Scenarios for Extreme Events

Alpha Phase Modelling Report

April 2024

10078787

COMMERCIAL IN CONFIDENCE

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Date:	April 2024		
Classification:	COMMERCIAL IN CONFIDENCE		
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Executive Summary

High-impact, low-probability "extreme events" pose significant threats to the Great British (GB) whole energy system. As the system undergoes rapid transition, characterised by increased reliance on renewable generation and growing electrification, particularly related to electric vehicles and domestic heating, its vulnerability to extreme events is amplified. The escalation in frequency of extreme weather events, coupled with the risk of geopolitical events such as COVID-19, or conflicts, can directly and indirectly affect the energy system and consumers. Whilst UK government and the regulator Ofgem currently carry out qualitative scenario planning assessments to understand energy system resilience, gas and electricity assessments are undertaken independently, and a quantitative approach does not exist for understanding the strengths, weaknesses, opportunities and threats for the whole energy system.

This project aims to enhance understanding of how extreme event scenarios could affect energy consumers by developing an innovative whole energy system resilience modelling framework to simulate and understand the outcomes of shock events. The insights from this simulation methodology, herein referred to as 'the model', will help to protect end users from future disruptions to their supply, which can have high financial, social, health and economic consequences for society and individuals, including increased mortality rates for vulnerable consumers.

This report represents the output of Work Package 4 in the Scenarios for Extreme Events (SfEE) project which comprises five work packages to build prototype capability for addressing this challenge: 1) designing a risk assessment framework; 2) developing scenarios; 3) developing resilience metrics; 4) prototype model development (this report); and 5) cost benefit analysis.

This document presents the proposed model architecture following an iterative design process. The highest risk elements of the resilience model design have been prototyped to de-risk the full development of the resilience model, testing the performance under a weather and non-weather scenario. Through the prototyping work carried out in this phase of the project we are now able to proceed with much greater confidence into any future development work, having de-risked some of the key challenges, namely:

- Demonstrating that it is possible to develop a fast running, whole energy system model that calculates the effect of severe shocks to the electricity and gas network infrastructure, including interactions between them.
- Demonstrating methods to calculate customer focused outputs from whole energy system level calculations, such as customers in vulnerable situations disconnected.
- Demonstrating that an innovative simulation scaling approach can be used to model a variety of scenarios quickly at different levels of granularity.
- Demonstrating that the approach is capable of modelling outages caused by transmission line overloads where network constraints are reached.

We also identified a new opportunity for the model:

- Automatically searching for weaknesses in the system by calculating the effect of breaking components and training an AI agent to search for severe outcomes. This approach could provide insights into where unexpected extreme event scenarios might occur in future, which can be used to develop a better whole energy system risk register, alongside human judgement and past scenario data. Reinforcement learning is one approach to achieving this goal and it is recommended that this is explored in future to maximise the benefits of a developed model.

A series of features for future development have been recommended alongside the opportunity described above, including developing a probabilistic output to capture confidence in the results, expanding the prototype to whole of GB and including additional system components.

In summary, this project marks a significant milestone in modelling extreme events, facilitating open and transparent dialogue between industry and government. It identifies opportunities to develop resilience standards and measures to reduce impact. This work package specifically has significantly reduced risks associated with future developments in this capability.

Contents

Glossary

Table 1: Glossary of key terms and abbreviations. Within the definition if another key term is used, they are denoted within square brackets.

Term	Abbreviation	Definition
Above Ground Installation	AGI	Within this document AGI refers to any part of the gas network that is installed above ground.
Critical Services	-	Critical services have been defined for this project as [essential services] which could experience high levels of disruption during a short-term energy disruption and which other [essential services] have a 'high' dependency on.
Combined Cycle Gas Turbine	CCGT	A power station that generates electricity by means of a number of gas turbines whose exhaust is used to make steam to generate additional electricity via a steam turbine.
Distribution Network Operator	DNO	DNOs own and operate [electricity distribution] networks which deliver electricity from the transmission system grid supply points to customers . In Great Britain they are: Electricity North West, Northern Powergrid, Scottish & Southern Energy Networks, SP Energy Networks, UK Power Networks, Western Power Distribution.
Electricity Distribution	-	Electricity distribution is the process of delivering electricity from the transmission system to individual consumers. It involves reducing the high voltage from the transmission grids to a lower voltage suitable for use by organizations and individuals. This is achieved through a network of substations, transformers, and distribution lines. The voltage is further reduced near the customer's premises for safe use in lighting, industrial equipment, and household appliances.
Electricity Transmission	-	A high-voltage electric power network that serves the majority of Great Britain and some of the surrounding islands. It ensures that electricity generated anywhere on the grid can be used to satisfy demand elsewhere. It is owned and operated by National Grid plc in England and Wales. In Scotland, the grid is owned by Scottish Power Transmission in the south, and by Scottish and Southern Electricity Networks (SSEN) in the north. Infrastructure connecting offshore wind farms to the grid is owned by offshore transmission owners.
Essential Services	-	Essential services are those that the public rely upon on a daily, or near daily, basis.
Electricity Ten Year Statement	ETYS	The Electricity Ten Year Statement (ETYS) is the ESO's view of future transmission requirements and the capability of Great Britain's National Electricity Transmission System over the next ten years. It contains a suit of supporting data.
Gas Distribution Network	GDN	Gas is distributed to consumers from the [National Transmission System] through Gas Distribution Networks (GDNs). There are 8 GDNs, which are managed by 4 companies. The GDNs in the UK are: East of England, North London, North West, West Midlands, Northern Scotland, Southern, Wales and West. These GDNs are

		managed by: Cadent Gas Ltd, Northern Gas Networks Ltd, SGN, Wales and West Utilities Limited
GB Whole Energy System	None	The Great Britain (GB) whole energy system encompasses the electricity and gas networks, along with their associated interactions. This term covers the generation, transmission, and distribution of energy throughout the country.
Impact Estimates	-	The [resilience model] outputs that represent impacts to electricity or gas customers including, critical services or vulnerable customers due to a [stress event scenario]. These can be compared to [resilience metrics] thresholds to give impact scores in the [risk framework].
Local Distribution Zones	LDZ	The areas of the GDNs are split into local distribution zones for gas accounting purposes.
Local Transmission System	LTS	The Local Transmission System (LTS) delivers gas from National Transmission System (NTS) offtakes to consumers.
Middle Super Output Area	MSOA	Middle layer Super Output Areas (MSOAs) are a geographic hierarchy designed to improve the reporting of small area statistics in Scotland, England and Wales. They comprise between 2,000 and 6,000 households and have a usually resident population between 5,000 and 15,000 persons. MSOAs fit within local authorities.
Modelled Area	-	A region in northern Scotland used as a test bed for prototype resilience model development in alpha phase. This includes [electricity transmission], [electricity distribution], [gas transmission] and [gas distribution], and for prototyping purposes has excluded the specific substations: Inverarnan, Cruachan, Dalmally.
National Transmission System	NTS	The National Transmission System (NTS) transports high-pressure natural gas from entry terminals to offtakes, which are either directly connected daily metered consumers, such as large industrial sites, or to non-daily metered [Local Distribution Zones (LDZs)].The NTS is owned and operated by National Gas Transmission.
Optimal Power Flow	OPF	Optimal Power Flow (OPF) is a mathematical optimisation problem aimed at finding the most cost-effective way to operate a power system within its operational and physical constraints, such as generation limits and network capacities.
Resilience Model	-	The extreme events model which generates [impact estimates] to consumers based on defined [stress event scenarios].
Resilience Metrics	-	Descriptions of impacts to end-users of the [GB Whole Energy System] with associated numerical thresholds for [impact estimates] on a scale of 1 to 5 (insignificant to high).

Risk Framework		The methodology to quantify risk to the GB energy network, using [stress event scenarios] input to the [resilience model] to generate [impact estimates].
Scottish and Southern Electricity Networks	SSEN	An electricity transmission network owner operating in Scotland.
Stress Event Scenario	-	Definition of an event (linked to the UK National Risk Register) that could strain the GB energy network and lead to negative operational impacts.
Value of Lost Load	VoLL	VoLL quantifies the cost to consumers for lost energy supply, reflecting how much consumers would pay to prevent outages. For the prototype resilience model described in this report, VoLL is used to estimate the cost of energy not supplied.

1 Introduction

High-impact, low-probability "extreme events" pose significant threats to the Great British (GB) whole energy system. Whilst UK government and the regulator Ofgem currently carry out qualitative scenario planning assessments to understand the energy system resilience to extreme event shocks there does not currently exist a quantitative approach to understand the strengths, weaknesses, opportunities and threats for the whole GB energy system.

From July 2024, National Grid ESO will transition to National Energy System Operator (NESO), becoming wholly government-owned and independent from National Grid. A NESO licence condition will be to produce Resilience Assessment Reports on regular intervals, that will need to be data-driven, evidence based, and support the case for resilience investment [1]. The resilience modelling tool, developed by this Strategic Innovation Fund (SIF) project, aims to model risks associated with stress event scenarios and their effects on end consumers.

The system operator envisions using the resilience model to understand GB's whole energy system vulnerabilities to various events, including electricity and gas disruptions, assessing the effect on customers including critical services and vulnerable consumers, and considering dependencies with essential services beyond the energy system. A longer-term objective is to utilise this model to appraise future energy systems that integrate the role of hydrogen. This approach will help to build a more resilient system for the benefit of consumers and wider society.

Following a successful Discovery phase, this project, named Scenarios for Extreme Events (SfEE), is now within an Alpha phase, comprising five work packages:

- Work Package 1 involves designing the risk assessment framework.
- Work Package 2 determines the scenarios to be modelled. It will investigate a high wind speed weather scenario and gas supply loss non-weather scenario.
- Work Package 3 focuses on developing resilience metrics to gauge the severity of impacts, allowing scenarios to be compared.
- Work Package 4 focuses on the design and development of a resilience model capable of simulating the impacts of extreme events. This model aims to demonstrate the functionality of the selected modelling approach by calculating the impacts of example events. This will help to inform future resilience model design and planning decisions.
- Work Package 5 entails the cost-benefit analysis of the resilience model.

This report represents the output of Work Package 4. Our project partners, the University of Strathclyde and the Met Office, supported us in completing this work. The University of Strathclyde provided two literature reviews providing support on the scope for the project, these are submitted separately as standalone documents. The Met Office provided significant support in the weather scenario identification and model input, their work has been attached as an appendix to the Work Package 2 report [2].

1.1 Risk Assessment Framework

For the majority of extreme events there is limited historic data to understand which sections of the energy networks are most susceptible to failures and which areas could experience the greatest impact if failures did occur. A resilience model can help us by simulating extreme events across the networks to better understand the impacts of failures and whether appropriate measures should be taken to mitigate the severity of outage impacts.

The resilience model, depicted by the blue box in Figure 1, illustrates how it can be used within a broader risk framework developed within the wider project. The black and yellow box represents the work done in Work Package 2 on the scenarios and blue boxes represent the work done in WP3 on the resilience metrics. The resilience metrics provide a total impact score allowing comparison between scenarios. Knowledge gained from the resilience model will then feed back into the scenario definition creating an annual cyclic risk assessment process.

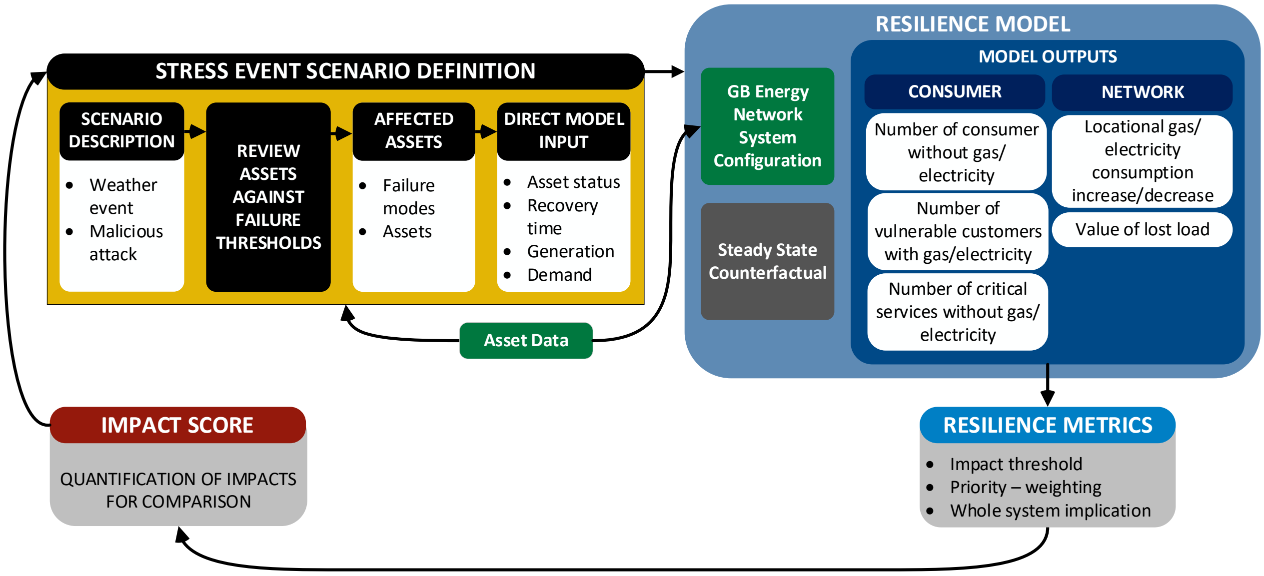

Figure 1: Risk assessment framework. The black and yellow box is the scenario assessment (Work Package 2) which produces inputs to the resilience model (Work Package 4). These outputs are translated into the resilience metrics, facilitating comparison of impact scores between scenarios across the energy sector (Work Package 3).

The remainder of this report outlines how the Alpha phase resilience model was developed and tested, then provides recommendations for how the model should be developed before deploying it as a business-as-usual toolset.

Section 1.2 provides ESOs modelling requirements. From our understanding of these requirements, we describe the process for designing the resilience model and the concluding model architecture in section 2. Section 3 discusses why and then how different areas of the resilience model were focussed on in the prototype. Section 4 tests the resilience model prototype to evaluate if it can successfully use known inputs to create novel customer focussed outputs. Section 5 describes the next steps and the vision for the resilience model beyond Alpha. Lastly, we present the main conclusions of the report in section 6.

1.2 Resilience Model Requirements

At the start of the Alpha phase, the project partners formed an initial vision and use cases for the resilience model. This was documented in the Basis of Design Report [3]. Since then, we have refined our vision and developed specific modelling requirements for Alpha phase, Beta phase and beyond.

Table 1 outlines prototype modelling requirements for Alpha phase, which are derived from the use cases defined in the Basis of Design Report [3].

Key terms are included within square brackets, such as: [resilience model]. These are defined in the Resilience Metrics and Risk Framework [4] and repeated in the Glossary.

Table 2: Alpha phase resilience model requirements. Key terms are included within square brackets.

ID	Requirement	Parent Use Case(s)
1	The [resilience model] shall represent the [electricity transmission] and [electricity distribution] and the [National Transmission System] and [gas distribution] networks in the [modelled area].	"Input System Configuration"
2	The [resilience model] shall generate [impact estimates] for each [stress event scenario].	"Generate Area Specific Vulnerability Estimates"
3	The [resilience model] shall produce visualisations of [impact estimates] for the [modelled area], for each [stress event scenario].	"View Vulnerability Estimates"
4	The [resilience model] shall generate geospatial estimates for unmet demand for each [stress event scenario].	"Generate Area Specific Vulnerability Estimates"
5	The [resilience model] shall represent interactions between gas and electricity networks.	"Generate Area Specific Vulnerability Estimates"
6	The [resilience model] shall be able to input a range of [stress event scenarios].	"Input Weather Scenarios"; "Input Non-Weather Scenarios"
7	The [resilience model] shall generate [impact estimates] defined in the [resilience metrics] for the [modelled area].	"Generate Area Specific Vulnerability Estimates"

2 Resilience Model Design

This section details the process followed to develop the Alpha phase resilience model to meet the resilience model requirements outlined in Section 1.2. It also includes considerations for future model development.

2.1 Designing the Model and Selecting Software

2.1.1 Required Granularity

To design a resilience model that is high-quality, performs well and is usable, we first need to consider the model's granularity. The granularity refers to the level of abstraction used to simplify real world complexity into a simulated version that allows for meaningful experimentation. Granularity can be better understood by considering the following attributes:

- Resolution: the level of detail at which a model captures or represents phenomena.
- Accuracy: the degree of closeness between the model's output and the true outcome.
- Efficiency: the ability of a model to achieve its objectives with minimal computational resources or time.
- Flexibility: the capacity of a model to adapt or be modified to easily accommodate different data or tasks.
- Simplicity: the degree to which a model's structure or design is straightforward and easy to understand or implement.

Taking each term in turn allows us to better understand how the model requirements map to the model's design:

- Resolution: Extreme events affect both the transmission and distribution on the electrical and gas networks to different extents. We are interested in the large effects that are likely to be caused by failures on the electricity transmission networks and will therefore model grid supply points (typically 400 kV to 132 kV) and bulk supply points (132 kV to 33 kV). We recognise that failures are more likely at the electrical distribution network level so will also seek to include primary substations (33 kV to 11 kV). However, the number of distribution substations mean detailed models of each distribution substation (11 kV to 400/230V) will increase the calculation time without necessarily providing additional insight. Therefore, further abstraction of the distribution substations should be considered in future phases. Similarly, for the gas networks we are interested in the National Transmission System (NTS). However, we will consider abstraction on the local distribution zones (LDZs), to reduce calculation time.
- Accuracy: Validation for extreme events poses challenges due to their stochastic nature of their impacts and the rarity of such events in recent history. The outputs from the resilience model should still align with the effects from recent extreme events within reasonable error bounds to provide confidence in the model. The challenge with this is that the model won't just consider failures of individual nodes, but the interactions between nodes and the effect that node failures could have on the remainder of the network. Cascading outages could feasibly be caused by relatively small perturbations but have widespread effects across the network. Accurate modelling of cascading outages requires analysis of the dynamic response to events which would come at the cost of computational efficiency.
- Efficiency: The resilience model will be used to be inform an annual resilience report which considers the risks from plausible extreme events. Given large numbers of events could be simulated, model run times should not be prohibitive. However, while run times should be reduced where possible, this resilience model is not currently expected to be used reactively to extreme events when they occur.

- Flexibility: The resilience model needs to be highly flexible due to great variation in potential extreme events. The model should also be flexible to future increases in its functionality, for example using probabilistic or reinforcement learning techniques.
- Simplicity: In its simplest form, a model could consider each substation or line as an isolated node and assign probabilities to the likely failure of those nodes during an outage to calculate impacts. However, such an approach neglects the interconnected nature of the energy networks and the impact one node failure could have on another. Appropriately representing the interconnectedness while still efficiently solving the model is a non-trivial challenge.

2.1.2 Software

To capture the complexity of extreme events interacting with the whole energy system, gas and electricity network models are required.

Various potential calculation methodologies exist to simulate the electricity networks' response to events or disturbances. The most common approaches in order of increasing complexity are summarised below:

- Transport power flow models are commonly used for steady-state power flow analysis to give a basic understanding of the behaviour of the grid. They simplify the representation of the power system by neglecting certain nonlinear effects and focusing on the main components of the network (buses, branches, generators, loads).
- Optimal power flow (OPF) models extend the basic transport power flow model to introduce optimisations such as minimising generation costs, thereby providing a framework for determining the most efficient and cost-effective way to allocate electricity generation and distribution resources while adhering to system constraints. OPFs can be calculated using a linearised DC approximation of the actual AC-OPF problem. OPFs can be further distinguished by the following variants:
  - Linear OPFs assume linear relationships between control variables such as generator outputs and objective functions such as costs and losses.
  - Security constrained linear optimal power flow (SCLOPFs) models add in security constraints to ensure the reliability and security of the power system under various operating conditions including outages.
  - Non-linear optimal power flow (NLOPFs) account for the non-linear relationships between variables such as voltage magnitude and reactive power. NLOPFs are used for detailed optimisation of power system operation including economic dispatch, optimal power flow and voltage/ reactive power control considering economic and security constraints.
- Root mean squared (RMS) models calculate the dynamic behaviour of the system in response to a disturbance over timespans ranging from seconds to minutes.
- Electromagnetic transient (EMT) models focus on capturing the phenomena that occur during fast transient events such as faults, switching operations and lightning strikes over timespans ranging from microseconds to milliseconds.

Gas network modelling approaches can generally be categorised as capacity or fluid-dynamic models. Capacity models are analogous to linear OPFs, as they are more flexible and require less computational time, however, ignore short-term transient effects. Fluid-dynamic models, at the scale of gas networks, require significant computational time but more accurately capture transient behaviour and dynamic effects. For the prototype resilience model, we have assumed that short-term transient effects are of less interest for the gas model and have instead focussed on tools that include a capacity model.

Table 3 presents software commonly used for power systems analysis alongside the calculation approaches each package can perform. Further reading on this subject is provided by the University of Strathclyde's paper on 'Choosing appropriate power system simulation models for different events' [5].

Table 3: Commercially available software and Python packages commonly used to perform power systems analysis [6].

Software	Transport Model	Linear OPF	SCLOPF	NLOPF	RMS	EMT
Commercially available software						
MATPOWER [7]	✓	✓		✓		
PLEXOS [8]	✓	✓	✓			
PowerFactory [9]		✓	✓	✓	✓	✓
TIMES [10]	✓	✓				
PowerWorld [11]	✓	✓	✓	✓	✓	✓
Python packages						
Pandapower [12]	✓	✓		✓		
PYPOWER [13]	✓	✓		✓		
PyPSA [6]	✓	✓	✓	✓		
Calliope [14]	✓					

Although commercially available software such as PowerFactory and PowerWorld can assess the dynamic response of the system to disturbances through RMS or EMT calculations, they lack the flexibility of Python packages. A key requirement of the resilience model is to simulate both the gas and electricity transmission and distribution networks, capturing this multi-vector analysis would be much more challenging using dedicated packaged electricity network software [6].

Python packages provide the flexibility to perform multi-vector analysis whilst enabling further functionality to be added to the model in future such as probabilistic or reinforcement learning AI optimisation techniques. Of the available Python packages, PyPSA was selected as it compares well to the other available Python packages in meeting our resolution and efficiency requirements by performing OPF calculations across large networks. It includes multi-period optimisation, meaning the response to networks to events over time can be analysed. PyPSA is relatively simple to use and enables us to simulate both gas and electricity networks.

We recognise that PyPSA is currently incapable of meeting all our accuracy requirements as it cannot assess the dynamic response of the system to disturbances. Further research is required in the next phases of the project to assess whether RMS, EMT or alternative approaches could be integrated into a Python model to enable us to better understand the risk of cascading outages without compromising the model's efficiency.

2.2 Resilience Model Architecture

Figure 2 summarises the model architecture we have developed to simulate the impact of extreme event scenarios on the gas and electricity transmission and distribution networks.

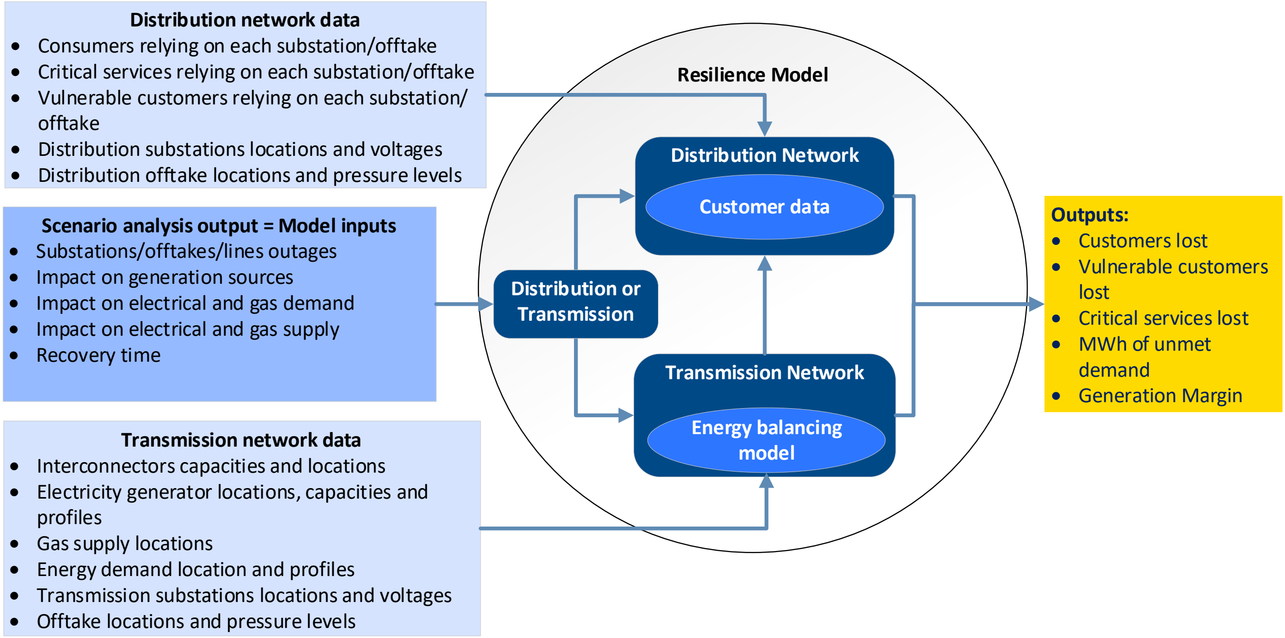

Figure 2: Resilience model architecture

The networks are first represented in the model with substations/offtakes inputted as nodes. Each node is then connected to other nodes in the model via branches which represent lines or pipework. Each node and branch have a series of characteristics assigned to it which represent the electrical or gas networks. This includes their geo-coordinates to represent their locations as well as information on connected customers, ratings, demand levels and generation capacities.

An extreme event scenario is then overlayed on top of this network model. This is represented by the likely outages of nodes or lines over a time series and their anticipated response time to an outage. A decision logic algorithm is applied to the scenario inputs to determine whether a full electricity or gas transmission network calculation is required for the scenario, or whether the scope of the scenario only interacts with the distribution networks and consumers. If required, PyPSA then runs an OPF calculation for the electricity networks and a capacity calculation for the gas networks across each timestep. This simulates the impact of an outage on the remaining nodes and lines across the network to determine whether additional outages are likely to occur.

The model then outputs key metrics which describe the impact of the event on customers.

2.2.1 Scenarios Analysis

There are a wide range of possible extreme events that could be represented as scenarios for input to the model [15]. Work Package 2 details how those scenarios fit into the risk assessment framework. Work Package 2 additionally describes how the scenarios then provide event specific information for asset failure likelihoods, estimated recovery times and whether the scenario also effects generation or demand [2]. These items are then used as inputs to our resilience model. To demonstrate the model functionality for this project phase, example scenarios were selected for a loss of gas supply and a high windspeed event (see Section 4).

2.2.2 Representing the Distribution Networks

Most customers are connected to the distribution networks rather than the transmission networks, which requires the resilience model to capture distribution network information. However, given the number of nodes and lines on the distribution network, appropriate abstraction is required to efficiently represent this in the model.

Figure 3 provides a simplified view of a radial and a meshed network. Meshed networks are inherently more resilient as if one line fails, then alternative lines can still meet the demands of that node. For the prototype resilience model developed in this phase of the project, the distribution networks considered are all radial. This means that we can simplify the analysis by assuming that an outage at one electricity substation will lead to outages at all substations supplied from it. We therefore chose to not to simulate OPF calculations for the distribution network and instead modelled these for the meshed transmission network.

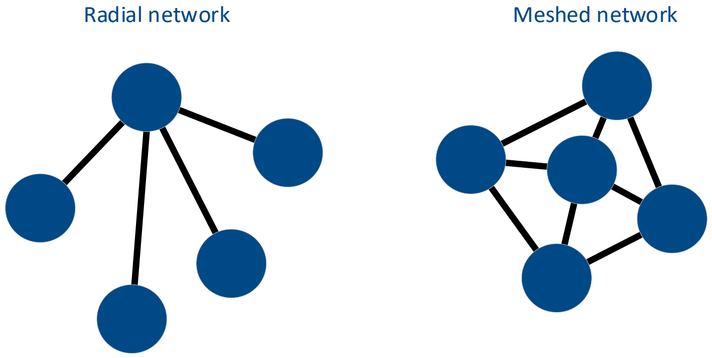

Figure 3: Simple illustrations representing the different connected structures of radial and meshed networks.

Not all distribution networks can be precisely modelled as radial networks. In areas such as London and around Liverpool, the electricity distribution networks are extensively meshed. Extending the model to cover these networks will require application of OPF methodologies, and complex load flow analysis calculations as a minimum to understand the system response to an outage.

2.2.3 Gas and electricity network interactions

The model includes both the gas and electricity networks. Combined cycle gas turbine (CCGT) plants are currently the primary interface between the gas and electricity models. CCGT plants currently dispatch a large proportion of electricity demand in GB. Hence, during a severe gas outage scenario, CCGT plant available capacities may reduce which could negatively impact the capacity margin and system flexibility.

In the resilience model, we have examined further interactions between the energy networks, particularly the increase in electricity demand triggered by gas outages, primarily due to an increased dependence on electric heating. However, to gain a comprehensive understanding of this and additional interactions, further investigation is necessary.

2.2.4 Model outputs

Work Package 3 focussed on identifying relatable metrics which could support future investment discussions with Ofgem and government. The following metrics were identified which the resilience model will output beyond Alpha:

- Number and duration of customer disconnections
- Number and duration of vulnerable consumer disconnections
- Number and duration of critical service disconnections
- Energy Not Supplied (MWh)
- Cost of energy not supplied (£)
- Generation margin (MW)

These outputs are a mix of novel customer related outputs and traditional energy metrics.

Within Alpha, we have focused on the first five outputs with the generation margin not yet calculated. The duration of disconnection is also currently an input to the resilience model, based on scenario analysis. More discussion of these output metrics can be found within the Resilience Metrics and Risk Framework slides (021700-142266V) [4].

2.3 Future Development Considerations

The model architecture we have developed is flexible to further improvement. Our literature review led us to a notable paper titled "From Reliability to Resilience: Planning the Grid Against the Extremes", authored by a group of eight academics specialising in resilience and extreme events research [16]. The paper introduces a modelling framework aimed at enhancing grid resilience under extreme conditions, referred to as the Moreno paper hereafter. It consolidates various studies in this field and supports the approach we have taken.

The Moreno paper suggests the following framework, for a proposed two-stage model [16]:

1) Intelligently selects specific network investments out of a set of candidate options
2) Tests those investments by quantifying their resilience benefits in probabilistic outage scenarios originated by stochastic simulation of natural hazards.

The stochastic generation and assessment of hazard and outage scenarios is carried out through the below simulation-based steps:

1) *Hazard characterisation*: generate various hazards with random magnitudes and locations, including spatiotemporal profiles for events such as storms.
2) *Vulnerability assessment of system components:* use fragility curves to determine:
    a. hazard-dependant failure probabilities of each network component (towers, lines, substations, generation equipment),
    b. the outage scenarios across the system which are randomly generated from these probabilities.
3) *System response*: simulate for each outage scenario potential system cascades from automatic power flow rerouting, load/generation disconnection and post-contingency redispatch. Assess the spatially resolved volumes of energy not supplied and associated cost impacts.
4) *System restoration*: simulate the reconnection of failed/ damaged network components including load/generation.

The intelligent selection of options then follows the below steps:

5) *Monte Carlo simulation*: re-run the stochastic generation and assessment of hazard and outage scenarios thousands of times. Each time, randomly select hazards, generating outages and generating equipment repair times. Collate the worst scenarios ranked by total impact.
6) *Investment optimisation.* For a selected budget, identify a shortlist of potential resilience measures. Restimulate the model allowing an optimisation algorithm, such as a machine learning agent, to select the best combination of additional resilience measures to lower the impacts across the collated worst scenarios.

Our current model architecture design and wider risk assessment aligns with steps 1-4 of the Moreno paper. We intend to build on this in future development phases to better capture the detail necessary for steps 1-4 and to begin to integrate the Monte Carlo simulation and investment optimisation from steps 5 and 6.

2.4 Design Conclusions

We have selected the Python package PyPSA as the basis for our model design as it:

- Can simulate the gas and electricity transmission and distribution networks with large numbers of nodes and lines meaning it can capture the GB energy networks.
- Calculates multi-period OPFs for the electricity networks meaning it can model the system response to events over time.

- Uses the Python programming language, meaning it can easily interact with other Python packages.

Our model architecture integrates PyPSA with models of the gas and electricity transmission and distribution networks allowing us to understand the response of networks to extreme events. We then output appropriate resilience metrics.

A key limitation of this approach is the dynamic response of electricity networks to perturbations over short time periods. Further research is required to better understand this and the impact on modelling cascading outages.

We have developed our model architecture with future improvements in mind and have identified a modelling framework which we will aim to follow in future development phases.

3 Prototype Resilience Model

In this section, we discuss the resilience model prototyping work carried out during this Alpha phase to de-risk the eventual business as usual (BaU) resilience model design.

3.1 Prototype Functionality

An assessment was carried out to focus the Alpha prototype resilience model development on addressing the most challenging, risky, and innovative components of the eventual solution. By prioritising development on these tasks, we aimed to gain insights to inform our approach in future stages of the project.

Table 4 below outlines the functionality in the resilience model beyond Alpha, along with the associated development risk level and the corresponding de-risking approach tested in the prototype resilience model to mitigate the challenge level of the task involved in creating the final resilience model beyond Alpha.

Table 4: Resilience model functionality risk assessment.

Eventual Solution Functionality	Functionality Risk Level	Risk Reasoning	Alpha Phase Mitigation Approach
Capability to analyse multiple scenarios	High	Creating a model that is a valuable tool for use at evaluating a variety of hazards will be challenging.	A scenario agnostic model design has been developed and will be tested on multiple types of scenarios in the prototyping stage.
Calculate cascading outages	High	Challenging to model due to the complex and variable nature of cascading outages.	We will model line capacities in the Alpha model, so that initial outages may cause some lines to become overloaded and further outages occur. However, beyond Alpha we will need to understand the mechanisms that cause cascading outages better so we can capture them in the simulation.
Capture interactions between gas and electricity network	High	A whole system energy model for GB does not currently exist at this scale within ESO and project partners. It might be challenging to link two separate optimisation models.	The main interactions between gas and electric network will be incorporated to assess the feasibility of this approach.
Evaluate meshed networks	High	Meshed networks typically necessitate energy balancing or power systems analysis for comprehensive evaluation.	We will model the meshed networks on the energy transmission system and investigate potential methodologies for evaluating meshed networks on the distribution network.

Eventual Solution Functionality	Functionality Risk Level	Risk Reasoning	Alpha Phase Mitigation Approach
Validation against past event	High	Extreme events are highly unlikely and for many events past data is limited or non-existent.	High winds will be one scenario that is tested so that outputs can be sense checked against report by Ofgem on Storm Arwen. A validation plan will be developed in future development phases that looks at validating components of the resilience model in isolation.
Calculate critical services disconnected	Medium	Availability of critical services location and offtake data is unknown, and could be important to acquire to understand cascading effects of extreme events.	Speak to DNO and ESO stakeholders to assess the availability of data and options for acquiring it. If the data is not available immediately, create a methodology for estimating critical services disconnected in the prototype based on open source infrastructure data.
Evaluate the whole GB energy system	Medium	A whole system energy model for GB does not currently exist at this scale within ESO and project partners. However, some components of it do exist already.	For the prototype resilience model, we will build a representation of SSENs area for both gas and electricity. Once one area is modelled in, this can be expanded upon in future development phases.
Implement a stochastic approach	Medium	Probabilistic modelling takes additional computational resources to carry out, so models must be relatively efficient and quick to run.	We will aim to create a fast-running deterministic approach in the prototype resilience model using a format that allows for easier addition of a probabilistic approach later. We will assess the speed of the scenario runs for some of the slowest to calculate scenarios to inform the feasibility of probabilistic modelling.
Calculate customers disconnected	Low	Availability of customer data is unknown, and customer focussed metrics are novel.	Speak to DNO and ESO stakeholders to assess availability of data and options for acquiring it. Create an estimate based on open source population data for the prototype.
Calculate energy not supplied, cost of energy not supplied and generation margin	Low	These are common energy modelling metrics that have standardised methodologies.	While the customer focused outputs will remain a focus of the project, we will calculate the energy not supplied and associated cost (using a value for VoLL) in the prototype. In future phases we will incorporate generation margin too.

3.2 Prototype Decision Logic

The resilience model prototype comprises four distinct modelling components: electricity distribution, electricity transmission, gas distribution, and gas transmission. The specific components accessed depend on the scenario being analysed. Certain scenarios may solely affect the electricity or gas distribution model, in which case only the relevant distribution model is utilised. Should the transmission system be affected, the corresponding distribution network will also be utilised to leverage the integrated consumer-related data, including critical services and number of connected customers.

The sequencing of the components is decided by interpreting the input scenario and determining which, and in what order, the gas and electricity models are executed; the outputs from one component can be used as inputs for a subsequent model. There is potential for these components to be more seamlessly interconnected and optimised together in future development phases, but this was not a focus of the de-risking exercise during this prototyping phase.

3.3 Electricity Modelling Component

3.3.1 Transmission

The electricity transmission network spans across GB and comprises a mixture of overhead cables, underground cabling and subsea cables – the size of these assets varies from of 400kV, 275kV and 132kV assets. These are all linked together via substations across the country that then connect separately owned generators, interconnectors, large demands, and distribution systems. Here, ‘transmission’ means assets at 132kV or above as we are initially only modelling SSENs area in Scotland. In England and Wales, transmission relates mainly to assets at 275kV and above.

The transmission model is required to capture scenarios that affect higher voltage levels, energy generation, demand, energy storage or cause constraint issues on the network. For these reasons, and that the transmission network is a meshed network, it requires an optimal power flow model which we used PyPSA to create. To create a representation of the electricity transmission system we downloaded asset data, containing information such as capacities, voltage levels and locations from the ESO ETYS dataset [17]. The connection between the Spittal and Blackhillock substations is a HVDC cable rather than a 275 kV circuit (as labelled on Figure 4). However, for the purposes of this prototype, we have evaluated it as a 275 kV line. Figure 4 shows the geographical scope of the model used in this prototype phase.

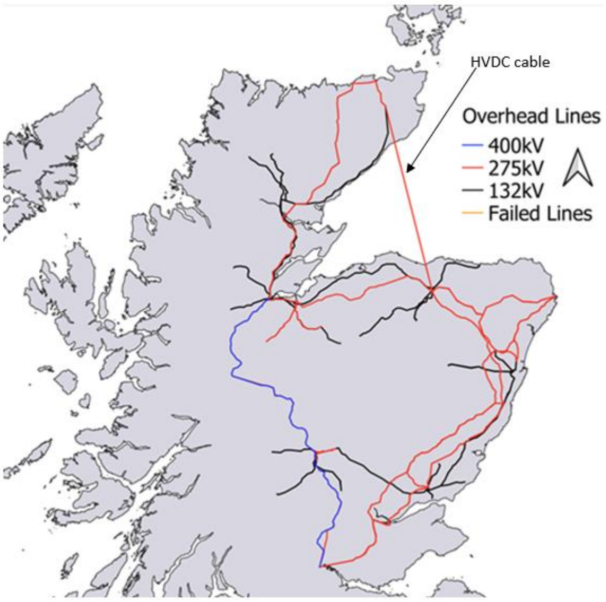

Figure 4 : SSENs transmission system and area modelled in this prototyping phase.

A PyPSA model was developed using a slightly simplified (lower resolution) version of the electricity transmission network within SSEN's service area in Scotland. For prototyping purposes, 132 kV substations were combined, and the estimated mid points of the overhead lines were used in place of a high-resolution path. The PyPSA prototype model currently incorporates line capacities to allow for some exploration of cascading outages to be explored in the scenarios. However, due to time constraints, it does not yet include considerations such as voltage, resistance, current, efficiencies, and reactive power. PyPSA possesses the capability to integrate these elements and we plan to explore the benefits of adding these features in further development stages.

To simulate the energy demand of the transmission network, half hourly electricity demand time series profiles of the GB network were taken from ESOs data porta [18]. This demand profile was then scaled by substation capacity, to generate a demand profile each substation in the model transmission network. Beyond Alpha we would like to engage with the networks and ESO teams to acquire more accurate time series data for each substation and offtake, as more granular data will increase the accuracy of the modelling results.

Half-hourly generation profiles for wind and hydro generation were similarly taken from ESOs data portal and scaled based on the capacity of the site. Substation locations, capacities and where these sites were connected to were extracted from the ETYS dataset [17].

Balancer nodes were introduced to model the rest of GB, which provided both demand and generation when necessary. The cost of generation for these balancer nodes was taken as the cost of energy in GB. Electricity prices were taken from the Low Carbon Contracts website [19]. Cost of electricity is important to consider for the unit commitment of generation within the model, ensuring that cheap renewable generation is the used where possible for meeting demand (economic dispatch).

3.3.2 Distribution

Electricity distribution comprises network below 275kV in England and Wales and 132kV in Scotland which transports electricity from transmission to consumer.

The electricity distribution infrastructure of SSENs area resembles a radial network (see Section 2.2.2), meaning that we can simplify the analysis by assuming that an outage at one electricity substation will lead to outages at all substations supplied from it. We therefore chose not to simulate OPF calculations for the distribution network, since a data store lookup could be used to rapidly provide all the required consumer demand information necessarily to calculate the resilience outcome metrics.

Data containing location and capacities for grid supply points and primary substations was acquired from SSENs data portal [20]. The prototype resilience model’s scope extends down to the primary substation level, with secondary substations not factored into the analysis at this prototyping stage.

Whilst the assumption of a radial distribution network was deemed appropriate for the prototype resilience model covering Scotland’s distribution areas, this assumption would not be accurate if extended to the rest of GB, due to meshed networks elsewhere in the country. It is likely that some OPF calculations will be needed to model the effect of extreme events on the distribution network level for some regions in GB and approaches will need to be trialled and validated in future stages of the project.

3.4 Gas Modelling Component

The gas modelling component consists of a graph-based representation of the National Transmission System (NTS), which is the high-pressure system responsible for transporting natural gas from entry terminals to offtakes, which are either directly connected daily metered consumers, such as large industrial sites, or to non-daily metered Local Distribution Zones (LDZs). Gas is transported based on the configuration of the NTS compressor fleet, to ensure the system remains within operational pressure limits and gas can be delivered to the extremities of each LDZ. The gas networks are less susceptible to dynamic stress events, when compared to the electricity networks, as the gas pipelines themselves act as storage, known as linepack, creating availability during short-term events. The gas model does not currently consider linepack, although this functionality is being considered for future development phases.

3.4.1 Transmission

We used publicly available data sourced from the NTS Data Portal to find asset data and build the gas transmission model [21]. There were geographical inconsistencies in the data between the locations of the pipes and the sites. Therefore, the resilience model used a geographical approximation technique to bring the closest points on pipes to adjacent sites. Figure 5 demonstrates the components in the resilience model which are the Entry points, Above Ground Installations (AGIs), CCGTs, the NTS Links, and the Compressor Station. Balancer nodes were included to simulate any demands on the NTS from outside the prototype scope boundaries. The blue lines show the geographically accurate location of the NTS for comparison with the green lines which indicate the assumed approximate positions in the prototype resilience model.

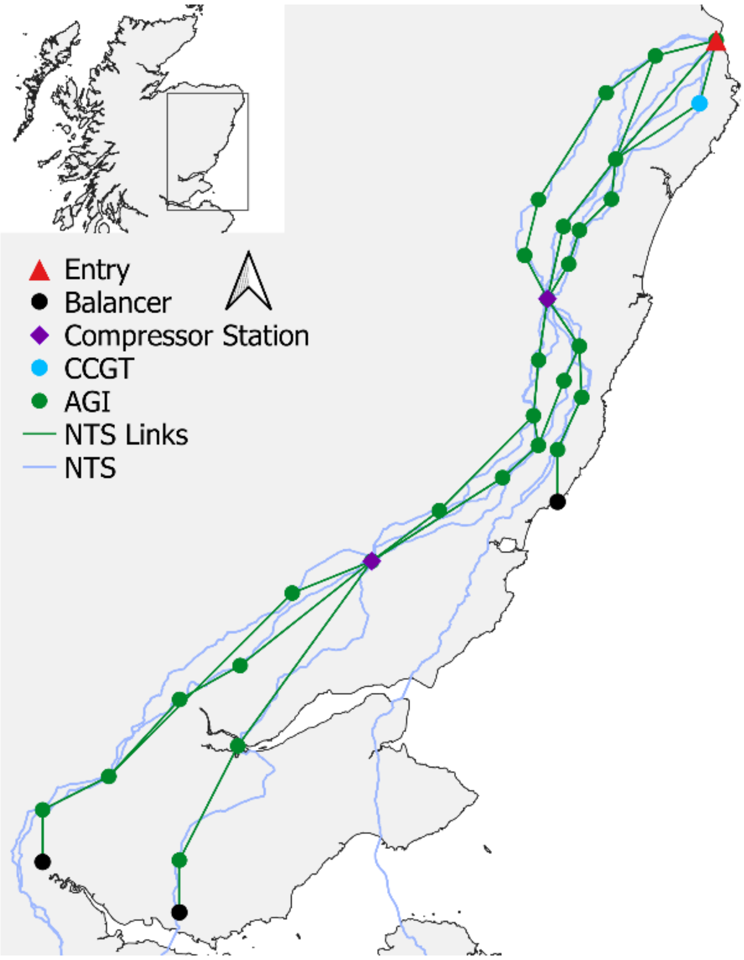

Figure 5: National Transmission System (NTS) in Northern Scotland. Data was taken from National Gas Transmission website [21].

Entry terminals, represented by red triangles in Figure 5, illustrate where gas enters the network, with only St Fergus gas terminal in the geographic region of interest. All AGI data obtained are assumed to be daily-metered offtakes to industrial sites or local distribution zones. CCGTs are connected to the closest proximity AGI, creating an interface with the electricity model.

Pipeline capacities in million cubic meters (mcm) were interpolated from their diameters using a second-order polynomial fitting of the SciGRID Gas IGGIELGN dataset of European transmission pipeline data [22]. These capacities were converted from mcm to MW based a 39.6 MJ/m^3 calorific value of natural gas, as described in the Gas Demand Forecasting Methodology published by National Gas Transmission (formerly National Grid Gas Transmission) [23] .

3.4.2 Distribution

The distribution networks are responsible for transporting gas to the end consumer through the LDZ at gradually reduced pressures. The model currently generalises LDZs, which are operated and maintained by the Gas Distribution Networks (GDNs), to a single offtake on the NTS, as distribution asset data was not available as part of this project. To model events at gas distribution level, regional gas demand data at Middle layer Super Output Area (MSOA) granularity was applied to normalised annual gas demand profiles to generate time-resolved gas demand profiles, as demonstrated in Figure 6 [24] [25] [26]. The profiles were generated for domestic and non-domestic (industrial and commercial) consumers and aggregated to the closest AGI on the NTS, based on MSOA centroid locations.

Preferably, GDN asset data could be used to build the gas model, however, as part of this Alpha phase project we were unable to obtain access to SGNs asset data within project time constraints. For future development phases, access to GDN's assets would allow for more accurate representation of the Local Transmission System (LTS), and therefore capture of regional characteristics contributing to resilience issues. Additionally, lower pressure asset data, pertaining to the location of individual LDZs, would allow better geospatial segregation and generate more accurate consumer impacts.

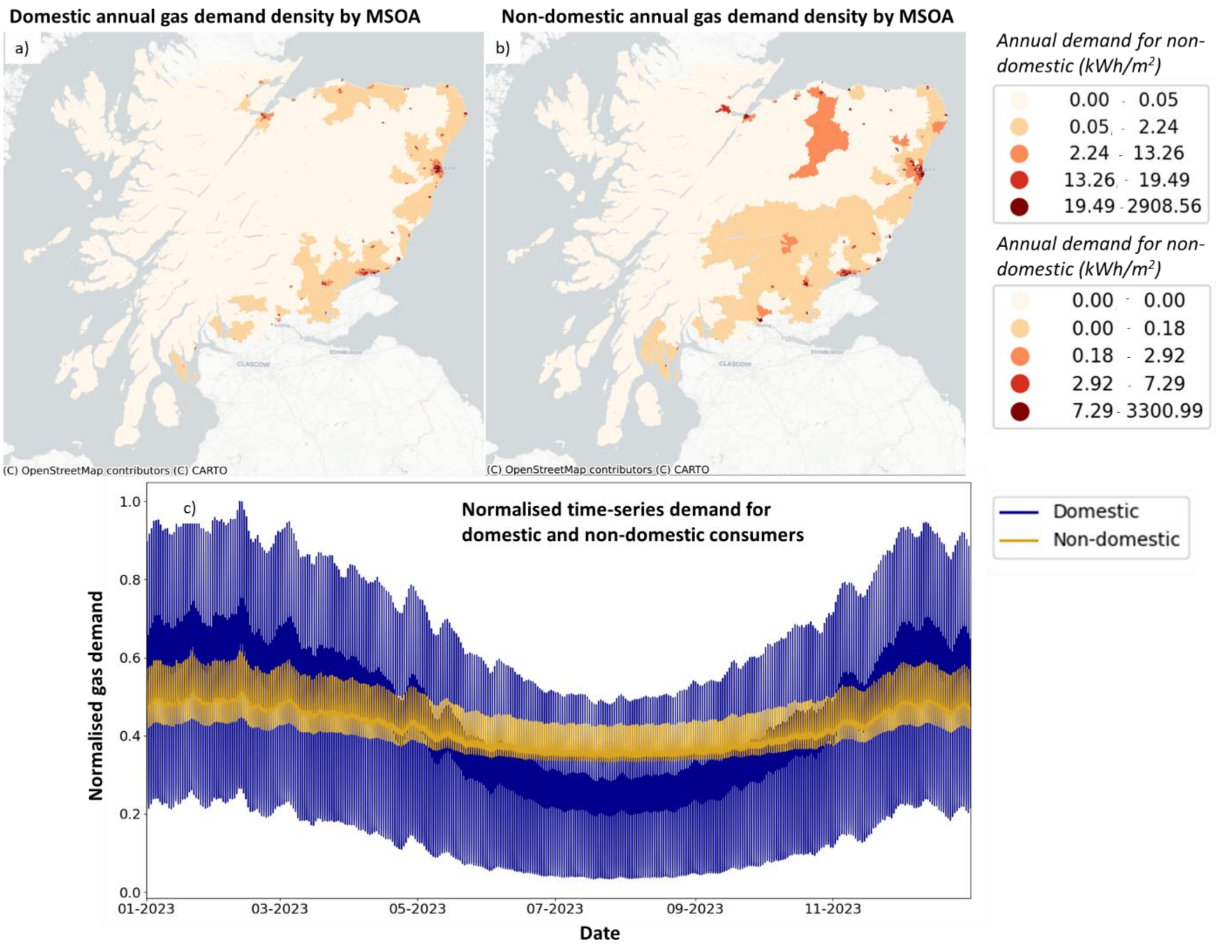

Figure 6: (a) Map of annual domestic gas demand density by MSOA, (b) Map of annual non-domestic gas demand density by MSOA, (c) Normalised time-series gas demand for one-year.

3.5 Inputs

The resilience model requires inputs to define the scenario being simulated. Inputs include the starting conditions for price, generation capacities, storage capacities, and energy demands, in addition to identifying which assets have failed, their recovery times and any time-varying details for the other input parameters. To determine which assets are likely to fail under a given extreme event scenario, and their respective recovery times, a dedicated analysis (separate from the resilience model) is required. The nature of this analysis will vary according to the scenario in question. This approach allows us to keep the resilience model fast and flexible to all kinds of possible current and future extreme event scenarios, since it is only concerned with modelling the shock to the system and its consequences, rather than being concerned with what prior events caused the shock to occur.

Assessing the scenarios effects on generation and demand poses a challenge due to the extensive amount of time series data and the unpredictability of extreme event timing. Following the development of an approach to simulate the full time-history of extreme event scenarios, we developed an alternative approach to improve the flexibility and speed of the OPF calculations – transforming all time-series data into distributions from which samples are drawn prior to the simulation. Consequently, the resilience model is also designed to accept percentage values as inputs for sampling these distributions. For instance, an input of 50% for demand corresponds to the median demand time series, with the length of the time series representing the recovery time for the asset, assuming constant outage starts and duration for each failed asset. Similarly, an input of 99% corresponds to the 99th greatest percentile of demand, over the same recovery time, as shown below in Figure 7.

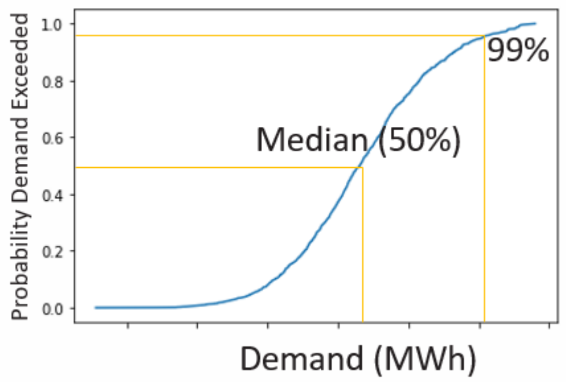

Figure 7: Example energy demand distribution and sampling of the 50th and 99th percentiles.

This approach presents several advantages compared to running the event at a specific instance in time, or across all time points. It enables us to link demand and supply more easily with events, it facilitates conducting sensitivity studies, and it improves our understanding of scenario likelihoods.

Currently, the prototype assumes all assets fail at the same time and have the same recovery time. Beyond Alpha, we plan to incorporate a dynamic analysis where assets will have varying recovery times and the duration of the simulation chosen will reflect this.

To summarise the resilience model requires following inputs:

- Which assets have failed, found by completing separate scenario analysis.
- Asset recovery time, found by completing separate scenario analysis.
- Percentiles or time-series profiles for prices, generation, and demand.

3.6 Gas and Electricity Interactions

As the ESO transitions to the NESO, it is crucial to develop a comprehensive whole-system energy model that captures interactions between the gas and electricity networks to provide accurate calculations of our customer outputs.

The gas and electricity interactions currently captured in the prototype are:

- We assume that when a customer is disconnected, the domestic space heating demand is shifted to the electricity network. Given that 77% of gas demand is typically allocated for space heating, we project that 77% of the gas demand will be transferred to the geographically closest substation [27].
- The CCGT plants are interconnected between the two models. Therefore, any changes in demand or supply of the CCGT will affect both models.

3.7 Outputs

3.7.1 Customers and Vulnerable Customers

The number of customers, including vulnerable customers, within SSEN's service area was provided by ESO. To determine the effect of substation failures on customer disconnections, we needed to distribute this data across specific substations and offtakes. Therefore, we employed a scaling method based on the energy demand of each substation or offtake. This approach involved calculating the proportion of a substation's or offtake's capacity relative to the total capacity within the SSEN area, and then applying this proportion to estimate the number of customers and vulnerable customers associated with each location. For example, the formula used was:

$$customers\ relying\ on\ substation = \left(\frac{substation\ capacity}{total\ capacity\ in\ SSEN\ area}\right) \times (number\ of\ SSEN\ customers)$$

In subsequent phases beyond the prototype, efforts will be made to obtain data regarding the distribution of customers per substation and offtake by engaging with the Distribution Network Operators (DNOs) directly.

3.7.2 Critical Services

Data containing the locations and details of critical infrastructure is not easily available on the timescales for this prototype development. To address this issue and prepare for the possibility that such data might not be available in future project phases, we developed a methodology to map critical services, with schools used as an illustrative example. Utilising OpenStreetMap [28], we identified all schools within SSEN's area, then matched these schools to the nearest primary substation using geospatial data from the ETYS dataset [17]. The same process was applied to the gas network with schools being attributed to the closest proximity gas offtake.

In future development phases, efforts will be focused on acquiring information about which critical services depend on each substation and offtake from the DNOs. Should this prove challenging due to limitations in data availability or the sensitive nature of the information, the previously described methodology will be utilised for other critical services to estimate the allocation of critical services to each substation and offtake.

3.7.3 Energy Not Supplied and Cost Implications

Energy not supplied during an extreme event is one of the key metrics to be calculated by the resilience model. At the distribution level, the capacity of each failed substation is known, and this is aggregated and multiplied by the sampled demand profile, providing the energy not supplied. Energy not supplied due to impacts at the transmission level, is more easily calculated through the OPF calculation.

The cost of energy not supplied is important output from the resilience model as it enables the estimation of financial losses resulting from power outages. For electricity the current Value of Lost Load (VoLL) is set at £6,000/MWh, as determined by Ofgem's Balancing and Settlement Code (BSC), specifically in the Balancing and Settlement Code (BSC)

P443 report [29]. This value of VoLL was multiplied by the energy not supplied to provide an estimate of cost of the outage. To enhance the model's efficiency in resource allocation, further refinement could be achieved in future development phases by segmenting the willingness to pay for avoiding outages according to customer types and preferences. This approach aligns with methodologies documented in the relevant literature [30].

Regarding the VoLL for gas, industry values are less standardised in comparison to those for electricity. Consequently, the Customer Standards of Performance, which outline compensation entitlements for consumers in the event of service interruptions, serve as a proxy for VoLL [31]. According to Guaranteed Standard 1 (GS1), compensation is set at £70 per day of disruption for domestic customers and £115 per day for non-domestic customers, with gas consumption not exceeding 73,200 kWh. For this study we have assumed that consumers exceeding 73,200 kWh are also entitled to £115, as their arrangements are not under GS1 and, to our knowledge, are not publicly available.

4 Testing and Analysis

To test and learn from the prototype functionality, we ran multiple high wind speed scenarios and gas pipe failure scenarios with the prototype resilience model to calculate the outcome metrics of interest. The objective was to evaluate the effectiveness of the model methodology from start to finish.

4.1 Weather Scenarios

4.1.1 Resilience Model Inputs and Scenario Analysis

To simulate a high wind weather scenario which could test the resilience of Scotland's energy networks, we collaborated with the Met Office, who provided wind speed data across the network area for a significant windstorm event. For resilience model testing purposes, we used this data to develop two scenarios using simplified assumptions on network failure conditions:

- **Moderately Severe Scenario:** Here we assumed that the transmission network overhead line assets failed at wind speeds of 40 m/s or more and the distribution network assets fail at speeds of 35 m/s or more.
- **Extremely Severe Scenario:** Here we assumed that the transmission network overhead line assets failed at wind speeds of 35 m/s or more (simulating higher than expected deterioration of transmission line condition, or additional impacts to lines from debris) and the distribution network assets fail at speeds of 35 m/s or more.

These thresholds were established based on insights gathered from the Met Office's literature review[1]. In particular the paper titled Fragility Curves for Assessing the Resilience of Electricity Networks and the Resilient Electricity Networks for Great Britain (RESNET) project report, played a key role in identifying the thresholds [32] [33]. In our analysis, we have assumed all faults to be permanent, indicating lasting infrastructure damage requiring repair, unlike transient faults, which are temporary and self-resolving.

Furthermore, for the Moderately Severe Scenario, we assumed that storm occurs during a median (50th percentile) hour of a typical mid-winter day with respect to generation and demand profiles. For the Extremely Severe Scenario we assumed that the storm occurs during a 99th percentile hour of a typical mid-winter day with respect to generation and demand profiles. For both scenarios we assumed that onshore and offshore wind generation assets are prevented from generating at speeds over 25 m/s to prevent mechanical overloading [34], which would represent a worst-case scenario. This assumption may be considered conservative, as the analysis currently applies peak wind speeds, rather than sustained wind speeds.

A 19-hour recovery period is assumed for asset repairs based on the average recovery duration observed following Storm Arwen, a comparable high-speed event, ignoring the phased return of recovered assets during the repairing process. This recovery timeframe was derived from analyses conducted using the National Fault and Interruption Reporting Scheme (NaFIRS) dataset [35]. The two scenarios are summarised below in Table 5.

Table 5: Resilience model inputs

Scenario Assumption	Moderately Severe Scenario	Extremely Severe Scenario
Wind generation timeseries percentile	50	1
Hydro generation timeseries percentile	50	1
Electricity import price timeseries percentile	50	99
Demand timeseries percentile	50	99
Transmission line wind speed failure threshold (m/s)	40	35

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[1] Attached at an appendix to the Stress Event Scenarios Report [2]

Distribution line wind speed failure threshold (m/s)	35	35
Transmission line recovery time (hours)	19	19
Distribution line recovery time (hours)	19	19

4.1.2 Moderately Severe Scenario

In the Moderately Severe Scenario, no lines failed on the transmission network. However, as Figure 8 and Figure 9 demonstrate there are significant effects felt on the distribution network. The majority of the effects occur in the NE of Scotland as this is where the storm is centred.

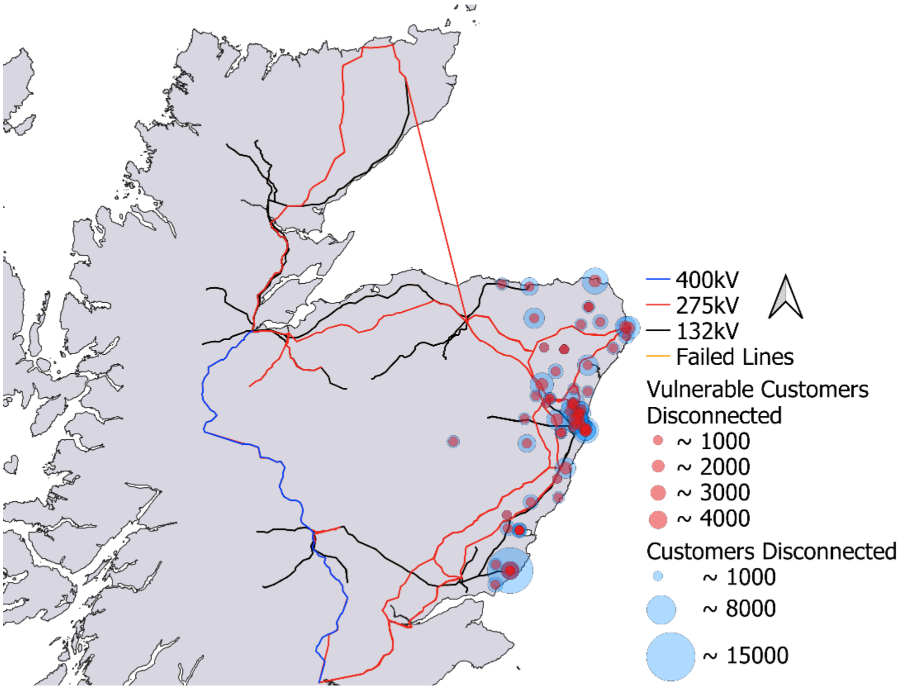

Figure 8: Customers disconnected during the Moderately Severe Scenario.

The effect of the Moderately Severe Scenario on schools disconnected is shown below in Figure 9. Schools were used as an illustrative example to test our methodology for mapping critical services disconnected.

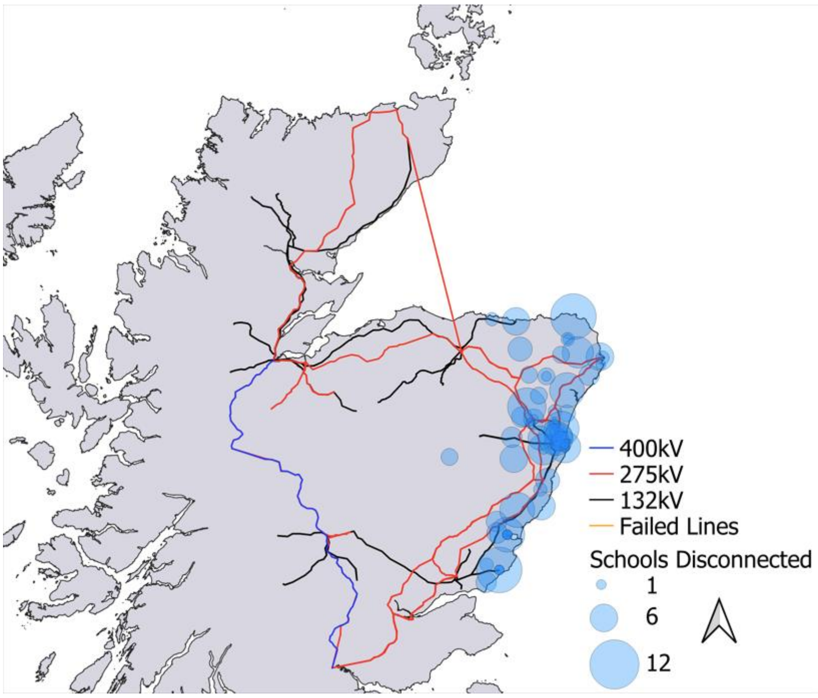

Figure 9: Schools disconnected in the Moderately Severe Scenario.

Table 6 presents the effects from the Moderately Severe Scenario.

Table 6: Moderately Severe Scenario outcome summary (for a 19-hour outage)

	Customers disconnected	Vulnerable customers disconnected	Schools disconnected	Energy not supplied (MWh)	Cost of energy not supplied (£)	Failed substations
Transmission outcome	0	0	0	0	0	0
Distribution-only outcome	187,000	44,500	220	4,990	30,000,000	69
Outcome Summary	**187,000**	**44,500**	**220**	**4,990**	**30,000,000**	**69**

The above results show that within a Moderately Severe Scenario that there are significant effects on the distribution network, but no impact on the transmission network. These results are in the rough order of magnitude of Storm Arwen where 144,000 customers were disconnected SSENs area [36].

4.1.3 Extremely Severe Scenario

As shown below in Figure 10 the Extremely Severe Scenario significantly affects the transmission system, where failures are denoted by the yellow lines.

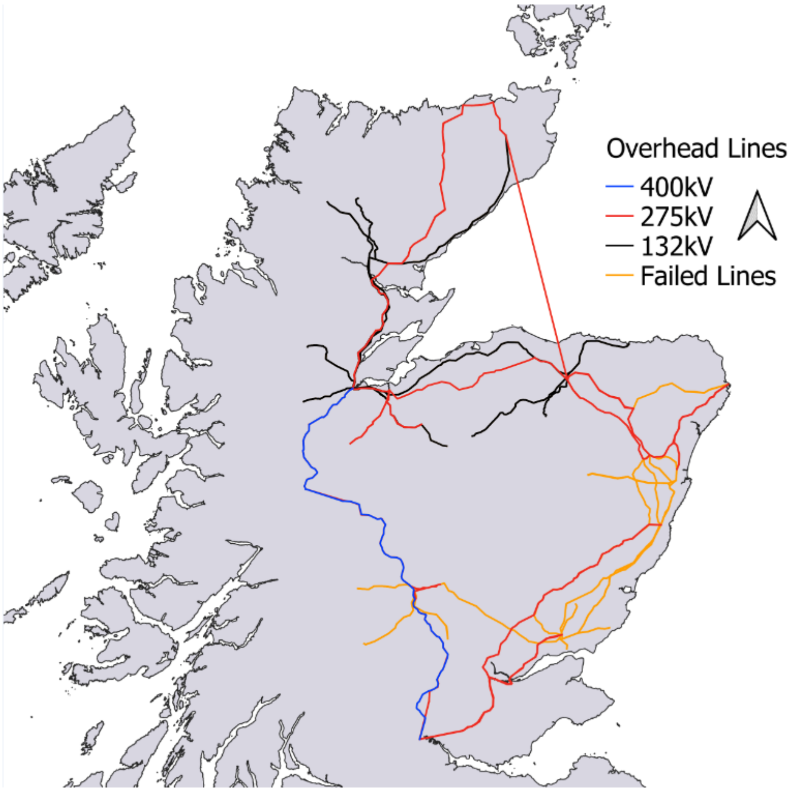

Figure 10: Failed lines during the Extremely Severe Scenario.

These failed lines result in two substations to become completely disconnected from the rest of the networking leading to a consistent level of unmet demand on the transmission network, as demonstrated in Figure 11. Furthermore, the availability of renewable energy sources is insufficient, owing to wind speeds being excessively high, which prevents generation to avoid mechanical overloading [34]. Consequently, the network relies on CCGT to meet demand.

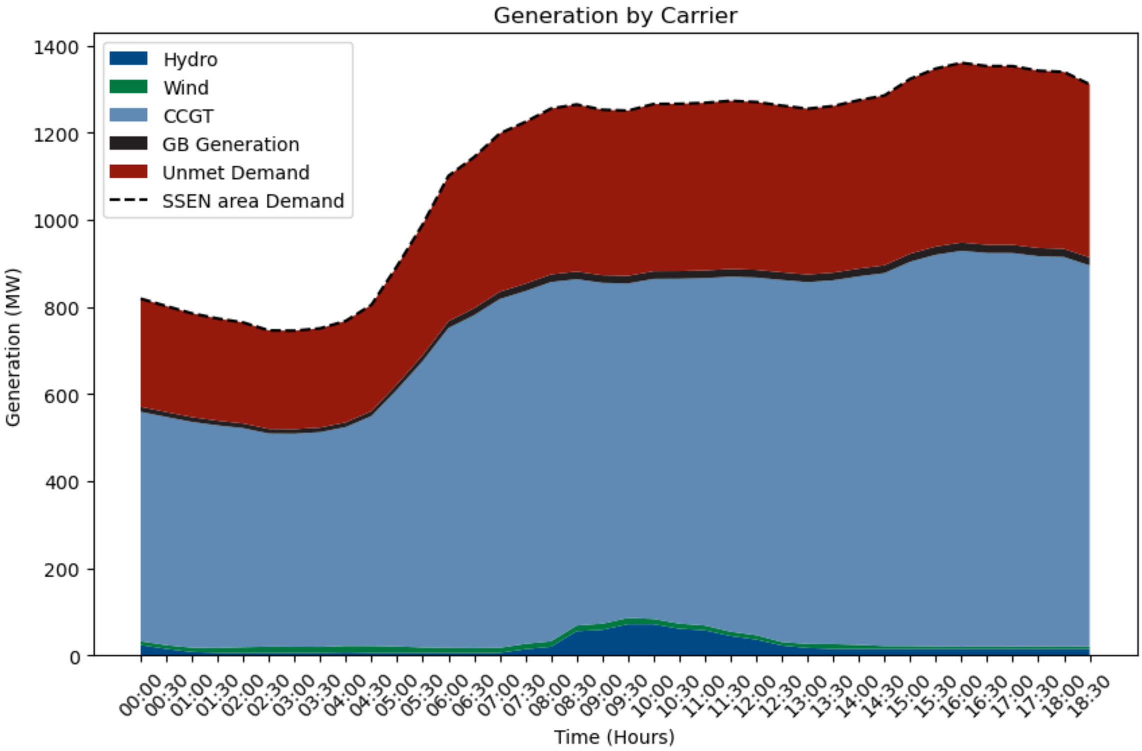

Figure 11: Extremely Severe Scenario analysis of electricity dispatch time series post-event until recovery time

Figure 11 demonstrates when there is minimal wind generation the CCGT capacity is required to meet demand. From a whole system modelling perspective this increase in gas usage had a negligible impact on the gas transmission infrastructure and capacity, which remain well within operational limits. A similar analysis covering a larger area, whereby a greater number of CCGTs are required to meet demand, may provide more strain on gas supply.

The impact of the Extremely Severe Scenario on customers disconnected is shown below.

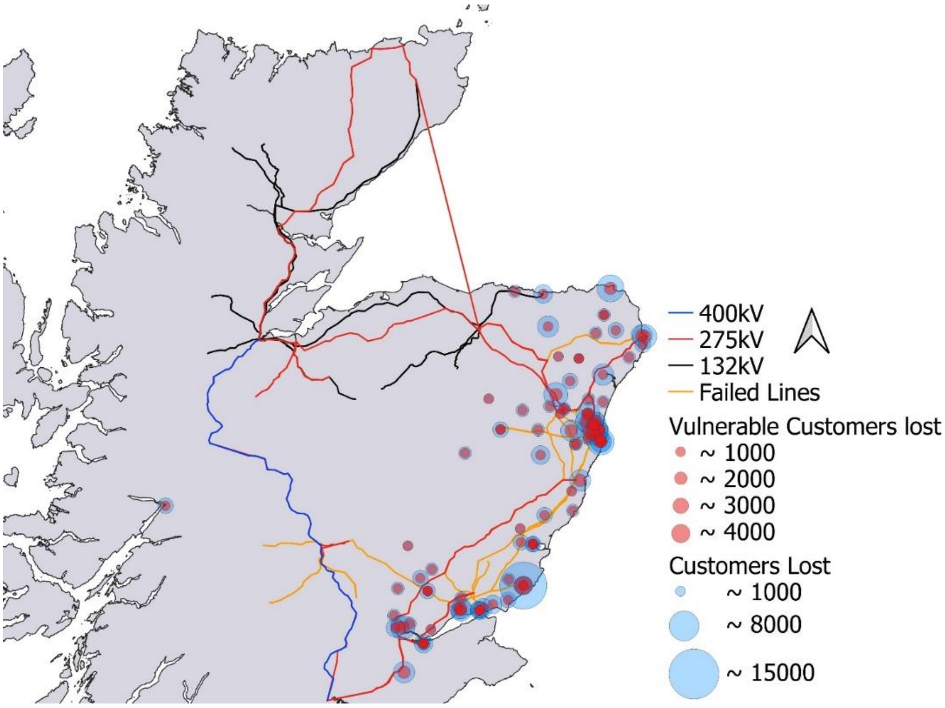

Figure 12: Customers disconnected during the Extremely Severe Scenario.

The effect of the Extremely Severe Scenario on schools disconnected is shown below.

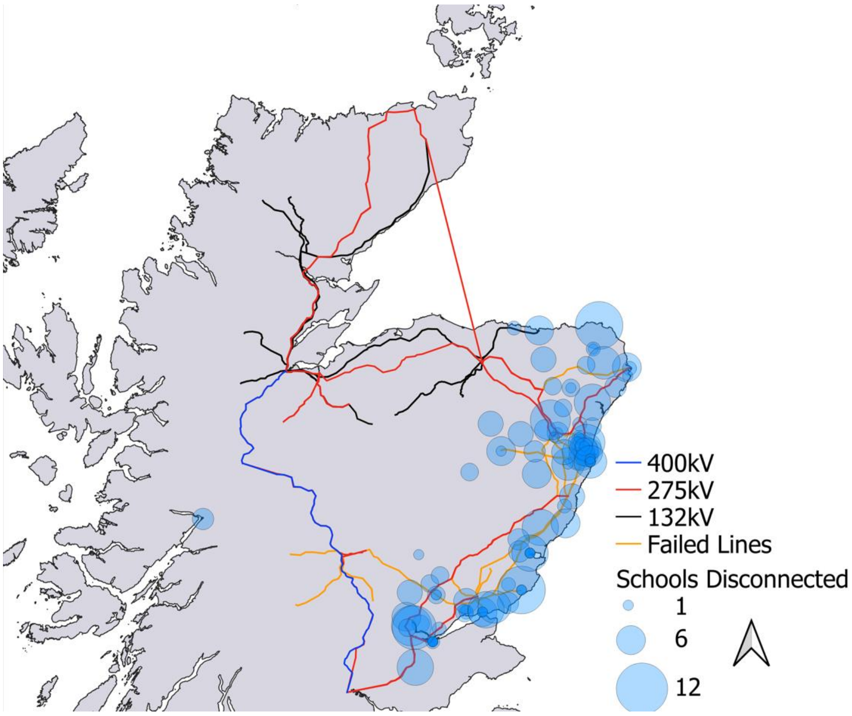

Figure 13: Schools disconnected in the Extremely Severe Scenario. Schools have been included to demonstrate the capability to model loss of critical services.

Table 7 presents the outcomes from the Extremely Severe Scenario. Within this extreme scenario there are higher number of customers disconnected which are primarily caused by outages on the transmission network.

Table 7: Extremely Severe Scenario outcome summary (for a 19-hour outage).

	Customers disconnected	Vulnerable customers disconnected	Schools disconnected	Energy not supplied (MWh)	Cost of energy not supplied (£)	Failed substations
Transmission outcome	170,000	40,600	210	6480	38,900,000	2
Distribution-only outcome	126,000	29,900	145	4060	28,600,000	69
Outcome Summary	**296,000**	**70,600**	**355**	**10,500**	**67,500,000**	**71**

The outcomes in the Extremely Severe Scenario surpass the effects of Storm Arwen. While it is clear that such substantial effects on the transmission network are improbable considering recent past storm events, additional investigation is necessary to estimate the likelihood of the Extremely Severe Scenario.

Table 7 demonstrates the intrinsic resilience of the transmission system, attributable to its meshed network structure. Despite the failure of 11 circuits within the transmission network, only two substations on the network experienced a lack of energy supply. In this scenario, the winter rating capacities of the transmission lines, derived from the ETYS dataset [17], did not restrict the energy transfer, indicating that cascading outages due to thermal overload might not be a concern. However, further investigation is necessary to comprehensively understand the potential for other mechanisms, as well as line ratings, to cause cascading outages under these conditions.

The effect of this scenario on the gas network is an increase in CCGT energy demand (shown in Figure 11) and 296,000 customers are unable to use their boiler for heating, causing a decrease in demand for gas domestically. During the peak winter period, this could have severe consequences for the health of vulnerable (and non-vulnerable) customers, particularly if the asset repair time extended beyond the assumed 19 hours.

Each of the scenarios took 0.5 minutes to run on a standard 1.7 GHz i5 CPU machine with 16 GB installed RAM.

4.2 Non-weather Scenarios

To capture the effects of a non-weather event, we have modelled two scenarios that result from mechanical failures on the gas transmission system:

- **Scenario 1 - Northern Transmission Line Outage:** SGN operate a high-pressure LTS pipeline, the Northern Transmission Line, which transports natural gas from the NTS compressor station in Aberdeen to locations beyond the city of Inverness, some of the most remote regions at the extremities of the gas system. Scenario 1 models an unplanned outage at the Aberdeen compressor station, including failure of any local site emergency mitigation measures, preventing transmission along the LTS Northern Transmission Line, as shown on the left in Figure 14.
- **Scenario 2 - St Fergus Gas Terminal Supply Loss:** St Fergus Gas Terminal is one of the largest entry points on the NTS, with natural gas conventionally being transported South. This scenario assumes an extremely unlikely event of a complete gas supply outage from St Fergus during peak demand conditions, and consequent Aberdeen compressor station failure preventing gas from reaching offtakes between St Fergus and the Aberdeen compressor

station, highlighted on the right in Figure 14. This scenario results in loss of supply downstream of each offtake, including Aberdeen compressor station, which means that the Northern Transmission line also experiences an outage.

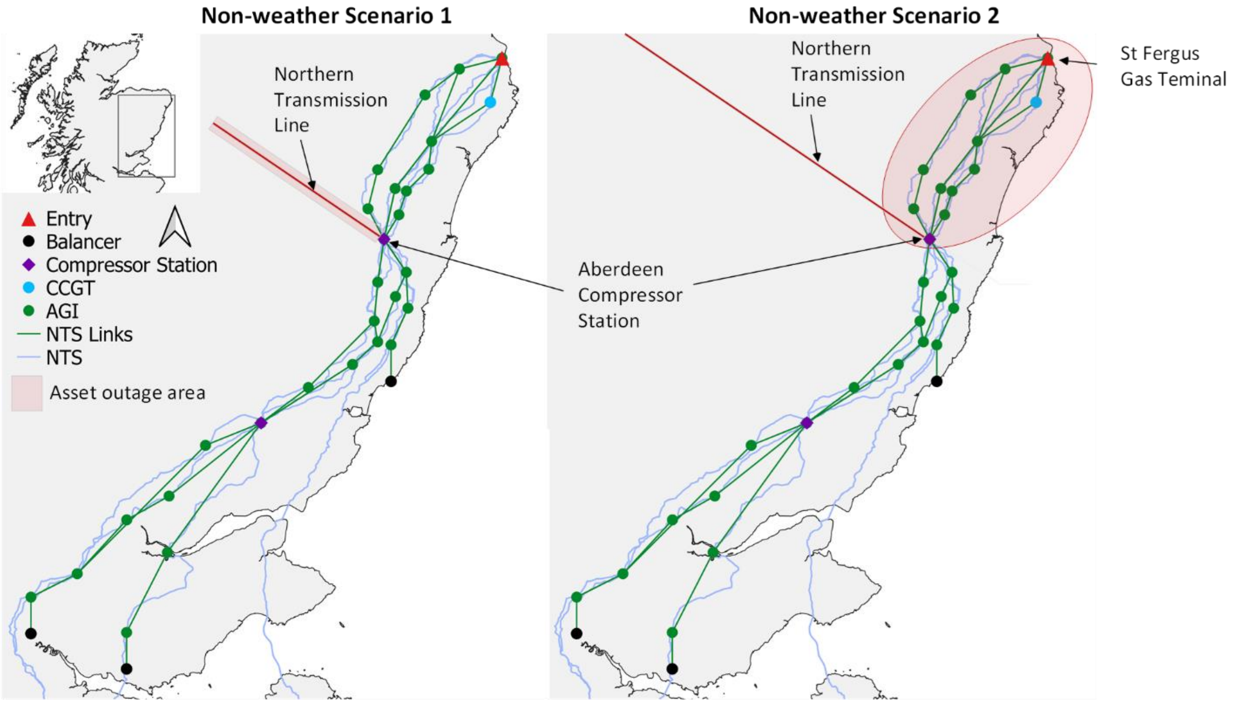

Figure 14: Failed assets in Non-weather Scenario 1 (Northern Transmission Line Outage – left panel) and 2 (St Fergus Gas Terminal Supply Loss – right panel).

The simulated duration of both scenarios was 4-days, aligned with a historic gas outage of roughly 4-days at Falkirk, due to a distribution level regulator outage [37]. Each of the scenarios took less than two-minutes to run on a standard 1.70GHz i5 CPU machine with 16.0 GB RAM.

4.2.1 Results

Figure 15 demonstrates the number of domestic customers and customers in vulnerable circumstances disconnected from their gas supply due to the non-weather scenarios. Figure 16 highlights the number of schools and non-domestic customers disconnected from their gas supply, for both the non-weather scenarios. Figure 15 and Figure 16 demonstrate the impacts of Scenario 2 are more severe. The results from both scenarios are summarised below in Table 8.

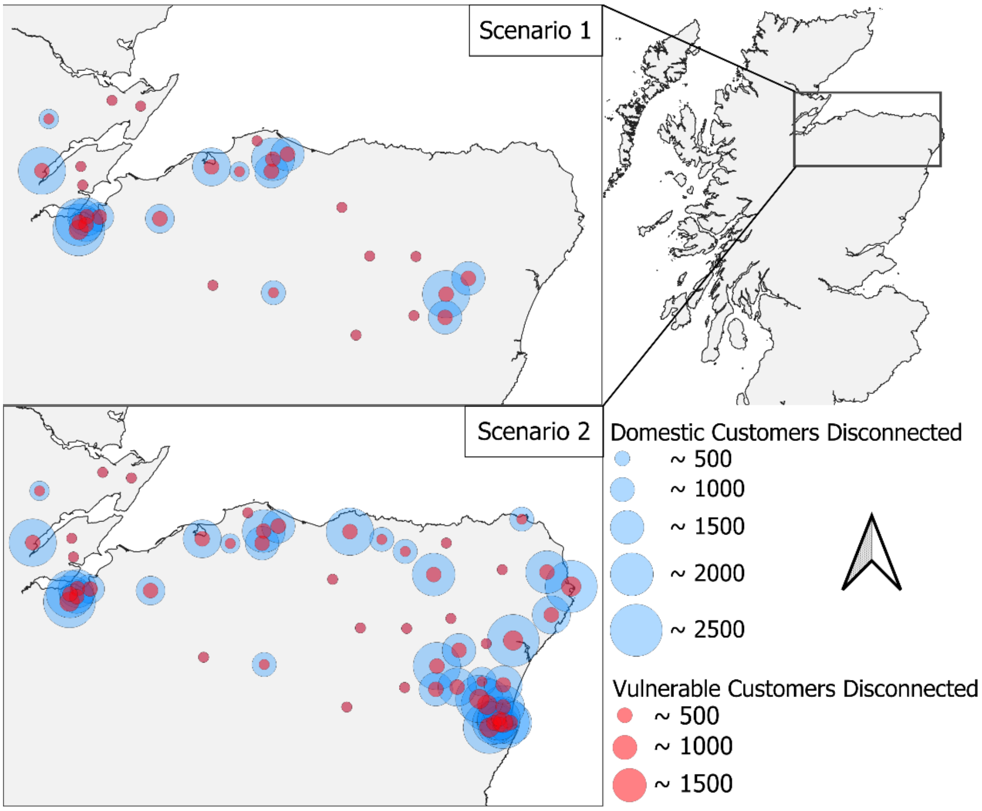

Figure 15: Domestic customers disconnected from gas supply for the non-weather scenarios.

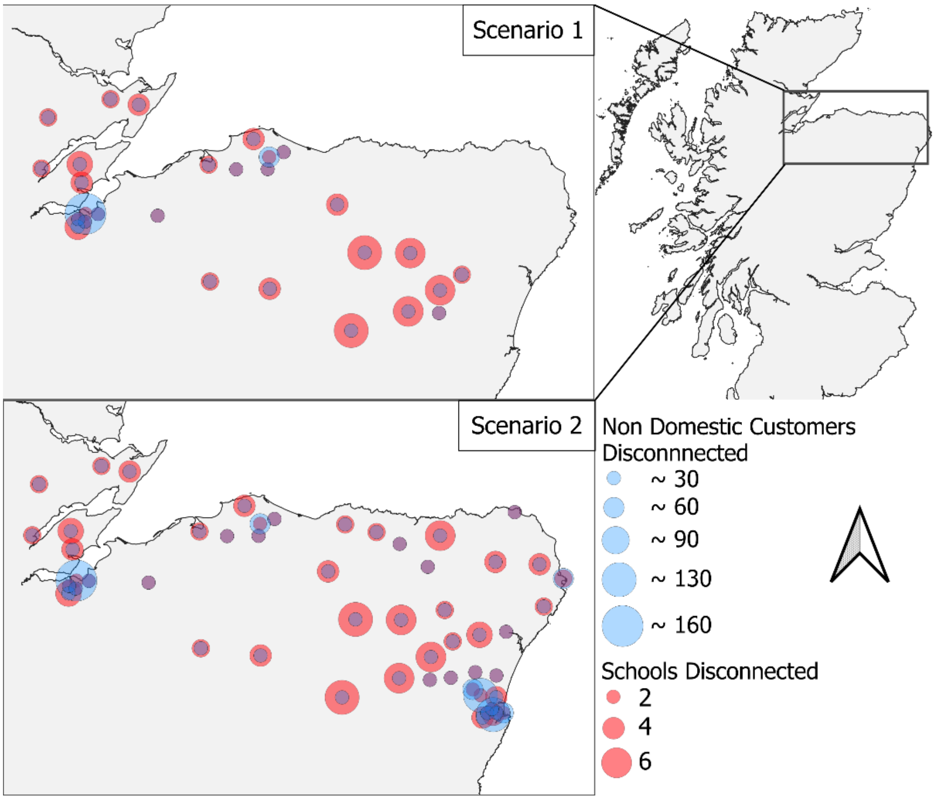

Figure 16: Non-domestic customers and schools disconnected from gas supply for both non-weather scenarios.

Table 8: Summarised results for the non-weather scenarios

Scenario	Customers disconnected	Customers disconnected in vulnerable situations	Energy not supplied (MWh)	Schools disconnected from gas supply	Cost of energy not supplied (£)
1) Northern Transmission Outage	25,870	6,000	39,000	95	7,319,000
2) St Fergus Supply Loss	69,910	15,700	68,300	162	18,899,000

Further analysis of the results, presented in Table 9, illustrates that despite the significantly lower number of non--domestic gas customers experiencing disconnections they represent the majority of the energy not supplied and VoLL. For the scenarios studied there was a disproportionate effect of disconnections on non-domestic users, due to their greater energy demands, which implies that critical infrastructure and commercial or industrial consumers should be considered for further analysis and when determining the potential benefits of developing this resilience modelling capability further. As detailed previously in Section 3.7.3, further investigation is necessary to ascertain precise values of the VoLL for gas, as its application within the gas sector is not as widespread as in the electricity sector.

Table 9: Break down of results between domestic and non-domestic.

Non-weather Scenario	Number of domestic consumers off gas (property)	Domestic energy not supplied (MWh)	Number of non-domestic consumers off gas (site)	Non-domestic energy not supplied (MWh)
1) Northern Transmission Outage	25,500	9,900	370	29,100
2) St Fergus Supply Loss	66,000	28,700	910	39,600

4.2.2 Gas and electricity interactions

Outages on the gas network have two primary effects on the electricity network: reduced flexible generation capacity from CCGT and increased electrical demand from space heating. Depending on the duration of the gas outage, vulnerable consumers are provided with electric heaters [38], and it is anticipated that other consumers will resort to electric heating to compensate for their loss of heating. This leads to an increased load on local electricity distribution substations.

The prototype resilience model was used to re-simulate the non-weather extreme event scenarios with the inclusion of the mitigation approach that transfers customers to temporary electric heating. We assumed, based on analysis done of UK home gas consumption [27], 77% of domestic gas demand was for space heating purposes and we ran the scenarios during a typical winter peak electricity demand load. In Scenario 1, the analysis revealed that demand would surpass the capacities of 29 primary substations which provide electricity to 73,000 customers. Scenario 2 resulted in a more severe outcome of 57 substations surpassing capacity, which provide electricity to 157,000 customers.

Therefore, in both scenarios there is the potential for customers being disconnected from not only the gas network but the electricity network as well. These findings are illustrated in Figure 17 below.

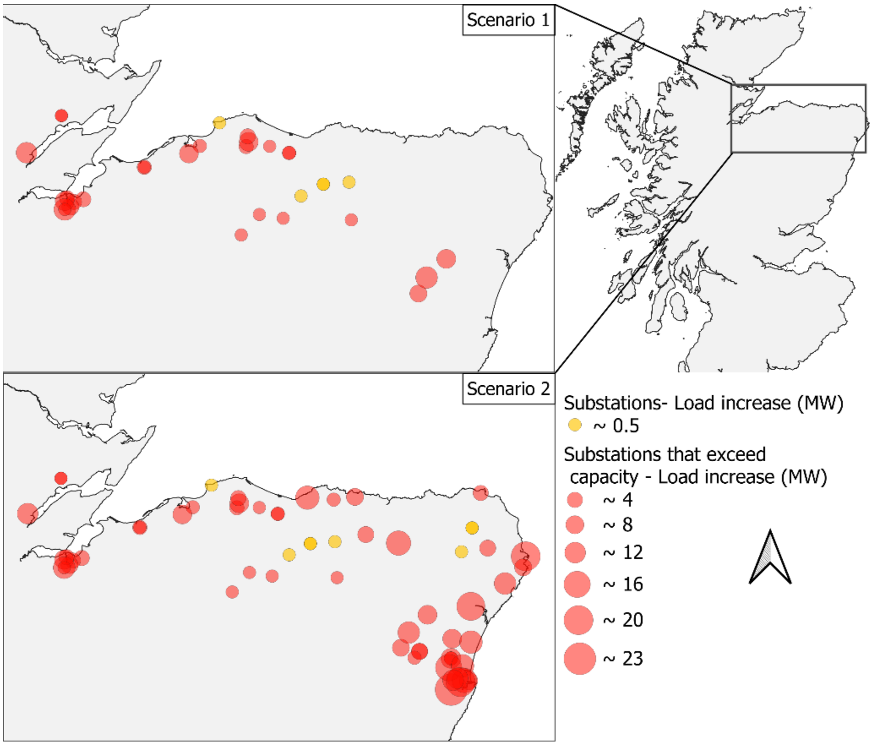

Figure 17: Predicted increase in primary substation loads for non-weather scenario 1 and non-weather scenario 2 with P99 demand levels.

The findings presented in Figure 17 are observed solely under scenarios of exceptionally high demand within both the electricity and gas networks. Should a median demand value be applied to both networks, our analysis reveals no instances of substations exceeding their capacity.

4.3 Prototype Resilience Modelling Summary

Through the creation of a model architecture to efficiently simulate different types of resilience events on a subsection of the whole GB energy system we demonstrated it was possible to:

- Calculate the effect of extreme events based on customer focused metrics, including: vulnerable customers disconnected, energy not supplied and its associated cost.
- Run a range of extreme scenarios for comparison and analysis within sensible timescales (weather and non-weather scenarios ran in under 0.5 minutes and under 2 minutes respectively).
- Begin modelling some of the cascading effects of outages by considering line ratings on the electricity transmission system to understand where demands cannot be met due to line failures and maximum capacities.
- Capture the interactions between the gas and electricity networks in a whole system model.

The following insights have been drawn from the prototype resilience model analysis:

- After testing the resilience modelling framework, including scenario development, analysis and whole system energy resilience modelling, the prototype performed sufficiently well for SSEN’s network area, suggesting that the project will succeed if extended to a larger scale GB model.

- Due to the substantial uncertainty in various parameters such as recovery times, effects on demand and generation, and failure rates, a stochastic method will be needed to better understand the reasonable worst case for a given extreme event scenario.
- Our resilience model prototype showed some accuracy with the Moderately Severe Weather Scenario providing numbers of customers lost similar in magnitude to those seen in Storm Arwen [36]. However, reasonably detailed analysis work may be needed to develop realistic and accurate scenario input values for each kind of extreme event.
- Non-weather mechanical failures in regions upstream of important high-pressure distribution, or LTS, systems can cause significant interruptions downstream, impacting gas network consumers.
- A disruption in gas supply to domestic homes could potentially overload the electricity network if the demand for space heating is transferred to the electricity network from gas.
- The PyPSA package selected for use in the prototype energy resilience model was able to adequately calculate the effects we needed for these scenarios, but there may be ways to further optimise its use within the project by purchasing access to faster commercial optimisers. Due to the modular way we have designed the resilience model, it should also be possible to swap out the PyPSA model for a commercial solution such as PLEXOS [8], or others that are developed in the future.
- Whilst appropriate for this stage in the project lifecycle concerned with prototyping the solution, the set up and running the resilience model is currently a manual process that is only possible to do if you are comfortable developing and running relatively complex Python code. In future, significant, but feasible, effort will be needed to turn this capability into a flexible tool that allows ESO to run resilience scenarios for the whole of GB and investigate outcomes and mitigation measures across a range of extreme events.

5 Beyond Alpha

Table 10 below summarises areas of functionality that our investigative development work to date has revealed should be considered in any future development task to realise the expected benefits of a national whole system resilience model.

Table 10: Beyond alpha functionality in the resilience model required.

Functionality Challenge or Opportunity	Recommendations, Considerations and Activities
Outcome confidence	We ran the model using a deterministic approach for both weather-related and non-weather scenarios. This revealed that, due to the substantial uncertainty in various parameters such as recovery times, effects on demand and generation, and failure rates, adopting a stochastic method is needed to define a reasonable worst case scenario outcome with confidence. This method involves switching from fixed values to probability distributions, such as fragility curves for failure rates and distributions for recovery times. Furthermore, validation of the model components and review by expert independent panel will improve confidence and trust in the results.
Network definition	The prototype model was built to explore the as-is energy network in Scotland. It is recommended that future work build out this network to cover the rest of GB and interconnectors to Europe. Following this, functionality to import a network definition structure will be needed to investigate how system resilience is affected by future network designs.
Intuitive model interface	The prototype model works by command line in Python, since this was adequate for development to date and maximised the time available to test model features. However, once multiple scenarios are being explored and more users are using the model to analyse events, a more intuitive interface for the model will be required and a quality assured process for defining scenarios, network structure, running the model and visualising outputs.
Dynamic outages	Currently, in the resilience model, all outages occur simultaneously, and the failures are directly inputted from the scenario analysis. In the future, additional development is needed to refine how we model not only the pre- and post-event phases but also how we break down the event itself and model it accordingly. This is crucial as some scenarios may unfold over an extended period, necessitating accurate capture within the resilience model.
Cascading failures	Our current prototype resilience model partially addresses cascading outages by considering line capacities, which restrict power flow to prevent thermal overload. However, further efforts are needed in this area, as it's acknowledged cascading failure are one of the primary challenges caused by extreme events on the electricity networks [39].
Ancillary services	In grids experiencing a rise in renewable generation and a decrease in inertia and spinning reserve, resilience is diminishing. It's crucial that the future resilience model consider inertia and other ancillary services to address this challenge effectively.

Functionality Challenge or Opportunity	Recommendations, Considerations and Activities
Gas and electricity interactions	In the prototype resilience model, we have identified certain interactions between the gas and electricity networks. However, there is a need for further integration to encompass additional interactions between these energy networks. This includes assessing the dependence of Pressure Reducing Stations (PRS) and Governor systems on electricity, as well as examining the extent to which a gas outage influences electricity demand.
Hydrogen networks	We do not currently model hydrogen. However, we may want to model potential future networks in which we will see an increase in the number of direct interfaces between gas and electricity networks, resulting in more significant whole-system cross-vector operational considerations during extreme events.
Evaluation of energy software and packages	Once we have determined the scope of our evaluation regarding cascading outages, dynamic failures, and cascading failures, it will be necessary to assess the software requirements and ascertain whether PyPSA remains the best-suited package. Even if PyPSA remains preferred, it may be beneficial to deploy a faster commercial optimiser to solve the energy dispatch calculations.
Data acquisition and security	Additional data is necessary to enhance customer-focused outputs. However, caution is warranted as this data may become sensitive, depending on the granularity chosen for the resilience model, so development must be carried on appropriately secure IT infrastructure.
Scenario development feedback loop	It was identified during this prototyping stage that the resilience model may be put to use in different ways to support the same goal of understanding energy system resilience. As well as the approach described to date (using human judgement to define extreme event scenarios and testing them using the model), the model can be put to work searching for weaknesses in the system. This approach could provide insights into where unexpected extreme event scenarios might occur in future, which can be used to develop a better energy system risk register, alongside human judgement and past scenarios. Reinforcement learning is one approach to achieving this goal and it is recommended that this is explored to maximise the benefits of a developed model.

6 Conclusions

Within work package four of the Scenarios for Extreme Events project we have developed a resilience model architecture that allows ESO to calculate resilience metrics (focussed on consumer outcomes) for a subset of the GB whole energy system (gas and electricity). This resilience model sits within a larger analysis framework that will allow ESO to quantitatively evaluate GB whole energy system resilience risks to supplement qualitative resilience assessments. This has not previously been achieved and will not only provide a much greater level of insight for identifying and prioritising risk to enhance resilience but also facilitate the detection of any inconsistencies in the level of resilience across the GB whole energy system. Such insights are crucial for pinpointing opportunities to develop resilience standards and establish possible impact reduction measures.

The modelling approach prototyped in this phase of the project and described in this report will allow resilience scenarios to be efficiently analysed by interpreting the type of scenario, which system components it affects, and therefore which modelling calculations are required to simulate the outcomes. Calculations within the resilience model are only carried out at the minimum granularity required to increase the speed to the analysis, opening the possibility for probabilistic modelling and optimisation approaches to provide greater insights in future developments.

Through the prototyping work carried out in this phase of the project we are now able to proceed with much greater confidence into any future development work, having de-risked some of the key challenges, namely:

- **Demonstrating that it is possible to develop a fast-running, whole energy system model that calculates the effect of severe shocks to the electricity and gas network infrastructure, including interactions between them.** We have successfully developed an energy generation, demand, transmission and distribution model for North Scotland, which has been subjected to stress tests encompassing both weather-related and non-weather-related scenarios. The resilience model effectively simulates the interactions between electricity and gas through CCGTs and consumer space heating demand. The resilience model has been designed to assess hazards in a computationally efficient way, completing the scenarios used in testing in under two minutes.
- **Demonstrating methods to calculate customer focused outputs from whole energy system level calculations**, such as customers in vulnerable situations disconnected, customers disconnected, and critical services disconnected.
- **Demonstrating that an innovative simulation scaling approach can be used to model a variety of scenarios quickly at different levels of granularity**. We developed energy models for both the distribution and transmission networks for gas and electricity. To conserve computational resources, not all models are activated for every hazard scenario. Instead, the prototype resilience model assesses the necessary level of granularity for each scenario and selectively runs the appropriate energy models.
- **Demonstrating that the approach is capable of modelling outages caused by transmission line overloads where network constraints are reached.** We modelled line capacities in the prototype model using the PyPSA software, so that initial outages may cause some lines to become overloaded and further outages occur. Further investigation is required to comprehensively understand and integrate other mechanisms that could cause cascading outages, such as frequency instabilities, into the resilience model.

We also identified a new opportunity for the model:

- Automatically searching for weaknesses in the system by calculating the effect of breaking components and training an AI agent to search for severe outcomes. This approach could provide insights into where unexpected extreme event scenarios might occur in future, which can be used to develop a better energy system risk register, alongside human judgement and past scenario data. Reinforcement learning is one approach to achieving this goal and it is recommended that this is explored in future to maximise the benefits of a developed model.

A series of features for future development have been recommended alongside the opportunity described above, including developing a probabilistic output to capture confidence in the results, expanding the prototype to whole of GB and including additional system components. In summary, this project marks a significant milestone in modelling extreme events, facilitating open and transparent dialogue between industry and government. It identifies opportunities to develop resilience standards and measures to reduce impact. This work package specifically has significantly reduced risks associated with future developments in this capability.

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Annex A - Model Status Report

A.1 Model status summary

Version name and date:	Prototype resilience model v0.1 March 2024
Core model components:	PyPSA gas and electricity transmission models. Radial distribution models developed in Python. Basic model logic framework to efficiently run scenarios based on type.
Model scope:	SSEN's area in Northern Scotland
Model owner:	Chris Williams (Frazer-Nash Consultancy) Jenna Macgregor (ESO)
Verification and testing activities undertaken:	Self-checking and basic peer checking for key functionality. No level of quality assurance is claimed for this model version.
Validation activities undertaken:	Results from the moderately severe weather scenario have been compared to Storm Arwen and are comparable within an order of magnitude check.
Claimed accuracy of results:	No claim is made on the accuracy of the modelling results at this stage in model development.
Language and versions:	Python version 3.12.1
Version control system:	Git
User interface maturity:	None

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