the network. An example of this shown in Figure 19, with three faults, one which is 'nested', that is within an area of network de-energised by other faults.

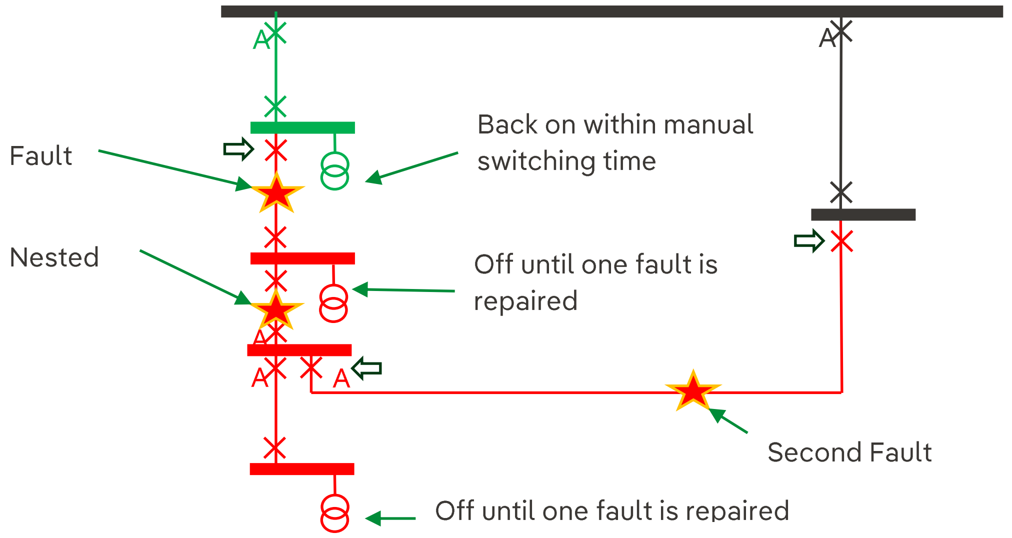

Figure 19: Example network with multiple faults following manual switching

4.4. Identifying offline customers

The final stage in the vulnerability methodology is the calculation of customers offline, considering their vulnerability status. Customers are considered to be offline when the transformer feeding that customer is offline, and a transformer is considered to be disconnected when there is no path from the transformer to the root node that does not pass through a fault or an open switch.

Each transformer is characterised in terms of the number of each type of customer fed as shown in Table 8.

Table 8: Transformer customers parameters

Customer type	Definition
Total customer count	The total number of customers (of all types) fed from the transformer
Priority Services List	Number of customers identified as being on the Priority Services List (PSL) as defined in the Electricity Supply Emergency Code [13]
Highly Vulnerable Customers	Number of customers fed by the transformer who are identified as being particularly vulnerable during power outages due to factors such as being medically dependent on electricity or having a mental of physical impairment which may affect a customer's ability to access support services during an outage.
Extra Care Register Customers	The number of customers fed by the transformer who are identified (or who self-identify) as being vulnerable and requiring additional support during an outage. This excludes customers identified as being highly vulnerable.
Number of EV charge points	The number of service points fed by the transformer where an EV charge point is installed

Customer type	Definition
Number of supermarkets and convenience stores	The number of supermarkets and convenience stores fed (or assumed to be fed)[5] by the transformer.
Number of pharmacies	The number of pharmacies fed (or assumed to be fed)[6] by the transformer.

This data can then be aggregated by transformer or by fault to enable the prioritisation of repair activities (Section 5.3), and the quantification of customer impact (Section 6).

Customer count data is first extracted for only the transformers that are affected by failures on the network (previous section), and returned in two forms:

- **Offline customers** – customer counts for each transformer/fault combination. This allows for consideration of a transformer that is affected by multiple faults later in the process.
- **Vulnerability data** – the customers fed from each transformer/fault combination. The list of customers affected by each fault is required for later customer impact calculations (Section 6) and customer counts split by vulnerability category can then rolled up to each fault, allowing for prioritisation of the repair activities (Section 5.3).

4.5. Identifying Nested Faults

Through representing the network as described in this section it is possible to more realistically represent "nested faults". Nested faults can occur when multiple faults exist between the root supply node and transformers, meaning some customers can still experience no power even after a fault is repaired.

The described methodology will only return the *first* fault encountered when navigating the minimum cost path between the root supply node and transformer. This forces the model to discover these nested (also known as "hidden" faults) as they become relevant, rather than identifying them all upfront.

5. Operational Response

5.1. Overview

The purpose of the operational response (OR) methodology is to estimate how long customers may be offline for while the faults on the network are repaired. While the approach does not attempt to optimise the response or represent fine details that could impact a customer's experience, it does consider information such as prioritisation of repair activities and resource constraints to allow estimation of which customers may be most exposed during outages.

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[5] *Where data on the nature of business of each customer is not available, this data may be obtained by identifying the number of applicable premises within the geographic area served by a given substation*

[6] *Where data on the nature of business of each customer is not available, this data may be obtained by identifying the number of applicable premises within the geographic area served by a given substation*

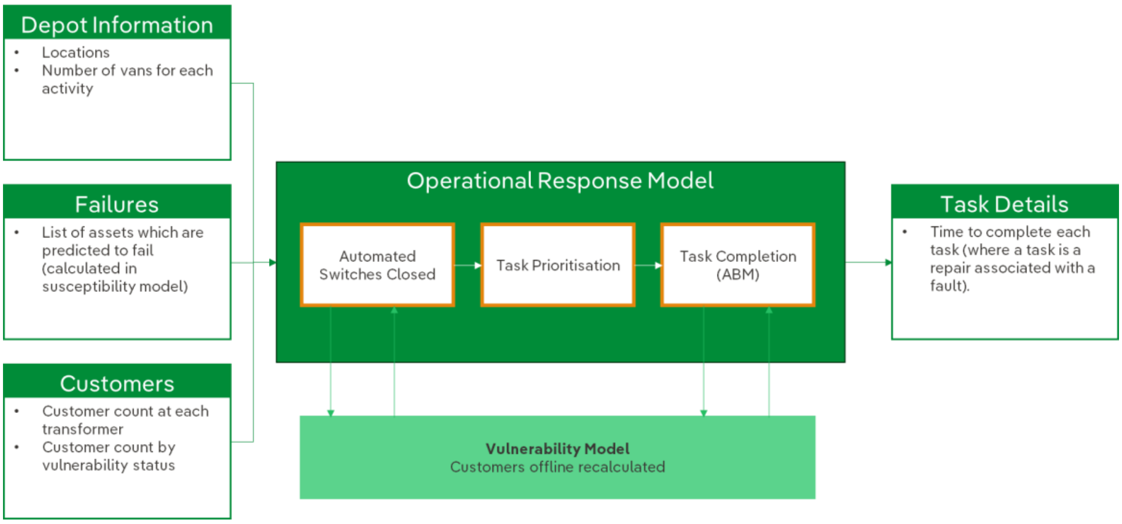

Figure 20: Overview of the OR methodology key processes, inputs, and outputs. The methodology requires three data inputs: depot information, failures, and the associated customers offline identified by the vulnerability methodology and returns information on how long repairs and other tasks are estimated to take to complete.

The core concept within the operational research methodology is that the operational response is conducted by a set of one or more autonomous depots, each serving a distinct geographical region. Each depot has a defined and finite set of resources which must be dispatched to conduct actions on the network by an incident controller in that depot to restore supplies as quickly as possible. It is assumed that resources do not move between geographical regions.[7]

During an incident, the incident controller will not be initially aware of the exact location of damage on the network; only the elements of the network de-energised via tele-controlled or telemetered devices. As such, in the methodology, switch operation, repair, and tree clearance tasks cannot be commenced straight away, as the damage location first needs to be 'discovered' by the reconnaissance (recce) task.

5.2. Automated Responses

Immediately after a fault occurs on the network, automatic closure of some switches can occur to ensure uninterrupted power supply to customers. The abstract network contains information on whether a switch asset can be closed remotely or not, meaning the first stage of the OR methodology is to close the automated switches (as described in Section 4.3.3) that can restore power to offline customers. After this action, the vulnerability methodology is re-run to calculate the new list of offline transformers and customers.

5.3. Tasks and Task Prioritisation

Once the automated switching has been completed, a list of tasks is compiled for the operational response. These tasks reflect the different teams that may be responsible for

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[7] *In reality, resources may be moved between regions, or between network operators under Northern Eastern Western and Southern Area Consortium (NEWSAC) arrangements, but this is dependent on damage being geographically concentrated such that some areas have underutilised resources. As such, this transfer usually happens later in an incident once any the response is complete in less affected areas, so this has been omitted from the model to maintain the deterministic nature and avoid any assumptions as to at what stage other resources may become available.*

activities during an outage and will take different durations to complete, so have different types as described in Table 9 below.

Table 9: OR methodology task type definitions. Approximate durations reflect times to complete a typical activity of this type, excluding travel time.

Task	Description	Duration
Reconnaissance	Investigation into the cause of a fault, and what activity may be required to address it.	1 hour
Manual Switch	Close a manual switch on site.	2 hours
Repair	Generic repair to repair a pole failure fault and restore supplies through that element of the network.	5 hours
Tree Clearance	Time to clear a network fault caused by falling trees	2 hours

Similarly, the resource available have different skills sets and authorisations, and are there able to conduct different tasks as shown in Table 10.

Table 10: Resource and Task Types

Resource Type	Description	Task Types			
		Reconnaissance	Manual Switching	Repair	Tree Clearance
Recce Team	Resources able to survey an area to identify the location of a fault but with no operational authorisations	•			
Authorised Person (AP)	Person suitably authorised to conduct manual switching	•	•		
Lines Team	Resource able to effect repairs on the network. It assumed that lines team will have an embedded Authorised Person to enable switching		•	•	
Vegetation Management Team	Resource able to clear vegetation from overhead lines				•

The transition logic for tasks is outlined below.

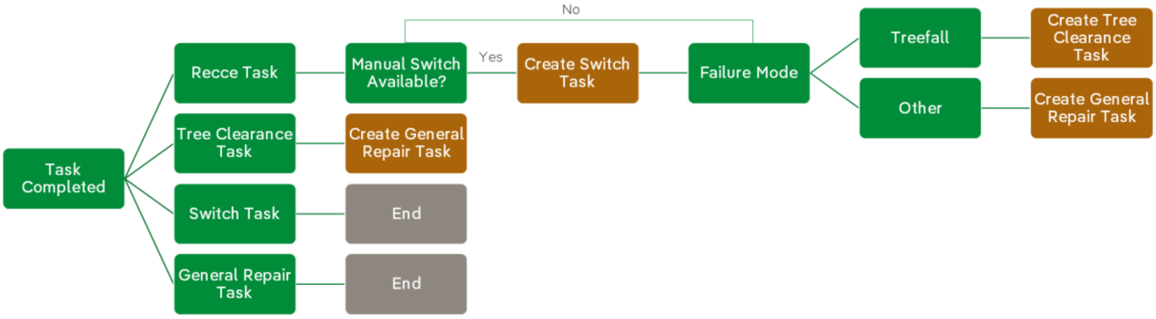

Figure 21: Task transition logic for each of the four tasks. On completion of a task, depending on the type, the model may create additional tasks to be carried out. Dark orange boxes indicate new tasks being created and grey boxes indicate no additional tasks being created.

The task list is then prioritised according to the factors shown in Table 11.

Table 11: Task Ranking Parameters

<table>
<tr><th>Ranking Parameter</th><th>Nomenclature</th><th>Considerations</th></tr>
<tr><td>Number of customers associated with this task, where a higher customer count results in a higher priority task.</td><td>$R_{Customer}$</td><td>The number each type of customer is also incorporated here to generate a ‘sensitivity factor’ (S) (Equation 20) to enable faults serving more vulnerable customers to be prioritised.

Equation 20: Sensitivity Factor

$$S = \left(\frac{aC_{PSL} + bC_{HV} + cC_{PSR}}{C_T} \right)$$

where C_T is total number of customers, C_{PSL} is the count of customers registered on the Protected Sites List under the Electricity Supply Emergency Code (ESEC), C_{HV} is the count of customers categorised as highly vulnerable, C_{PSR} is the count of customers listed in the Priority Services Register, and a, b, and c are weightings applied to each category. The absolute values of a, b, and c are unimportant as these weightings define the relative importance of each type of customer, and therefore the relative priority of each fault within the operational response. These may differ by network operator, but default values are provided in Table 12.

Table 12: Default Customer Sensitivity Weightings

<table>
<tr><th>Parameter</th><th>Value</th></tr>
<tr><td>a</td><td>1</td></tr>
<tr><td>b</td><td>0.2</td></tr>
<tr><td>c</td><td>0.1</td></tr>
</table>

The sensitivity is then used to derive customer count parameter $R_{Customer}$:

Equation 21: Customer count impact

$$R_{Customer} = C_T(1 + S)$$</td></tr>
</table>

Task duration, where shorter tasks result in a higher priority task.	$R_{Duration}$	The task duration is the active time on task, excluding any travel time, but including any logistical difficulties which may result in the task taking longer to conduct. This will have the effect prioritising switching tasks over repair tasks, and simpler repair tasks over more complex ones.
Distance from the depot, where closer tasks result in a higher priority task.	$R_{Distance}$	This evaluates the travel time to conduct a task to reflect the desire the maximise the efficiency of the response by conducting tasks close to existing resources before those requiring resources to spend time travelling.

Tasks are ranked on each ranking parameter and then sorted used a weighted rank as shown in Equation 22, such that tasks affecting many customers, which take a short amount of time to complete and are closer to the depot are prioritised to completed first.

Equation 22: Weighted Rank

$$R_{Weighted} = 0.7R_{Customer} + 0.15R_{Duration} + 0.15R_{Distance}$$

Once the task list is prioritised, they are passed into the task completion model.

5.4. Task Completion – Agent Based Model

5.4.1. Overview

The core of the operational research model is an agent-based model (ABM) which allows the network operator's response to be simulated using a 'bottom-up' approach. Vehicles are represented by autonomous agents, which independently complete tasks to bring customers back online.

In addition to the tasks described in section 5.3, the ABM has three key components which are modelled, as outlined in Table 13.

Table 13: Summary of the three key components of the model: scheduler, depot, and vehicle.

Component	Description
Scheduler	Manages task prioritisation and recalculation of the network state on completion of each task.
Depot	Represents the depot locations and set of resources available
Vehicle	Represents a single team able to be dispatched to complete task

5.4.2. Scheduler

The scheduler manages the order in which tasks are performed following the logic in Figure 22. The scheduler continues the logic until either there are no tasks remaining or all customers are back online.

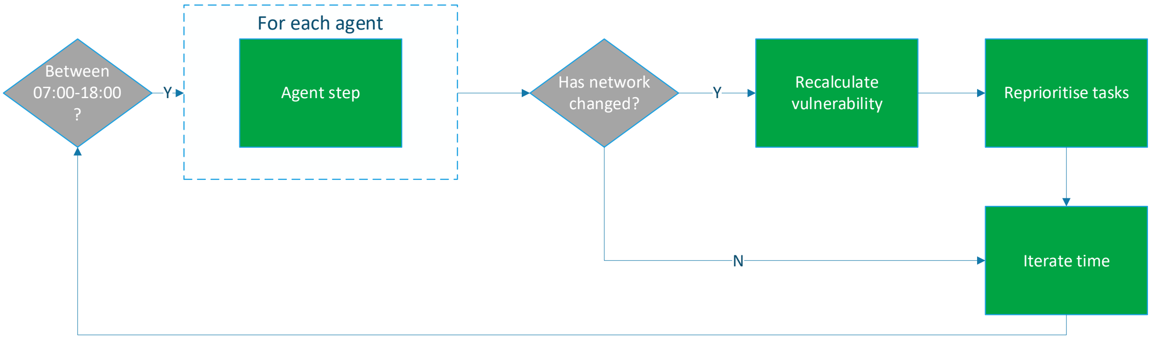

Figure 22: Scheduler Logic

As part of this process, the scheduler assumes that no tasks are performed overnight to represent the difficulties in safely conducting repairs overnight in darkness, and that 24-hour working is not sustainable during an extended incident. Tasks assigned after 18:00 within the model are therefore commenced at 07:00 the following day starting from the depot, although tasks already in progress at 18:00 are completed.

The scheduler also triggers the recalculation of the vulnerability model (section 4) following each task to update the energisation status of each transformer, and then re-prioritise the remaining tasks as described in Section 5.3.

5.4.3. Depot

The depot is a static class which represents a network's depot with:

- The depot location co-ordinates for estimating distance to repairs; and
- A finite number of vehicles of each resource type defined in Table 10

5.4.4. Vehicle

The vehicle component represents an individual or team of one of the types defined in Table 10 and models travel to a task and conduct of that task.

The vehicle logic has two key parts:

- Monitor the progress of ongoing tasks
- Generate follow-on tasks:

As shown in Figure 23, each vehicle first checks that the time is within the working period defined in Section 5.4.2, and then picks up the next applicable task from the prioritised list. The vehicle then calculates the travel time to determine the time of arrival, and on arrival calculate the task time to determine the time of completion. When the task completes, the logic to generate follow on tasks is triggered.

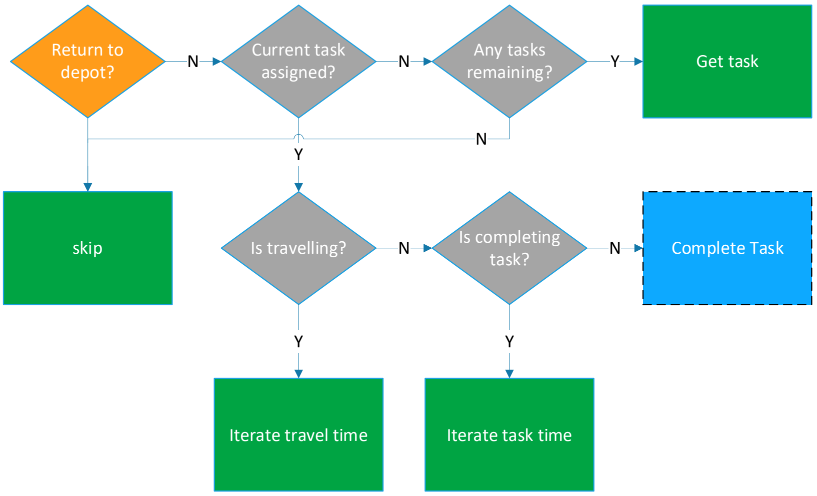

Figure 23: Logic followed by the vehicle in the OR model.

Following completion of a task, the next task or action is generated based on the task transition logic shown in Figure 21. This depends on the type of the task completed and the failure mode of the fault being addressed as shown in Figure 23.

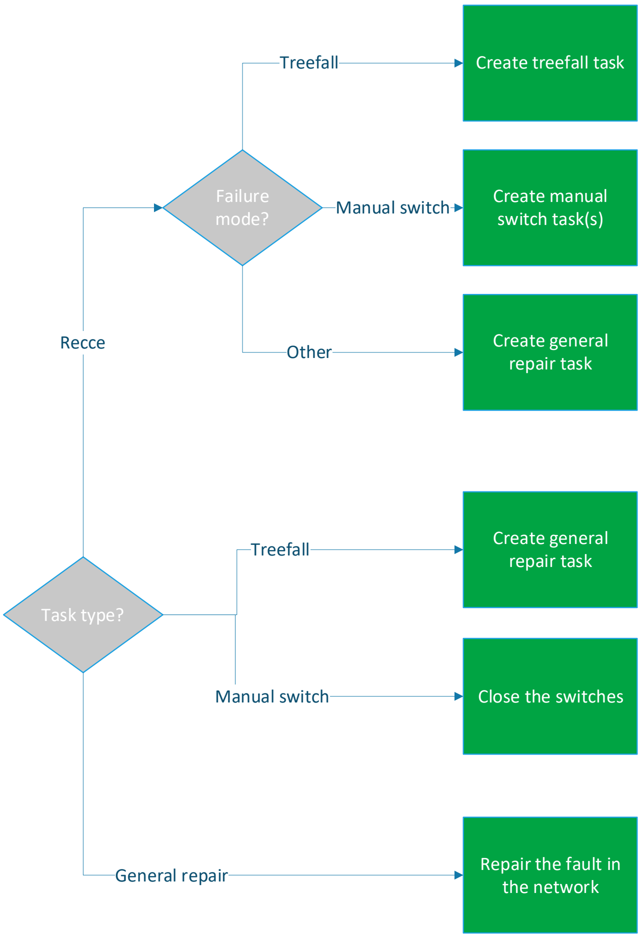

Figure 23: Logic followed by the vehicle in the OR model at the "Complete Task" stage.

6. Customer Impact Model

6.1. Overview

To ensure that the optimal resilience investments are undertaken, it is necessary to understand the customer impact of long-duration supply interruptions. To allocate resources efficiently, investments should be made that generate greater customer benefits than the costs incurred to deliver them. However, estimating these customer benefits is challenging and there is currently no established method to do this. While Ofgem's Value of Lost Load (VoLL) provides an established way of estimating the cost of short-duration outages, it does not adequately reflect the more extensive harms caused by long-duration interruptions. As VoLL is based on willingness-to-pay and willingness-to-accept measures for relatively short outage scenarios, it does not capture harms that are only incurred over longer-duration interruptions [14].

At RIIO-3, Ofgem are also placing increased emphasis on ensuring that consumer value is accounted for in network planning and investment decisions [15].[8] While the cost-benefit analysis methodology used in RIIO-ED2 submissions provides a robust baseline for assessing projects, it is relatively limited in scope and largely focuses on direct financial impacts to the network operator. While it does consider societal costs, these primarily focus on the environmental and safety drivers that support investment decisions, rather than the broader welfare impacts customers experience during extended outages [14].

Whilst research on the impact of long-duration interruptions is limited, a UK Energy Research Centre (UKERC) review of the literature [16] suggests that whilst loss of electricity (and in particular the loss of communication) is a major stressor, there is little evidence for loss of social cohesion and increased criminality during long duration interruptions. Where there are examples of increased criminality, this has been in the context of pre-existing societal issues. As such, increased criminality due to interruptions is not considered within this methodology.

This methodology uses the VoLL as a natural starting point for the costs of an outage. However, this omits certain types of harm that are specific to long-duration interruptions. As a result, this methodology identifies, quantifies and adds a selection of the most significant additional costs to the VoLL to generate a robust estimate of the cost of long-duration supply interruptions.

Specifically, this methodology estimates, in monetary terms, the cost to household customers of long-duration interruptions for the ten cost factors set out in the figure below.

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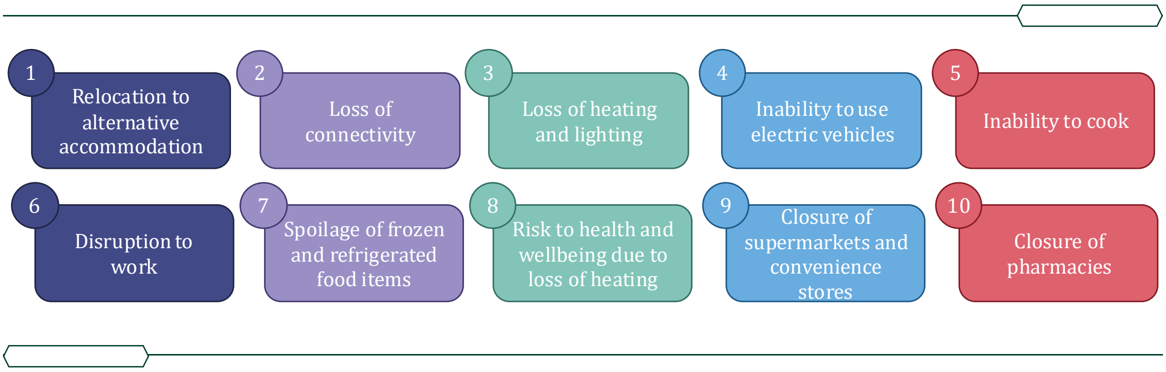
[8] *Page 98.*

Figure 24: Main additional categories of harm from long-duration interruptions



Source: Economic Insight analysis.

The methodology also accounts for the following factors:

- **Overlap with VoLL**: VoLL is considered to be a natural starting point for calculating the harm from outages, so this approach adds in additional elements that are not well captured by the VoLL.
- **Customer variation**: Costs differ across different customer groups depending on their characteristics, so this is captured within this methodology.
- **Outage scale and size**: Certain types of disruption will only occur during larger scale outages.
- **Second-order effects**: The methodology also incorporates indirect harms to households from the loss of access to local services during prolonged interruptions, such as supermarkets and pharmacies.

There is inherent uncertainty in any estimates of costs such as these, so costs provided within this methodology are intended to be indicative and of the correct order of magnitude to support investment decisions, rather than being a precise measure for each individual household.

To determine costs, a detailed bottom-up analysis has been conducted, first identifying the relevant costs, and then examining how these costs vary temporally, by household characteristics, and with respect to the geographic extent of the outage.

Building on this, the significance of each cost category has been assessed taking into account:

- the magnitude of the harm per household;
- the prevalence of the harm across the population; and
- the directness of the cost.

From this assessment a shortlist of the most significant costs to quantify has been identified to generate a robust estimate of the overall cost of long-duration supply interruptions, which fall into the following key categories.

- Loss of amenity

- Disruption
- Damage to goods
- Health risks
- Mitigation costs
- Loss of local services

In Table 14, the shortlist of the most significant costs is broken down by each of these categories. For each cost, the variability of these costs with the duration, geographical scope of the outage, and the characteristics of each household is described, alongside an assessment of the extent to which the costs can be assumed to be already captured within VoLL.

Table 14: Summary of most significant costs arising from long-duration outages

Cost category	**Costs**	**Description**	**Variation in costs**			**Are these costs likely to be captured in VoLL?**
			Temporal	***Geographic extent of the outage***	***Household characteristics***	
Loss of amenity	Loss of connectivity	Power outages cut access to the internet and prevent customers from charging their mobile phones, leaving people unable to access the internet or telecom services.	NA	NA	NA	Relevant for short-term interruptions. Severity increases with duration. *Partially included in VoLL.*
	Inability to use electric vehicles	Customers with electric vehicles will be unable to use them for travel due to the inability to charge them.	NA	The level of disruption depends on the extent of the area affected.	Only applicable for customers with electrical vehicles.	Not relevant for short-term interruptions. *Unlikely to be captured in VoLL.*
	Inability to cook	Households will be unable to prepare hot meals due to lack of electricity for kitchen appliances. They may have to find alternative food sources as a replacement.	NA	NA	Higher for vulnerable customers.	Relevance for short-term interruptions is low. *Unlikely to be captured in VoLL.*
Discomfort	Loss of lighting and heating	Power outages cause loss of heating and lighting which will cause discomfort to people.	Highest in winter.	NA	NA	Relevant for short-term interruptions. *Partially included in VoLL.*

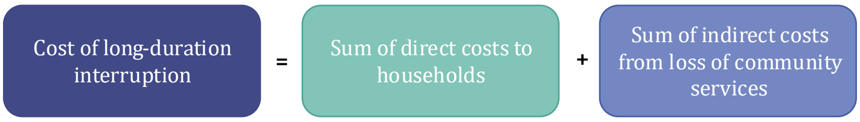
Cost category	**Costs**	**Description**	**Variation in costs**			**Are these costs likely to be captured in VoLL?**
			Temporal	***Geographic extent of the outage***	***Household characteristics***	
Disruption	Disruption to work	Power outages disrupt productivity for customers working from home.	Highest during working week.	NA	High for households with working professionals.	Relevant for short-term interruptions. Severity increases with duration. *Partially included in VoLL.*
Damage to goods	Spoilage of refrigerated or frozen food items	Perishable food items stored in refrigerators or freezers will get spoiled.	Highest in summer.	NA	NA	Relevance for short-term interruption is low. *Unlikely to be captured in VoLL.*
Health risks	Risk to health due to loss of heating	Loss of heating could lead to worsening of chronic illnesses or trigger new health problems.	Highest in winter.	NA	Higher for vulnerable customers.	Relevance for short-duration interruptions low. *Unlikely to be captured in VoLL.*
Mitigation costs	Relocation to alternative accommodation	Power outages may force people to relocate to alternative accommodation such as hotels, accruing additional costs and disruption.	NA	NA	NA	Not relevant for short-term interruptions. *Unlikely to be captured in VoLL.*

Cost category	Costs	Description	Variation in costs			Are these costs likely to be captured in VoLL?
			Temporal	*Geographic extent of the outage*	*Household characteristics*	
Loss of local services	Closure of supermarkets and convenience stores	Power outages can lead to the closure of supermarkets, limiting access to food and essential supplies.	NA	The level of disruption depends on the extent of the area affected.	NA	Not relevant for short-interruptions. *Unlikely to be captured in VoLL.*
	Closure of pharmacies	Customers will be unable to purchase medicines they take regularly or for emergency needs.	Highest in winter.	The level of disruption depends on the extent of the area affected.	Higher for vulnerable customers.	Not relevant for short-term interruptions. *Unlikely to be captured in VoLL.*

6.2. Overarching framework for quantification

The total harm from a long-duration supply interruption is the sum of the direct costs, borne by households when supply to their own property is lost, and the indirect costs, which arise when the outage affects community services or other locations that households depend on.

Figure 25: Overarching framework for quantification

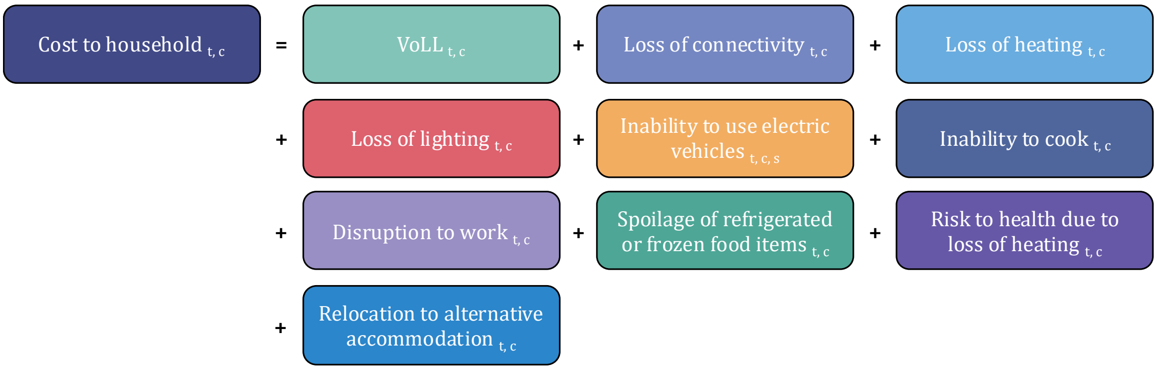


Source: Economic Insight analysis.

6.3. Direct costs to households

Conceptually, the approach to estimating the costs to households can be expressed as an equation, where the cost of a long-duration supply interruption to each household equals the VoLL plus each of the additional cost components identified; each evaluated for the outage in question. This equation is shown in Figure 26, below.

Figure 26: Overarching approach to estimating the direct costs to households



Source: Economic Insight analysis.

Each of these cost items will vary based on some combination of the following parameters:

- the duration of outage, denoted by subscript *t*;
- household characteristics, denoted by subscript *c*; and

- size of the outage, denoted by subscript *s*.

These direct costs are calculated at the household level, in line with the requirement that the methodology calculates the cost to customers at a service point level. The costs for each household affected by the outage can be summed to calculate the total direct costs to households.

As noted in Table 14, the harm associated with some cost categories varies by season. For example, the risk to health from the loss of heating will only be applicable in winter. Within the VoLL framework, this challenge was addressed by selecting a central estimate that reflects costs during a winter weekday at peak time. The same principle is adopted here, assuming peak harm rather than averaging over the year. This ensures that storm-resilience planning is grounded in the highest potential impacts, rather than being diluted by periods when the harm is lower.

The VoLL per household per day can be estimated in two ways:

(i) by applying the national average daily electricity consumption, or
(ii) by using the actual average consumption for a specific household, if data is available.

For the purposes of this report, the VoLL in 2025 prices has been calculated as £22,600 per MWh.[9] Using the average annual UK consumption of 2.7MWh[10] per household per year, this translates into a VoLL of £167 per household per day [17].

6.3.1. Loss of heating, lighting, and connectivity

6.3.1.1. Summary

The approach estimates the harm arising from the loss of heating, lighting, and connectivity jointly by using the cost of switching to alternative accommodation as a proxy. When customers seek out alternative accommodation, the issues that they are trying to address are the loss of heating and lighting, and connectivity. Therefore, this is a pragmatic way to estimate these difficult to isolate costs, as is detailed further below.

The daily cost of alternative accommodation is estimated to be **£111 per household,** calculated in Table 15. It is assumed that this accrues linearly over time given that customers will incur these costs from near to the start of the outage. This cost is applied to all households, regardless of whether they actually relocate because:

- If households relocate, they avoid the harm but bear the monetary cost of accommodation.
- If households remain at home, they experience the discomfort and disruption directly.

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[9] *We have inflated Ofgem's RIIO-1 VoLL estimate of £16,000 which is based on a July 2013 report to July 2025 prices using the CPIH index.*

[10] *'Average gas and electricity usage'. Ofgem.*

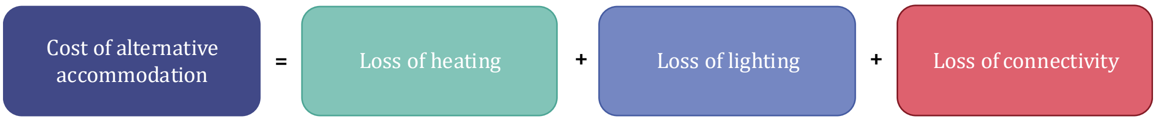
In both cases, the harm can reasonably be benchmarked using the market price of mitigation.

As outlined below, there is minimal overlap with the VoLL, and can therefore be added directly to the VoLL.

6.3.1.2. Approach

We estimate the cost of losing heating, lighting, and connectivity by drawing an equivalence between these harms and the cost of alternative accommodation. This is illustrated in Figure 27 below.

Figure 27: Overlap between cost of alternative accommodation and other harms.



Source: Economic Insight analysis.

This is a market-based proxy for these costs, grounded in the cost of mitigating this harm as well as revealed preference.

- Some households choose to seek alternative accommodation, demonstrating that the cost of a hotel intersects with some households' true but unobservable reservation values. This gives confidence that it can be used as a reasonable benchmark for the magnitude of these costs.

- Many households do not relocate during long-duration outages, but this decision is also influenced by uncertainty or affordability constraints rather than the absence of harm.

There are a number of factors that have implications for whether this proxy correctly measures the cost of losing heating, lighting, and connectivity:

- **Uncertainty**: Households may remain at home due to uncertainty over outage duration. With full information, more households might relocate, supporting the idea that hotel costs are a reasonable benchmark.

- **Affordability**: A household's decision not to relocate does not mean they avoid harm, only that the price of a hotel exceeds either their willingness or ability to pay. Even if a household cannot afford to seek alternative accommodation, their welfare loss remains real. Using market prices ensures these losses are recognised. In some instances, the DNO will pay for alternative accommodation but the methodology does not make a distinction between these instances and when customers bear the costs directly.

- **Additional amenities**: As hotels often provide additional amenities that go beyond heating, lighting, and connectivity, using hotel costs as a proxy has the potential to overstate the harm. To minimise this risk, the estimates are based on the cost of budget hotels. These offer a more limited service, reducing the likelihood that the estimate is inflated by unrelated amenities.

6.3.1.3. Key assumptions

In modelling the costs for this area, the following assumptions have been made:

- Households face two mutually exclusive options: relocate or remain at home without power. In both cases, the cost of lost services is reasonably approximated by the market price of alternative accommodation.
- The costs of moving to a budget hotel only reflects the costs of a loss of heating, lighting, and connectivity.

6.3.1.4. Overlap with VoLL

The approach is likely to result in a partial overlap between these costs and the VoLL, implying a risk of double counting due to the following considerations:

- **Connectivity**. For short outages, households can rely on mobile networks and device batteries. In long outages, these buffers erode. As a result, the loss of communication and connectivity becomes significantly more harmful in longer outages.
- **Heating**. Residual warmth cushions short outages, but harm increases significantly as outages lengthen.
- **Lighting**. On winter evenings, even short outages can cause disruption, though the impact can be partially mitigated by candles, torches, or simply delaying light-dependent tasks until power is restored. Over long outages, these coping strategies may be exhausted, and the persistent lack of lighting severely disrupts normal routines and heightens risks to safety and wellbeing.

Overall, while there is some overlap with the VoLL, primarily in relation to issues around lighting, this is limited. The harm in these areas from long-duration outages are significantly greater than those for short-duration outages, therefore no adjustment is made for overlap with the VoLL.

6.3.1.5. Calculations and proxies

To estimate the harm arising from a loss of heating, lighting, and connectivity the cost of a household relocating to a budget hotel is used a proxy. The calculations for the harm arising from this cost area are set out in Table 15 below.

Table 15: Calculation of cost of relocation to alternative accommodation

	Component	Value	Calculation steps
	Average daily rate for alternative accommodation	£93	A
divide	Average number of occupants per room	2	B

equals	Average daily rate for outside accommodation per person	£47	C = A ÷ B
multiply	Average size of household	2.38	D
equals	Average cost of outside accommodation per day per household	£111	C × D
	Cost of relocation to alternative accommodation per day per household	**£111**	

Source: Economic Insight analysis.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 16: Proxies used in the calculation of the cost of relocation to alternative accommodation

Component	Proxy	Source	Notes
Average daily rate for alternative accommodation	Average price paid by Premier Inn customers.	Best UK hotel chains for 2025 - Which?	Premier Inn is the biggest budget hotel chain in the UK and is a reasonable proxy for average price paid at budget hotels.
Average number of occupants per room		Group Bookings - Premier Inn	It is assumed that two adults can stay comfortably in a room. This aligns with Premier Inn's policy to not allow more than two adults to stay in a room.
Average size of household	Average size of a household in England	Households by household size - Office for National Statistics	Based on the 2024 estimate from the tab 'England' in the workbook.

Source: Economic Insight analysis.

6.3.2. Inability to use electric vehicles

6.3.2.1. Summary

The approach estimates the harm arising from an inability to use electric vehicles by using the cost of a rental vehicle as a proxy for the cost of mitigating this harm. It is estimated that the cost of a rental vehicle is **£35 per day**. This cost will only be incurred by households that have an EV charger installed.

It is assumed that harm does not occur immediately following an outage, as most customers will have some residual charge in their EVs. However, even with remaining charge, drivers are likely to experience range anxiety and restrict non-essential journeys.

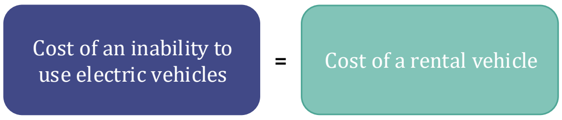
Additionally, customers are likely to need to travel further to acquire food or to access other services, depleting their battery more quickly than normal. As a result, these costs are considered to accrue from 24 hours into the outage.

As set out in Table 14, there is not considered to be any overlap with the VoLL as this cost will not be relevant for short outages.

6.3.2.2. Approach

The costs of losing the ability to use electric vehicles are estimated by using a market-based proxy grounded in the cost of mitigating this harm. This is illustrated in Figure 28 below.

Figure 28: Approach to estimating the cost of an inability to use electric vehicles



Source: Economic Insight analysis.

Although it is unlikely that most households would actually rent a replacement car during a long-duration outage, rental prices nonetheless provide a clear measure of what consumers are prepared to pay for access to mobility. The existence of a functioning rental market demonstrates that these prices intersect with at least some households' reservation values, meaning they are a reasonable benchmark for the harm from loss of access to mobility.

Rental prices vary significantly across vehicle types. However, much of this variation reflects the comfort, performance, or status of higher end vehicles rather than the basic value of mobility. To avoid overstating the harm, the estimate of the cost is based on of smaller economy vehicles.

6.3.2.3. Key assumptions

In modelling the costs for this area, the following assumptions have been made:

- It will be difficult for households to access alternative charging stations during outages, both because of reduced access to the internet and the likelihood of increased demand. The cost is therefore the loss of vehicle access rather than the additional effort of finding a charging point.

- Households will begin the outage with some residual charge. As a result, the harm only begins after 24 hours rather than immediately from the start of the outage.

6.3.2.4. Calculations and proxies

The calculations for the harm arising from an inability to use electric vehicles in Table 17, below.

Table 17: Calculation of the cost of an inability to use electric vehicles

	Component	Value	Calculation steps
	Average car rental prices per day	£35	
	Cost of inability to charge EV per day per household	**£35**	

Source: Economic Insight analysis.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 18: Proxies used in the calculation of cost of inability to use electric vehicles

Component	Proxy	Source	Notes
Average car rental prices per day	Average daily price of rental for an economy car.	Cheap Car Rent UK: Key Insights and Rental Trends	Economy car rental prices included in this source as a conservative estimate. Economy cars price range: £20 to £50 per day., so the midpoint of this range (i.e. £35) has been used.

Source: Economic Insight analysis.

6.3.3. Inability to cook

6.3.3.1. Summary

The approach estimates the harm arising from an inability to cook by calculating the cost of replacement meals to account for the difficulties cooking during a long-duration power outage. The additional time taken to acquire food is also accounted for, as it is assumed that ordering food will not be possible during an outage.

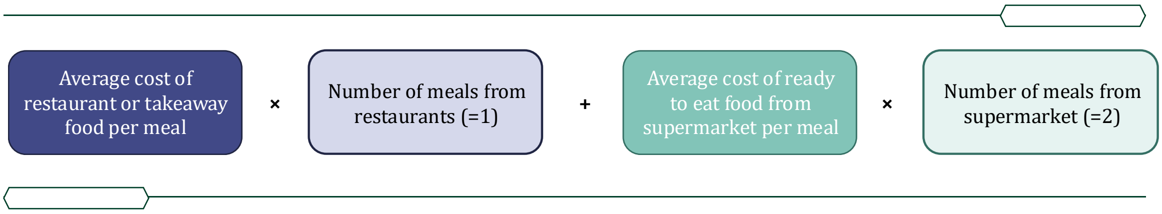
It is estimated that the cost of an inability to cook to be **£75 per day for non-vulnerable households**. It is assumed that customers that are considered to be highly vulnerable will incur greater costs as they will find it more difficult to travel and acquire food in the event of an outage. For this reason, a **1.5x scaling factor** is applied to the harm, implying a cost of **£113 per day for households with highly vulnerable customers**.

As set out in Table 14, there is no overlap with the VoLL as this cost will not be relevant for short outages.

6.3.3.2. Approach

Customers may rely on takeaway food or ready to eat meals from supermarkets if they are unable to prepare food at home. It is assumed that customers rely on supermarkets for 2 meals a day and rely on restaurant or takeaway food for one of their meals. While this may not be true for any specific customer, it is a reasonable behavioural assumption for an average customer.

Figure 29: Overarching approach to estimate harm from an inability to cook



Source: Economic Insight analysis.

Vulnerable customers will incur higher costs in this area. Not only will it be more difficult for them to seek out alternative food options, but they will also experience significantly more anxiety around food insecurity than non-vulnerable customers. For this reason, a 1.5x scaling factor is applied to this harm for customers who are categorised as 'highly vulnerable'.

6.3.3.3. Key assumptions

In modelling the costs for this area, the following assumptions have been made:

- The average person will rely on the equivalent of supermarket food for two meals a day and one takeaway or restaurant meal.
- Households with vulnerable customers suffer 1.5x as much harm from an inability to cook as households without vulnerable customers.

6.3.3.4. Calculations and proxies

The calculations for the harm arising from an inability to cook as laid out in Table 19, below.

Table 19: Calculation of the cost of an inability to cook

	Component	Value	Calculation steps
	Average cost of a restaurant meal	£14	
multiply	Number of meals from a restaurant	1	
equals	Average spending on restaurant meals	£14	A
	Average cost of supermarket meal deal	£4	
multiply	Number of meals from a supermarket	2	
equals	Average spending on supermarket meals	£8	B
	Average travel time to source food (mins)	16.5 × 2 = 33	C

	Component	Value	Calculation steps
multiply	Value of non-working time (£/min), in 2025 prices	£0.26 * 1.07 = £0.28	D
equals	Average cost of time spent travelling to source food	£9	E = C × D
	Average cost of an inability to cook per person per day	£32	F = A + B + E
multiply	Average size of household	2.38	
equals	**Average cost of an inability to cook per household per day**	**£75**	
multiply	Scaling factor for vulnerable households	1.5	
equals	**Average cost of an inability to cook per vulnerable household per day**	**£113**	

Source: Economic Insight analysis.

Note: The value of non-working time is published in 2023 prices. To be consistent with the price base of other values used in the calculations, the value of non-working time has been inflated to 2025 prices. The CPIH index for 2025 is, as of yet, only available for the first 8 months of the year. Therefore, an average of available data, i.e., CPIH index for January 2025 to August 2025 (inclusive) has been used to calculate the price base conversion factor.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 20: Proxies used in the calculation of the harm caused by an inability to cook

Component	Proxy	Source	Notes
Average cost of restaurant meal	Average price of pub hot meal and restaurant main course, as of 2025.	Shopping prices comparison tool - Office for National Statistics	Based on the average price of the following items for the year 2025 (Jan 2025 – Aug 2025 inclusive): Pub hot meal ID: 220107 Restaurant main course ID: 220128
Average cost of supermarket meal	Average price of meal deals across different supermarket chains in the UK, as of 2025.	Best value meal deal revealed as Asda launches £3.74 offer | The Independent	The average of the 2025 meal deal prices of supermarket outlets (without any membership).
Value of non-working time (£/min)	Based on the value of non-working time (£/hour) (i.e. £15.46).	TAG data book - GOV.UK	The market price value of non-working time for commuting, provided in tab ‘A1.3.1’.

Component	Proxy	Source	Notes
	Converted to value of non-working time (£/min) (i.e. £0.26). Note these values are in 2023 prices and are converted to 2025 prices as shown above in the above calculations.		
Average travel time to source food	Average travel time to reach town centre (in minutes).	Journey time statistics: data tables (JTS) - GOV.UK	Journey times to key services (JTS0102) which provides average minimum travel times to reach key services by mode of travel, from rural and urban areas in England. The 2019 data on the duration to reach a town centre by *car* under *all rural* has been used, as typically, they are more likely to be affected by long-duration outages.
CPIH Index	CPIH Index	Inflation and price indices - Office for National Statistics	Used to calculate the price conversion factor (1.07) to convert prices from 2023 prices to 2025 prices.
Average household size	Average size of a household in England.	Households by household size - Office for National Statistics	2024 estimate from the tab 'England' in the workbook.
Scaling factor for vulnerable individuals	Scaling factor (multiple)	Assumption	.

Source: Economic Insight analysis.

6.3.4. Disruption to work

6.3.4.1. Summary

The approach estimates the harm that customers incur as a result of disruption to their normal working habits. We have identified three main categories of harm in this area:

i. additional commuting costs;
ii. the loss of flexibility; and
iii. loss of productivity.

Each of these types of harm are applicable only to those who normally work from home. The estimates for these costs are set out in Table 21 below.

Table 21: Summary of costs of disruption to work

Component	Cost (per household per working day)
Additional commuting costs	£12
Loss of flexibility from working from home	£7
Loss of productivity	£6
Total	£25

Source: Economic Insight analysis.

As each household's individual working patterns cannot be observed, an average effect based on population-level parameters is applied. These costs are specified on a 'per working day' basis and only apply on weekdays.

As outlined below, we consider there to be minimal overlap with the VoLL.

6.3.4.2. Approach

Three main categories of harm that customers incur because of disruption to their normal working patterns due to long-duration supply interruptions have been identified. These are set out in Figure 30 below.

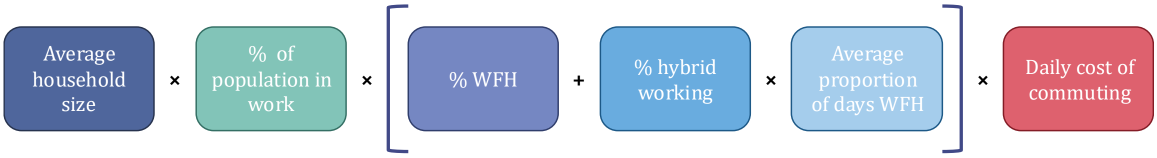
Figure 30: Overarching approach to estimate harm from disruption to work

Source: Economic Insight analysis.

1. Additional commuting costs

The additional commuting costs are calculated based on the proportion of the population that would otherwise have worked from home. It is assumed that affected individuals will need to relocate either to an office or another location with power and connectivity. The daily cost of commuting is valued based on the additional time spent commuting. The approach to this element of the harm is set out in Figure 31 below.

Figure 31: Additional commuting costs

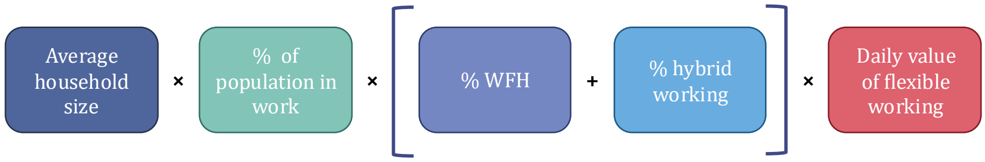


Source: Economic Insight analysis.

2. Loss of flexibility from working from home

The loss of flexibility associated with home working is calculated recognising that individuals value the freedom and convenience it offers. The cost of losing this flexibility is estimated using survey evidence on the value that workers assign to flexible working. This harm is applied to both hybrid workers and those who work exclusively from home. The approach to this element of the harm is set out in Figure 32 below.

Figure 32: Loss of flexibility of working from home

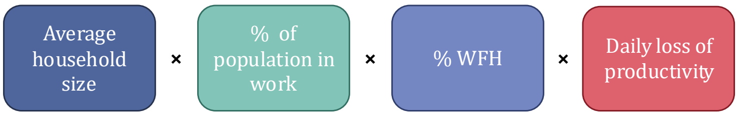


Source: Economic Insight analysis.

3. Loss of productivity

It is assumed that individuals who normally work from home will face reduced productivity when relocating to less suitable workspaces. This loss is valued on the basis that individuals will compensate for reduced productivity by working longer hours, using average weekly earnings to quantify the impact. The approach to this element of the harm is set out in Figure 33 below.

Figure 33: Loss of productivity



Source: Economic Insight analysis.

6.3.4.3. Key assumptions

In modelling the costs of disruption to work, the following assumptions have been made:

- That the only people that have to change their working behaviour during an outage are those who would otherwise work from home. Individuals who work in-person are unaffected. This is because places of work are usually unaffected by long-duration outages, as these outages are most likely to occur in remote or rural areas. In addition, those who work in-person will continue to receive pay even if their workplace cannot open.

- Individuals who usually work from home will face disruption and reduced productivity if they must change their place of work. By contrast, hybrid workers are assumed not to face a productivity impact, as they already spend part of their week working from an office.

- As these costs have been modelled in relation to the disruption to home workers, these costs are only incurred during the working week.

6.3.4.4. Overlap with VoLL

For short-duration outages, work disruption tends to be temporary. Tasks can often be delayed or rescheduled until power returns, and for desk-based roles, battery-powered devices and mobile networks may provide a buffer. In these cases, productivity losses are limited.

By contrast, in long-duration outages batteries deplete, and connectivity is more likely to fail. Those working from home are therefore more significantly affected, requiring adaptations such as relocation. These impacts are substantively different from the temporary adjustments seen in short outages. As such, the overlap between the work disruption effects of long-duration outages and the VoLL framework are minimal.

6.3.4.5. Calculations and proxies

The calculations for the harm arising from additional commuting costs are set out in Table 22, below.

Table 22: Calculation of additional commuting costs

	Component	Value	Calculation steps
	Average size of household	2.38	
multiply	% of population in employment in the UK	61%	
equals	Average number of working individuals per household	1.45	A
	% of population homeworking only	16%	B
plus	% of population hybrid working × Average proportion of days working from home in a week	28% × 40% = 11%	C
equals	% of population working from home	27%	D = B + C
	Average commuting time per day (minutes)	29 × 2 = 58	

	Component	Value	Calculation steps
multiply	Value of working time (£/mins)	£0.50 × 1.07 = £0.53	
equals	Daily cost of commuting	£31	E
	Additional cost of commuting per day per household	**£12**	A × D × E

Source: Economic Insight analysis.

Note: The value of working time is published in 2023 prices. To be consistent with the price base of other values used in the calculations, the value of working time has been inflated to 2025 prices. The CPIH index for 2025 is, as of yet, only available for the first 8 months of the year. Therefore, an average of available data, i.e., CPIH index for January 2025 to August 2025 (inclusive) has been used to calculate the price base conversion factor.

The calculations for the loss of flexibility of working from home are set out in Table 23, below.

Table 23: Calculation of cost of loss of flexibility of working from home

	Component	Value	Calculation steps
	Average number of working individuals per household	1.45	A
	% of population homeworking only	16%	
plus	% of population hybrid working	28%	
equals	Overall % of population working from home	44%	B
	Average daily earnings	£135	
multiply	Implicit pay rise from flexibility to work from home	8%	
equals	Value of flexibility to work from home per day	£11	C
	Cost of loss of flexibility to work from home per day per household	**£7**	A × B × C

Source: Economic Insight analysis.

The calculations for the loss of flexibility of working from home are set out in Table 24, below.

Table 24: Calculation of cost of loss of productivity

	Component	Value	Calculation steps
	Average number of working people per household	1.45	
multiply	% of population homeworking only	16%	
equals	Average number of individuals fully working from home per household	0.23	A

	Component	Value	Calculation steps
	Average daily earnings	135	
multiply	% reduction in productivity due to relocation	20%	
equals	Value of additional work due to loss of productivity	£27	B
	Cost of loss of productivity per day per household	**£6**	A × B

Source: Economic Insight analysis.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 25: Proxies used in the calculation of cost of disruption to work

Component	Proxy	Source	Notes
Average commuting time per day	Average commute time to work in Great Britain as of 2023 (based on all modes of transport).	Transport Statistics Great Britain: 2023 Domestic Travel - GOV.UK	The average commute to work in Great Britain in 2023 figure under 'Why people travel: Travelling to work"
Value of working time (£/hour)	Based on the value of working (employers' business) time (£/hour) i.e., £29.92. Converted to value of working time (£/min) i.e., £0.50. Note the values are in 2023 prices. These are converted to 2025 prices as shown above in the calculations.	TAG data book - GOV.UK	The market price value of working time for 'Average of all working persons' in tab 'A1.3.1'.
Average household size	Average size of a household in England	Households by household size - Office for National Statistics	2024 estimate from the tab 'England' in the workbook.
% of population in employment in the UK	Average employment rate of all aged 16 and above for the year 2025.	Employment, unemployment and economic inactivity - Office for National Statistics	UK employment rate (seasonally adjusted) for people aged 16 and above, taken as an average of the 3-month employment rate

Component	Proxy	Source	Notes
			(%) for the period Jan 2025 to Jul 2025 from the tab 'People' in the mentioned workbook.
% of population homeworking only	% of all individuals homeworking only	Characteristics of homeworkers, Great Britain - Office for National Statistics	Estimates for the % homeworking only (All persons %) in tab '1' calculated over the period Sep 2022-Jan 2023.
% of population hybrid working	% of all individuals hybrid working	Characteristics of homeworkers, Great Britain - Office for National Statistics	Estimates for the % hybrid working (All persons %) in tab '1' calculated over the period Sep 2022-Jan 2023.
Average proportion of days working from home	Based on the number of days the majority of hybrid workers spend in office	State of Hybrid Work 2024 | UK Report	Assumed to be 40% based on the finding that the majority of hybrid workers prefer going to the office three times a week.
Average weekly earnings	Average weekly earnings of whole economy – regular pay for 2025	AWE: Whole Economy Level (£): Seasonally Adjusted Total Pay Excluding Arrears - Office for National Statistics	Seasonally adjusted average weekly earnings. The average weekly earnings for the year 2025 are calculated using data from the period January to July 2025, inclusive.
Implicit value of flexibility to work from home	Average value people attribute to the ability to work from home two or three days a week	Remote working is probably here to stay, and these are the reasons why | Institute for Fiscal Studies	Hybrid workers value the flexibility to work from home equivalent to an 8% pay rise. This is based on data from the Survey of Working Arrangements and Attitudes and can also be found in [18].
% reduction in productivity due to relocation	% reduction in productivity due to relocation	Assumption	Assumed to be 20% reduction in average daily earnings.

Source: Economic Insight analysis.

6.3.5. Spoilage of refrigerated and frozen food items

6.3.5.1. Summary

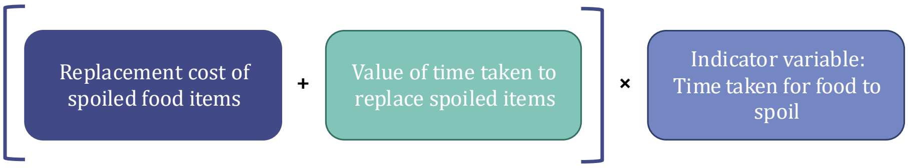
The cost of spoiled refrigerated or frozen food items is assumed to be **£86 per household**. Based on information from the Food Standards Agency, it is assumed that it takes 24 hours for food in a fridge/freezer to spoil, so this harm is incurred discretely for outages longer than 24 hours in duration.

As set out in Table 14, there is no overlap with the VoLL as this cost will not be relevant for short outages.

6.3.5.2. Approach

The approach to estimating the costs of spoiled refrigerated or frozen food items is based on the replacement cost of these items, as well as the time and effort expended in replacing them. These costs will be incurred only once, and only if the duration of the outage exceeds the average time it takes for frozen/refrigerated food to spoil.

Figure 34: Overarching approach to estimate harm from the spoilage of frozen and refrigerated food items.



Source: Economic Insight analysis.

6.3.5.3. Key assumptions

It is assumed that the average time taken for frozen and refrigerated food to spoil is 24 hours. This is based on information from the Food Standards Agency, which states that a fridge only remains cold for 4 hours in the event of an outage, and that a half full freezer remains frozen for 24 hours [19].

6.3.5.4. Calculations and proxies

The calculations for the spoilage of refrigerated and frozen food in Table 26, below.

Table 26: Calculation of cost of the spoilage of refrigerated and frozen food items

	Component	Value	Calculation steps
	Average time taken for food in a freezer to spoil (in hours)	24	
	Indicator variable: Has frozen food likely spoiled?	*Let d denote the duration of power outage.* $\begin{cases} 1, & if\ d \geq 24\ hours \\ 0, & otherwise \end{cases}$	A

	Component	Value	Calculation steps
	Average value of food items stored in fridge or freezer	£71	B
	Average time to travel to a food store (in minutes)	9×2 = 18	
plus	Average time spent in a food store (in minutes)	37	
equals	Average total time taken to visit a food store (in minutes)	55	
multiply	Average value of non-working time (£/min)	£0.26 × 1.07 = £0.28	
equals	Average value of time taken to replace spoiled food items	£15	C
	Average cost of the spoilage of frozen and refrigerated items	**£86**	A × (B + C)

Source: Economic Insight analysis.

Note: The value of non-working time is published in 2023 prices. To be consistent with the price base of other values used in the calculations, the value of non-working time has been inflated to 2025 prices. The CPIH index for 2025 is, as of yet, only available for the first 8 months of the year. Therefore, an average of available data, i.e., CPIH index for January 2025 to August 2025 (inclusive) has been used to calculate the price base conversion factor.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 27: Proxies used in the calculation of the average cost of spoilage of refrigerated and frozen food items

Component	Proxy	Source	Notes
Average value of food items stored in fridge or freezer	Average weekly expenditure of all households on food and non-alcoholic drinks	Family spending workbook 1: detailed expenditure and trends - Office for National Statistics	2024 edition of this dataset. The headline figure £70.50 tab 'A1' has been used.
Average time to travel to food store (in minutes)	Average minimum travel time to reach the nearest food store in rural areas (in minutes)	Journey time statistics: data tables (JTS) - GOV.UK	Journey times to key services (JTS0102) which provides average minimum travel times to reach key services by mode of travel, from rural and urban areas in England. The 2019 data on the duration to reach a town centre by *car* under *all*

Component	Proxy	Source	Notes
			rural has been used, as typically, they are more likely to be affected by long-duration outages
Average time spent in supermarkets	Average time spent in supermarkets	Brits will spend eight-and-a-half months of their lives in supermarkets | Wales Online	Assumed to be 37 minutes as mentioned in the article.
Average value of non-working time (£/min)	Based on the value of non-working time (£/hour) i.e., £15.46. We convert this to value of non-working time (£/min) i.e., £0.26. Note the values are in 2023 prices. We convert them to 2025 prices as shown above in the calculations.	TAG data book - GOV.UK	The market price value of non-working time for commuting in the tab 'A1.3.1'.
CPIH Index	CPIH Index	Inflation and price indices - Office for National Statistics	Price conversion factor (1.07) to convert prices from 2023 prices to 2025 prices.
Average time taken for food in freezer to spoil	Average time taken for food in freezer to spoil.	Food safety in a power cut - advice for consumers | Food Standards Agency	As stated in the source article, a fridge can stay cold for up to 4 hours when there is a power outage. It takes 48 hours for the frozen food to spoil if the freezer is full and 24 hours if the freezer is half-full. For simplicity, 24 hours is used as the threshold for the time it takes for both fridge and

Component	Proxy	Source	Notes
			freezer contents to spoil.

Source: Economic Insight analysis.

6.3.6. Risk to health

6.3.6.1. Summary

The approach estimates the cost of the risk to health to customers during a power outage by leveraging a study estimating the societal level harm and re-scaling the results to be able to apportion them to households experiencing a power outage. It is estimated that the health-related costs of cold homes for a highly vulnerable household are **£5 per day**.

As set out in Table 14, there is no overlap with the VoLL as this cost will not be relevant for short outages.

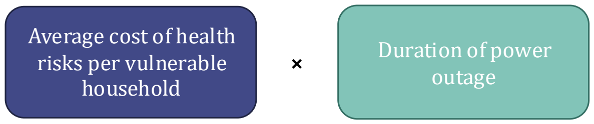
6.3.6.2. Approach

The approach to estimating the risk to health and wellbeing is based on determining the cost of increased risk to health issues during an outage based on a study which calculates the costs faced by the NHS due to lack of heating in homes. These societal-level costs are adjusted to calculate a cost per affected vulnerable household per unit time. These costs will only be applicable during winter months when heating is essential for households.

While all customers will incur the costs of discomfort relating to a loss of heating, the health risks will predominantly be borne by vulnerable customers with pre-existing medical conditions. Therefore, these societal costs are attributed to vulnerable customers only by dividing the societal costs by an estimate of the number of households living in excessively cold homes.

The high-level approach is illustrated in the figure below.

Figure 35: Overarching approach to estimate the cost of the risk to health due to lack of heating



Source: Economic Insight analysis.

6.3.6.3. Key assumptions

In modelling the cost of risk to health, the following assumptions have been made:

- The health costs of a chronically cold home are equivalent to the health costs relating to a loss of heating during a long-duration power outage. The health effects of a chronically cold house are likely to be greater than a long-duration outage due to the extended period of time that the individuals are exposed to the cold.

However, the cold experienced during a long duration outage may be more severe, as chronically cold homes may have some heating. Overall, it is considered that these two scenarios are sufficiently comparable for this analysis.

- The NHS costs relating to cold homes are an appropriate proxy for the harm that customers experience. While these capture the costs to the health system rather than individuals, they are driven by the same underlying health impacts that customers experience directly. The scale of NHS spending reflects the severity and prevalence of illness, making it a reasonable and evidence-based indicator of harm. While this approach does not capture all aspects of individual welfare loss, it provides a conservative estimate based on these tangible costs.

- Vulnerable customers will disproportionately bear the health impacts of long-duration outages due to pre-existing issues. As a result, it is assumed that the health effects are only incurred by customers that are categorised as 'highly vulnerable'.

- The changes to NHS treatment costs over time are due to inflation, and not to a change in underlying factors. Therefore, it is only necessary to make inflation adjustments to ensure consistency with the current price base.

6.3.6.4. Calculations and proxies

The calculations for the cost of the risk to health are laid out below in Table 28.

Table 28: Calculation of the cost of the risk to health

	Component	Value	Calculation steps
	Cost of cold homes per annum (in millions)	£544	A
	Number of households living in excessively cold homes (in millions)	0.72	B
	Cost of cold homes per home per annum (in 2019 prices)	£756	C = A ÷ B
	Price basis conversion factor	1.27	D
	Cost of cold homes per annum per home (in 2025 prices)	£962	E = C × D
divide	Days per year of cold weather (October to March, inclusive)	182	
equals	**Cost of cold homes per day per vulnerable household**	**£5**	

Source: Economic Insight analysis.

Note: Price basis conversion factor = 2025 CPIH / 2019 CPIH. The CPIH index for 2025 is, as of yet, only available for the first 8 months of the year. Therefore, an average of the available data, i.e., CPIH index for January 2025 to August 2025 (inclusive) has been used to calculate the price base conversion factor.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 29: Proxies used in the calculation of cost of risk to health

Component	Proxy	Source	Notes
Cost of cold homes per annum (in millions)	NHS costs of cold homes per annum (in millions)	BRE_cost of poor housing tenure analysis 2023.pdf	Total savings to the NHS from mitigating the 'excess cold' hazard in owner-occupied, private rented, and social rented homes. Relevant page numbers: 11, 15, and 18.
Number of excessively cold homes (in millions)	Number of excessively cold homes (in millions)	BRE_cost of poor housing tenure analysis 2023.pdf	Total number of owner occupied, private rented, and social rented homes facing the 'excess cold' hazard. Relevant page numbers: 11, 15, and 18.
Price basis conversion factor	CPIH index for the years 2019 and 2025	Inflation and price indices - Office for National Statistics	The conversion factor calculated to be 1.27 using CPIH index for the years 2019 and 2025.
Average household size	Average size of England household	Households by household size - Office for National Statistics	2024 estimate from the tab 'England' in the workbook.

Source: Economic Insight analysis.

6.4. Costs from the loss of community services

The main community services that would lead to customer harm if they were closed during an outage are supermarkets and pharmacies. Purchases from other retail outlets could likely reasonably be deferred until the outage was resolved at a minimal loss of utility.

The costs from the loss of community services are estimated at the service point level, with each service point representing the community service in question. In other words, the estimates capture the aggregate impact of losing each specific community service location.

6.4.1. Closure of supermarkets

6.4.1.1. Summary

The estimate for the cost of the closure of supermarkets during a power outage are based on the additional time it takes customers to find the next nearest open supermarket. The costs are scaled up based on the average number of households served by each supermarket. It is estimated the average cost of the closure of a supermarket to be **£3,248 per day.**

The incurrence of these costs will depend on the size of the outage. For example, small scale outages are unlikely to significantly impede finding an open supermarket. Therefore, these costs are only applied to large power outages (i.e. when more than 5,000 households are affected at once).

As set out in Table 14, there is no overlap with the VoLL as this cost will not be relevant for short outages.

6.4.1.2. Approach

The costs relating to the closure of supermarkets due to an outage is equal to the value of the additional time spent to reach an alternative supermarket that is not affected by said outage. The approach assumes that the customers will travel to an alternative location if their preferred supermarket is closed due to a power outage, and that it is unlikely that all the other supermarkets in the area will also be affected by the outage. It is assumed that it takes twice the average minimum travel time to the nearest supermarket to reach an alternative supermarket.

These additional travel costs are applied to the average number of households served by a supermarket. The number of people affected by the closure of a supermarket using ONS data on supermarkets per 10,000 people in the UK. This is then multiplied by the frequency of supermarket visits to account for the fact that customers do not shop every day based on the average number of supermarket visits per week. It is also assumed that households will shop collectively.

6.4.1.3. Key assumptions

The approach to estimating the costs of the closure of supermarkets is based on the following assumptions:

- Long-duration outages will be relatively localised, meaning households should be able to access an alternative supermarket within a reasonable time frame.
- The travel time taken to go to the next nearest open supermarket is twice the average minimum travel time to reach the nearest supermarket.

6.4.1.4. Calculations and proxies

We set out our calculations for the cost of closure of a supermarket below in Table 30.

Table 30: Calculations of the cost of closure of supermarkets

	Component	Value	Calculation steps
	Additional travel time to nearest open supermarket (in minutes)	9×2 = 18	
multiply	Value of non-working time (£/min)	£0.26 × 1.07 = £0.28	
equals	Cost of additional travel to next nearest supermarket	£5	A

Component		Value	Calculation steps
	Average number of people dependent on a particular supermarket	3704	
divide	Average size of household	2.38	
equals	Number of households affected by the closure of 1 supermarket	1556	B
	Frequency of supermarkets visits	3	C
	Cost of closure of a supermarket to the households served per week	**£22,737**	D = A × B × C
	Average cost of closure of a supermarket to the households served per day	**£3,248**	D/7

Source: Economic Insight analysis.

Note: The value of non-working time is published in 2023 prices. To be consistent with the price base of other values used in the calculations, the value of non-working time has been converted to 2025 prices. The CPIH index for 2025 is, as of yet, only available for the first 8 months of the year. Therefore, an average of available data, i.e., CPIH index for January 2025 to August 2025 (inclusive)has been taken to calculate the price base conversion factor.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 31: Proxies used in calculations of the cost of closure of supermarkets

Component	Proxy	Source	Notes
Additional travel time to nearest open supermarket (in minutes)	Average minimum travel time to reach the nearest supermarket (in minutes)	Journey time statistics: data tables (JTS) - GOV.UK	Journey times to key services (JTS0102) which provides average minimum travel times to reach key services by mode of travel, from rural and urban areas in England. The 2019 data on the duration to reach a town centre by *car* under *all rural* has been used, as typically, they

Component	Proxy	Source	Notes
			are more likely to be affected by long-duration outages It is assumed that the next nearest supermarket will take double the travel time of the nearest supermarket to reach.
Value of non-working time (£/min)	Based on the value of non-working time (£/hour) i.e., £15.46. Converted to value of non-working time (£/min) i.e., £0.26. Note these values are in 2023 prices and converted to 2025 prices.	TAG data book - GOV.UK	The market price value of non-working time for commuting in the tab 'A1.3.1'.
CPIH Index		Inflation and price indices - Office for National Statistics	The price conversion factor (1.07) has been used to convert prices from 2023 prices to 2025 prices.
Average number of people dependent on a particular supermarket	Calculated using supermarkets per 10,000 people.	Supermarkets - ONS	The number of supermarkets per 10,000 people in the UK, as of 2023. The number of people dependent on a supermarket equals 10,000 ÷ 2.7.
Frequency of supermarkets visits	Average supermarket visits per week	Brits will spend eight-and-a-half months of their lives in supermarkets | Wales Online	Assumed to be three times a week, as mentioned in the article.
Average household size	Average size of a household in England	Households by household size - Office for National Statistics	2024 estimate from the tab 'England' in the workbook.

Source: Economic Insight analysis.

6.4.2. Closure of pharmacies

6.4.2.1. Summary

The approach estimates the cost of the closure of pharmacies by calculating the cost of additional time to find an alternative pharmacy due to the closure of the regular pharmacy. These costs are scaled up based on the average number of households served by a pharmacy. The cost of the closure of a pharmacy is estimated to be **£393 per day**.

Similar to the estimation of the cost of closure of supermarkets, the cost of the closure of pharmacies will be significant only for large outages. Therefore, these costs only apply when more than 5,000 households are affected at once.

As set out in Table 14, there is no overlap with the VoLL as this cost will not be relevant for short outages.

6.4.2.2. Approach

The cost of closure of pharmacies is estimated by calculating the value of the additional time spent travelling to an alternative pharmacy. It is assumed that the additional travel time to find an alternative open pharmacy is equivalent to the average time taken to travel to the town centre.

ONS data on the number of prescribing dispensaries per 100,000 people is used to calculate the average number of people served by a pharmacy. Unlike supermarkets, visits to a pharmacy will be limited during a power outage, as where these visits can be deferred, they likely will be. Only people who urgently require medication will seek out a pharmacy in an outage.

The proportion of customers who may need access to pharmacy services during a power outage is based on based on the 'Public perceptions of community pharmacy' report. As per the report, as of 2023, 8% of respondents visit a pharmacy "*at least few times a month*".[11] It is assumed that only this group of people are likely to require medication and will therefore seek out an alternative pharmacy.

The number of affected people is further adjusted using the probability of a customer visiting a pharmacy on any particular day in a month, to account for the fact that not all customers who use a pharmacy "*at least few times a month*" visit a pharmacy daily. The travel costs apply to this adjusted number of affected individuals to calculate the cost of the closure of a pharmacy.

6.4.2.3. Key assumptions

The approach to estimating the cost of closure of a pharmacy is based on the following assumptions.

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[11] '*Public perceptions of community pharmacy 2023*'. Ipsos.

- Long-duration outages will be relatively localised, meaning households should be able to access an alternative pharmacy within a reasonable time frame.
- Only a small proportion of customers will sufficiently require emergency medication during a power outage that they will seek this out.

6.4.2.4. Calculation and Proxies

The calculations for the cost of closure of a pharmacy below in Table 32.

Table 32: Calculation of the cost of closure of pharmacies

	Component	Value	Calculation steps
	Additional travel time to town centre to find a pharmacy	16.5 × 2 = 33	A
multiply	Value of non-working time, (£/min)	£0.26 × 1.07 = £0.28	B
equals	Cost of additional travel time to pharmacies per visit	£9	C = A × B
	Average number of people per pharmacy	5,442	
multiply	% of population that visits pharmacy ‘at least few times a month’	8%	
multiply	Probability that a customer visits a pharmacy on any particular day in a month	10%	
equals	Number of people affected by closure of pharmacy per day	44	D
	Cost of closure of a pharmacy to the households served per day	**£393**	C × D

Source: Economic Insight analysis.

Note: The probability a customer visits a pharmacy on any particular day in a month is assumed to be to be 3/30. From an Ipsos 2023 report on ‘Public Perceptions of Community Pharmacy’, as of 2023, 8% of respondents in England visit a pharmacy ‘at least few times a month’. The number of days a customer (belonging to the 8%) visits a pharmacy in a month is assumed to be 3 times, assumed to be uniformly distributed throughout a month to determine the probability of a customer going to a pharmacy on any particular day in a month.

The sources of the components used in the above calculations are set out in more detail in the table below.

Table 33: Proxies used in the calculation the of cost of closure of pharmacies

Component	Proxy	Source	Notes
Additional travel time to town	Average minimum travel time to reach	Journey time statistics: data	Metrics from journey times to key

Component	Proxy	Source	Notes
centre to find a pharmacy (in minutes)	the town centre (in minutes)	tables (JTS) - GOV.UK	services (JTS0102) which provides average minimum travel times to reach key services by mode of travel, from rural and urban areas in England. 2019 data on the duration to reach a town centre by *car* under *all rural* has been used. It is assumed that the additional travel time to find an alternative pharmacy is equal to the time taken to travel to a town centre.
Value of non-working time (£/min)	Based on the value of non-working time (£/hour) i.e., £15.46. We convert this to value of non-working time (£/min) i.e., £0.26. Note the values are in 2023 prices. We convert them to 2025 prices as shown above in the calculations.	TAG data book - GOV.UK	The market price for the value of non-working time for commuting in the tab 'A1.3.1'.
CPIH Index		Inflation and price indices - Office for National Statistics	The price conversion factor (1.07) has been used to convert prices from 2023 prices to 2025 prices.
Average number of people per pharmacy	Number of community pharmacies in England and Wales	Number of prescribing pharmacies in local	The data in tab 'Table 1' to calculate average number of

Component	Proxy	Source	Notes
	divided by population	areas, England and Wales - ONS	people per pharmacy.[12]
% of population that visits pharmacy 'at least a few times a month'	% of respondent living in England that visits pharmacy 'at least a few times a month', as of 2023	Public Perceptions of Community Pharmacy 2023 Report - Ipsos UK KnowledgePanel	This data is obtained from Figure 3.1 on page 11, which shows the frequency of pharmacy use.
Probability that customer visits a pharmacy on a particular day		Assumption	The number of affected people has been adjusted using this probability to account for the fact that not all customers go to the pharmacy at once during a power outage. The rationale for this assumption is explained beneath Table 32.

Source: Economic Insight analysis.

6.5. Overall Cost

The estimates for each additional cost area relating to households is summarised in Table 34, below.

Table 34: Summary of additional costs of long-duration supply interruptions

Cost area	Nomenclature	Cost (£ per day)	Cost type	Factors driving cost variation
Value of Lost Load	*V*	£167	Continuous	NA
Loss of heating, lighting, and connectivity	*a*	£111	Continuous	NA

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[12] *This is based in the population in each LAD calculated in the following way: Population = (Number of dispensaries ÷ Dispensaries per 100,000 people) × 100,000. The number of people per dispensary is given by dividing the sum of the population by the sum of the number of dispensaries across all of England. This yields a figure of 5,442 people per dispensary.*

Cost area	Nomenclature	Cost (£ per day)	Cost type	Factors driving cost variation
Inability to use electric vehicles	*e*	£35	Continuous	Only applicable to owners of electric vehicles Only applicable during large outages (>5000 households). Is only incurred for outages longer than 24 hours.
Inability to cook	*c*	£75	Continuous	1.5x scaling factor for vulnerable customers.
Disruption to work	*w*	£25	Continuous	Only applicable on weekdays.
Spoilage of frozen and refrigerated food	*f*	£86	Discrete – One off	Incurred once for outages longer than 24hrs.
Risk to health due to loss of heating.	*h*	£5	Continuous	Only applicable to vulnerable customers.

Source: Economic Insight analysis.

The costs from the loss of community services are summarised in in Table 35, below. These costs are on a per establishment basis (rather than per household), so reflect the costs to the wider community of the loss of a supermarket or pharmacy respectively.

Table 35: Summary of additional costs of long-duration supply interruptions

Cost area	Cost (£ per location per day)	Cost type	Factors driving cost variation
Closure of supermarkets and convenience stores	£3,248	Continuous	Only applicable during large outages (>5000 households).
Closure of pharmacies	£393	Continuous	Only applicable during large outages (>5000 households).

Source: Economic Insight analysis.

The cost of an outage, C, is therefore:

Equation 23: Total cost of an outage

$$C = d\left(n\left(V + a + c + \frac{5}{7}w\right) + n_v\left(\frac{1}{2}c + h\right)\right) + (l * n * f) + g\left(l * n_e(d-1)(e) + \left(n_s s + n_p p\right)\right)$$

Where:

C	Total cost of the outage
n	Total number of customers affected
d	Length of the outage (in days)
V	Value of Lost Load (VoLL) per household per day
a	Daily cost of loss of heating, lighting, and connectivity
c	Daily cost of an inability to cook
w	Cost of an inability to work on a weekday
n_v	Total number of vulnerable customers affected
h	Daily cost of risk to health due to loss of heating.
l	$\begin{cases} 1\ if\ outage\ is\ over\ 24\ hours \\ 0\ otherwise \end{cases}$
f	Cost of spoilage of frozen and refrigerated food
g	$\begin{cases} 1\ if\ outage\ affects\ over\ 5000\ customers \\ 0\ otherwise \end{cases}$
e	Daily cost of an inability to use electric vehicles
n_e	Number of customers with an electric vehicle charge point
n_s	Number of supermarkets and convenience stores affected by the outage
n_p	Number of pharmacies affected by the outage
s	Daily community cost of the closure of supermarkets and convenience stores
p	Daily community cost of the closure of pharmacies

Substituting the values in Table 34 and Table 35 gives:

Equation 24: Total cost of an outage (with estimated costs)

$$C = d(370.86n + 42.5n_v) + 86 * l * n + g\left(35 l n_e(d-1) + \left(3248n_s + 393n_p\right)\right)$$

Evaluating this for a non-vulnerable customer without an electric vehicle results in the cost-time graph shown in Figure 36.

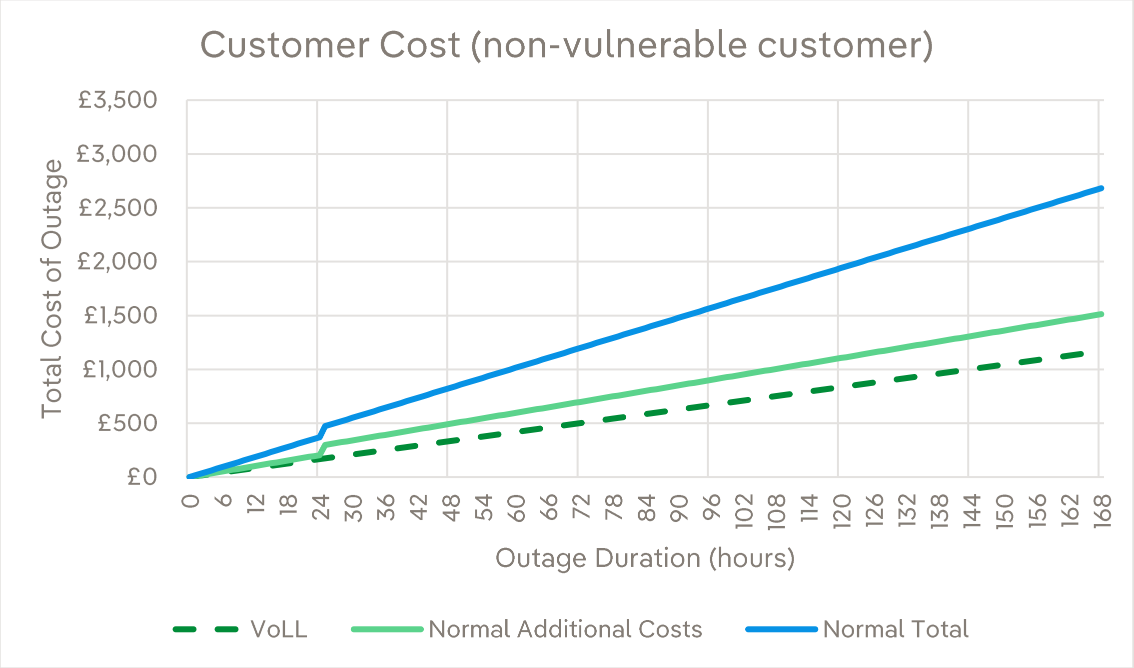

Figure 36: Customer Cost (non-vulnerable customer)

Adding in the additional costs which may be experienced by a vulnerable customer with an electric vehicle results in the cost-tome graph shown in Figure 37.

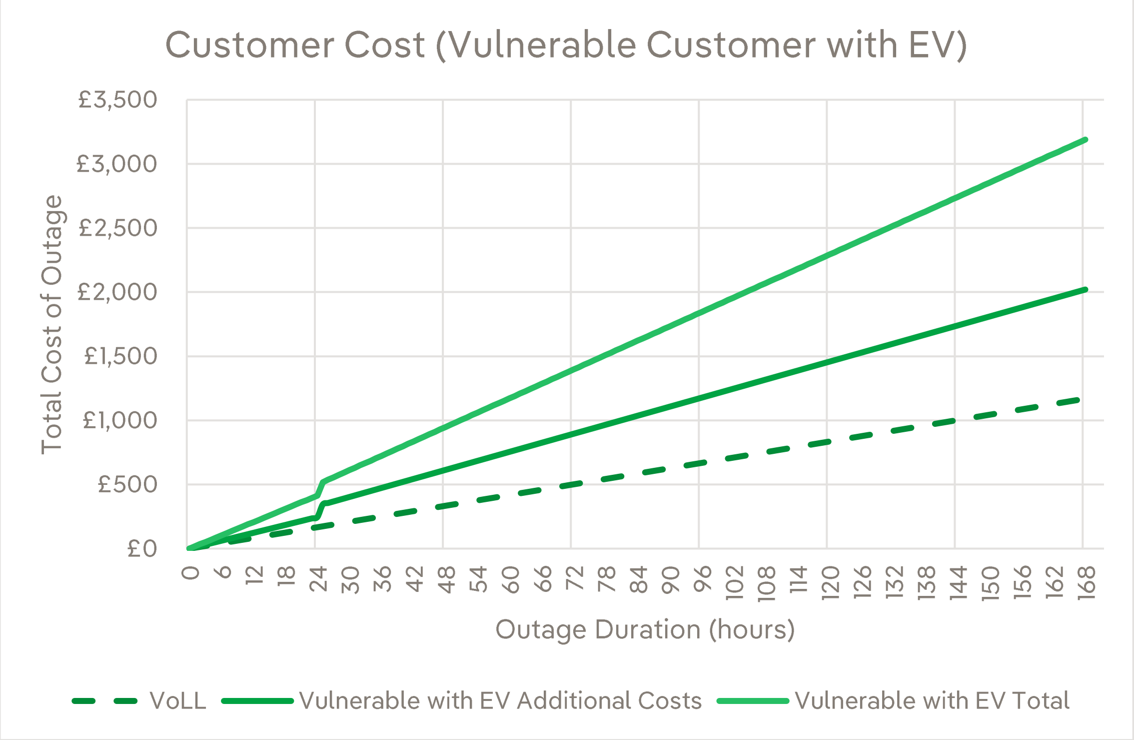

Figure 37: Customer Cost (Vulnerable Customer with EV)

7. Resilience Calculation

7.1. Combining Elements of Resilience

From the sections above, the impact of a given event is calculated based on:

- The set of asset failures predicted by the susceptibility model (Section 3);
- The transformers taken offline by the asset failures at each stage of the restoration process as calculated by the vulnerability model (Section 4);
- The time taken to complete each stage of the restoration process as calculated by the operational response model (Section 5);
- The social cost of the outage to each transformer given the type of customers fed by the transformer and the time offline as calculated using the customer impact model (Section 6).

By summing the social cost related to the outage of each transformer, the impact across the entire network can be calculated.

7.2. Network Resilience Score

The Network Resilience Score provides an overall quantification of the resilience of a given network, and therefore a headline metric to compare networks before and after an intervention.

The Network Resilience Score is calculated as the sum of the customer impact of all customers affected in the incident divided by the number customers fed by the network. As customer impacts are expressed in monetary values, this is nominally a monetary value and represents the total social cost of the incident. To enable comparison between networks, this value is then normalised by the number of customers fed to provide a cost per customer metric as shown in Equation 25.

Equation 25: Network Resilience Score

$$R = \frac{\sum_{i=0}^{n} C_i}{N}$$

Where:

R	Social cost of the incident (expressed as £/customer)
C_i	Total cost of the outage for customers fed from transformer i (as defined in in Equation 23)
n	Total number of transformers
N	The total number of customers fed by the network at the modelled voltage(s) or below.

Where multiple weather scenarios are used (as described in Section 2.2) the network resilience can be calculated for each scenario independently, and an overall network resilience score calculated as the mean score across all scenarios weighted according to the relevant likelihood of each of those scenarios occurring.

7.3. Evaluating Interventions

This single metric allows the effect of an intervention to improve, susceptibility, vulnerability or recoverability. The benefit of such an intervention is given by the difference between the Network Resilience Score pre and post intervention as shown in Equation 26.

Equation 26: Benefit of Intervention

$$B = R_{post-intervention} - R_{pre-intervention}$$

Potential interventions which could be evaluated and mechanisms to implement these within the methodology are shown in Annex A.

7.4. Fault Impact Score

A separate Fault Impact Score can be calculated to evaluate the customer impact of each fault on the network and therefore assist in identifying potential interventions. The Fault Impact Score can be calculated based on the number of customers downstream of a given fault, and resource time expended in rectifying it.

Equation 27: Fault Impact Score

$$F = \sum \frac{C_i}{n_i} \times (t_C + t_R)$$

Where:

C_i	Customer impact of the ith customer affected by the fault
n_i	Number of faults upstream of the ith customer affected by the fault
t_C	Time resource time taken to conduct the reconnaissance task on the fault (including any travel time) (in minutes)
t_R	Time resource time taken to conduct the repair task on the fault (including any travel time) (in minutes)

The time to conduct manual switching is not considered as manual switching may restore customers from several faults.

The Fault Impact Score is therefore proportional to both an estimation of the of the total customer impact which can be assigned to a given fault, and proportional to resource time expended in finding and repairing the fault.

8. References

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Annex A: Interventions

When work is carried out or planned on the network, the impact of that work can be evaluated by altering the input data to the model, and comparing the reliance score (Section 7.1) before and after the intervention.

Resilire is designed to support a wide variety of interventions, but a set of potential interventions are provided below along with a description of how they could be modelled within the framework.

Intervention	Model Area	Change	Section
Like for like pole replacement	Susceptibility	Set the age of the pole to zero and the health score factor to 1, increasing the pole $M_{crit,f}$	3.3.1
Rebuild of line to modern standard	Susceptibility	Set the age of the pole to zero, the health score factor to 1, the pole diameter to that or a modern standard pole and the span length to that of the modern standard. This will increase the pole $M_{crit,f}$, and reduce the moment exerted by wind, M_{wind}.	3.3.1
New Interconnect with neighbouring DNO	Vulnerability	Create a new 'Feeder' element at the point of connection to the adjacent network, providing an additional path to the root node.	4.2
New interconnect between network elements	Vulnerability	Create a new conductor between the end points of the new interconnector. If the new network is to be overhead, poles should also be created at regular intervals along the interconnect path and populated with data for modern standard lines.	3.3.1 4.2
Installation of switch automation	Vulnerability	Change the tags of the relevant switch to be 'tele controlled'	4.2
Undergrounding section of network	Susceptibility	Remove the relevant poles and conductors from the network and replace with a conductor connecting the two ends of the undergrounded section. This will remove any damage from that section of network.	4.2