Modelling the future GB power system

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Contents

[Contents 2](#_Toc146539471)

[Abstract 4](#_Toc146539472)

[Declaration of originality 5](#_Toc146539473)

[Intellectual property statement 6](#_Toc146539474)

[Acknowledgements 7](#_Toc146539475)

[1 Introduction 8](#_Toc146539476)

[1.1 Background and motivation 8](#_Toc146539477)

[1.2 Aims and objectives 10](#_Toc146539478)

[1.3 Report structure 11](#_Toc146539479)

[2 Literature review 12](#_Toc146539480)

[2.1 Introduction **Error! Bookmark not defined.**](#_Toc146539481)

[2.2 Detail **Error! Bookmark not defined.**](#_Toc146539482)

[2.3 More detail **Error! Bookmark not defined.**](#_Toc146539483)

[2.4 Summary **Error! Bookmark not defined.**](#_Toc146539484)

[3 Methods 22](#_Toc146539485)

[3.1 Introduction **Error! Bookmark not defined.**](#_Toc146539486)

[3.2 Detail **Error! Bookmark not defined.**](#_Toc146539487)

[3.3 More detail **Error! Bookmark not defined.**](#_Toc146539488)

[3.4 Summary 39](#_Toc146539489)

[4 Results and discussion 40](#_Toc146539490)

[4.1 Introduction 40](#_Toc146539491)

[4.2 Detail 40](#_Toc146539492)

[4.3 More detail 41](#_Toc146539493)

[4.4 Summary 41](#_Toc146539494)

[5 Conclusions and future work 42](#_Toc146539495)

[5.1 Conclusions 42](#_Toc146539496)

[5.2 Future work 42](#_Toc146539497)

[References 42](#_Toc146539498)

[Appendicies 43](#_Toc146539499)

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Abstract

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# Introduction

This chapter provides the background, context, and purpose of the project, highlighting the challenges facing the Great Britain (GB) power system during the ongoing energy transition. The GB power system is experiencing rapid change, shaped by evolving patterns of generation and demand as well as the wider transition towards a low-carbon future. Continuous investment across the transmission and distribution networks means the system is in a state of ongoing development, with its configuration and capabilities gradually adapting to new requirements.

In this context, the chapter introduces the motivation for adopting a modelling approach that can be automated and adapted to changing data and system conditions. It sets out the project’s aim and objectives and explains how the work supports future energy scenario analysis. The chapter also outlines the scope and intended outcomes of the study, while providing a foundation for the methodology and analysis presented in later chapters.

## Background

The Great Britain (GB) electricity transmission network is the backbone of the national power system. It carries electricity from large power stations and renewable generation sites to the regional distribution networks that supply homes and businesses. The onshore network is managed by three Transmission Owners (TOs): National Grid Electricity Transmission (NGET) in England and Wales, SP Transmission (SPT) in southern Scotland, and Scottish Hydro Electric Transmission (SHE Transmission) in northern Scotland. Since 2019, overall coordination has been carried out by the National Energy System Operator (NESO), which is responsible for balancing supply and demand and keeping the system secure [1]. Offshore Transmission Owners (OFTOs) also play an important role by connecting offshore renewable generation, especially wind farms, to the onshore grid.

In recent years, the GB power system has been changing quickly. The retirement of coal plants has almost completely removed coal from electricity generation [2]. At the same time, renewable energy sources such as offshore wind and solar power have grown strongly. For example, renewables supplied around 44% of the UK’s electricity in 2023 compared with only 7% in 2010 [3]. These changes have created new challenges, including more variable generation, new patterns of power flows, and the need for greater flexibility in the system [4].

To support this transition, there has been very high investment in the transmission network. One example is a £58 billion programme to expand capacity and build new high-voltage routes that will carry electricity from areas of high renewable generation in Scotland to centres of demand in England [5]. The energy regulator, Ofgem, has also approved £4 billion of investment to speed up grid upgrades and help meet the government’s clean energy targets for 2030 [6]. These investments show that the transmission network is not static but is constantly developing in response to new requirements.

This shows that the GB power system is undergoing continuous change, shaped by decarbonisation, decentralised generation, and large levels of network investment. Because of this, there is a clear need for approaches that can represent the system in a way that captures both its current state and how it is evolving. Such approaches provide the basis for future energy scenario analysis and long-term planning.

## Motivation

Models allow engineers and planners to understand how electricity flows across the network, identify potential bottlenecks, and evaluate the effects of different generation and demand scenarios. Recognising these constraints is important not only for maintaining secure operation but also for guiding long-term investment planning, for example through processes such as the Network Options Assessment (NOA). As the system becomes more complex, with higher shares of renewable generation and more variable power flows, modelling approaches must be adaptable and able to test multiple scenarios efficiently, as highlighted in the Future Energy Scenarios (FES) [7]. Such models are vital not only for planning and operational decisions but also for research that supports future policy and investment. Developing a model that is detailed, automated, and reproducible is therefore essential to address these challenges and provide a reliable tool for scenario and security analysis.

## The Research Problem

Even though data and modelling tools are available, building a detailed and repeatable model of the GB transmission system is still difficult. Many existing models are proprietary, hard to adapt, or need very powerful computers. This makes them hard to use for testing different future scenarios or for research outside the organisations that built them. As a result, there is a gap between the data that exists and the ability to use it in practice.

What is missing is a framework that can take large, publicly available datasets and automatically create a consistent and reproducible system model. Such an approach would reduce manual effort, minimise errors, and make it possible to study hundreds of scenarios efficiently. It would also ensure that models can be updated quickly as new data becomes available, making them more relevant for long-term planning. This study addresses that gap by developing an automated modelling framework for the GB transmission system, designed to be open, scalable, and directly applicable to scenario-based analysis.

## Aims and Objectives

The aim of this study was to develop and validate an automated model of the Great Britain transmission network using an open-source tools and public data, to enable scenario analysis and network security assessment.

The main objectives of this study were:

* To review and select a suitable modelling approach and tool for power flow and transmission network studies.
* To collect, extract, and process transmission network data, including lines, transformers, generation, and demand.
* To construct and automate the creation of a GB transmission system model using the selected tool.
* To validate the model against published system characteristics or reference data.
* To use the model to identify transmission lines that constrain the network and the FES conditions where N-1 security is not maintained.
* To produce documentation that ensures the model can be reused, reproduced, and extended in future work.

## Scope and Limitations

This study focuses developing an automated model of the Great Britain transmission network using an appropriate power flow approach. The work is limited to steady-state analysis and does not include detailed voltage behaviour, dynamic system responses, or integration with real-time control systems.

## Thesis structure

This thesis is comprised of five main body chapters.

Chapter 1 introduces the study. It explains why modelling the GB transmission network is important, outlines the aim and objectives, and defines the scope and limitations. The structure of the thesis is also presented.

Chapter 2 reviews and evaluates different modelling approaches and tools for automating the GB transmission network. It considers their strengths and limitations, before identifying the most suitable option. The chapter also discusses existing studies that have applied transmission system models and scenario-based analysis to the GB network.

**Chapter 3** sets out the methodology. It explains how the modelling framework was developed, including the use of public datasets, the automated creation of the network, and the steps taken to reproduce and validate the model. The procedures for scenario exploration and basic security studies are also outlined.

**Chapter 4** presents the results. The emphasis is on validation, showing that the model accurately reproduces network behaviour, with selected analyses included to demonstrate its capability for scenario-based studies when required.

**Chapter 5** concludes the thesis. It summarises the key findings, reflects on the effectiveness and limitations of the modelling framework, and places the work in the wider context of energy system research. The chapter also outlines directions for future extensions and opportunities for collaboration with industry and academia.

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# Background Research

This chapter reviews the literature relevant to automating the creation of a model of the GB transmission network. It introduces key concepts in power system modelling, compares different approaches and tools, and considers their strengths and limitations. The chapter also discusses previous studies on transmission system modelling and scenario analysis, highlighting how they inform the approach taken in this study.

## Need for Automated GB Transmission Modelling

While there is extensive literature on power system modelling and optimal power flow, very few studies focus on the automation of model creation for the Great Britain (GB) transmission network. Existing research on GB often relies on proprietary models or reduced-order representations. For example, Lyden *et al.* [8], [9] introduced PyPSA-GB, which provides a 29-bus and zonal representation for scenario studies. Such models are valuable for high-level planning and policy analysis but do not capture the full network detail of the GB transmission system. This leaves a gap for automated, high-resolution modelling that can link directly to large datasets and support systematic, reproducible scenario analysis.

Synthetic test systems such as those developed by Birchfield et al. [10] demonstrate how large, openly available transmission models can be constructed for research and benchmarking purposes. However, these are generic in design and do not reflect the specific characteristics of the GB system. Other studies use Future Energy Scenarios (FES) data to explore flexibility or renewable integration [11], but they typically focus on high-level system behaviour rather than automating the translation of public datasets into detailed transmission models.

As a result, there remains a clear gap in the literature: no study has yet demonstrated a fully automated framework that builds a detailed, reproducible model of the GB transmission system directly from large, publicly available datasets. Such a framework would bridge the gap between data availability and practical usability, making it possible to test hundreds of scenarios efficiently and consistently.

This gap is particularly significant because the GB transmission system is both large and rapidly evolving, with major changes in its generation mix and power flow patterns. These challenges underline the need for modelling approaches that are not only technically sound but also adaptable and automated.

## The Great Britain Transmission System

The Great Britain (GB) transmission network is among the most extensive and technically demanding in Europe. It spans long geographical distances, interconnecting diverse regional demand centres with major generation hubs. Much of the system is characterised by strong regional imbalances: renewable generation, particularly offshore wind, is concentrated in Scotland and along the east coast, while the highest demand is centred in the Midlands and South of England. This creates substantial north–south power transfers across the system [12].

The rapid expansion of renewable generation has amplified these flows, adding variability and uncertainty to system operation. Offshore wind, now the largest single source of new capacity, can fluctuate significantly over short timescales, while solar power introduces its own diurnal and seasonal patterns. These resources are often located far from demand centres, placing additional strain on transmission corridors. As a result, congestion has become a recurring feature of GB system operation, leading to redispatch actions and high curtailment costs [13].

Alongside congestion, the reduction in synchronous generation poses new operational challenges. With coal plants retired and gas generation operating more flexibly, system inertia has fallen, making the network more sensitive to disturbances. Maintaining stability and security of supply in this context requires careful planning and a clear understanding of how the system will evolve [14].

These characteristics underline the need for robust modelling of the GB transmission network. By capturing the relationships between generation, demand, and network constraints, modelling provides a means to evaluate system adequacy, assess the impacts of new generation patterns, and explore future scenarios. Such studies form a key part of long-term planning and are central to understanding how the GB system can meet its decarbonisation and security objectives.

## Power System Modelling Approaches

Power system modelling can take many forms depending on the questions being asked and the timescales of interest. As shown in Figure 2.1, these approaches span a wide spectrum, from fast transient studies to slower steady-state methods

A diagram of a diagram

Description automatically generated with medium confidence

Figure 2.1: Timescales in power system studies (adapted from [15]).

At the fastest timescales, electromagnetic transient models capture events in the order of microseconds to milliseconds, such as switching actions or the initiation of faults, and are mainly applied to protection and equipment-level studies [16]. At intermediate timescales, electromechanical or dynamic models, which run from seconds to minutes, are used to examine system stability, including frequency response and oscillations [17].

At the steady-state level, models represent the balance of generation and demand under normal operating conditions. They are widely applied in transmission planning, system loading studies, and assessing long-term network adequacy . Because they provide a clear and consistent picture of how electricity flows across the grid, steady-state models form the foundation for most planning and operational studies. This leads to **power flow analysis**, which has become a fundamental tool in power system engineering.

### Power Flow Analysis

Power flow analysis is one of the most widely used techniques in power system engineering. Its purpose is to determine the steady-state operating condition of the network by solving a set of algebraic equations that link power injections, voltages, and line flows. The key equations are derived from Kirchhoff’s laws and can be written in the form:

where ​ and ​ are the active and reactive power injections at bus , is the voltage magnitude, is the angle difference between buses, and , are the conductance and susceptance terms of the admittance matrix [18].

The set of equations describe how active and reactive power injections at each bus are related to bus voltages, angles, and the admittance matrix of the network. In practice, solving these nonlinear equations requires numerical methods that process known inputs to determine the unknown system state. This workflow is illustrated in Figure 2.2, where network data, generation data, and load demand are supplied to a power flow method, which then produces outputs such as bus voltages, line flows, and system losses.

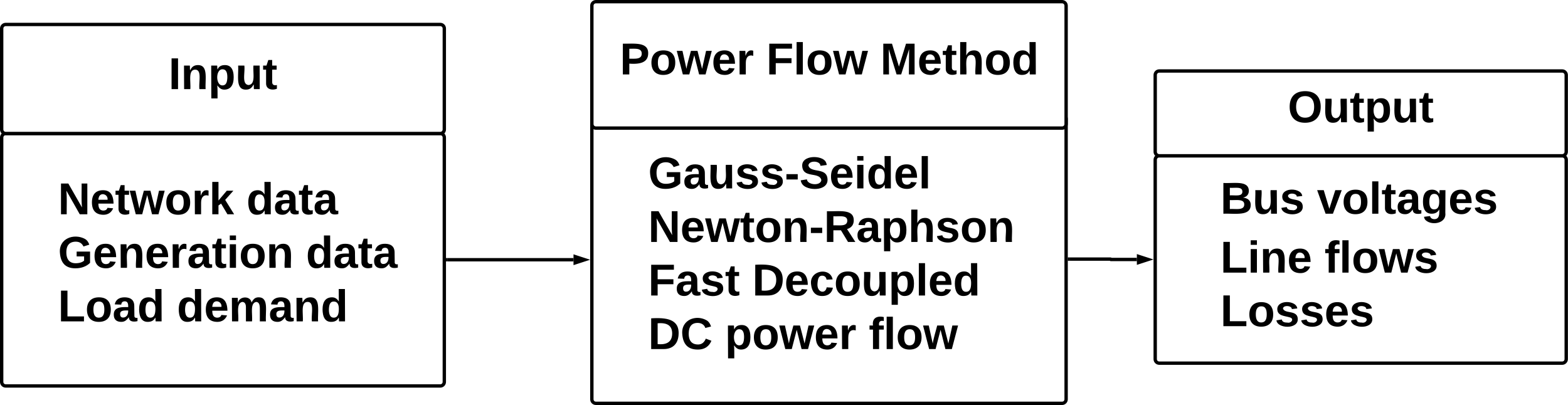


Figure 2.2: Power flow workflow

While the general formulation is common, different simplifications can be applied when carrying out the analysis. These lead to two widely used forms: AC power flow and DC power flow.

### AC and DC Power Flow

AC power flow uses the full set of nonlinear equations for ​ and above. It gives detailed information on both active and reactive power flows, voltage magnitudes, and system losses. For studies involving voltage stability, reactive power planning, or frequency support, AC analysis is essential. However, solving AC equations for a large network like Great Britain is computationally demanding and often requires advanced iterative methods such as Newton–Raphson [19]. The Fast Decoupled Load Flow (FDLF) method enhances computational efficiency by exploiting the weak coupling between active-power–angle and reactive-power–voltage relationships, though it still requires solving nonlinear equations and thus remains more computationally demanding than linearized approaches [19].

DC power flow is a simplified version that assumes all voltages are close to 1.0 pu, resistance in lines is negligible compared to reactance, and angle differences are small [20]. This reduces the AC equations to a linear form:

where ​ is the line reactance and is the phase angle at bus [21].

By neglecting voltage magnitudes, reactive power, and losses, DC power flow is limited in scope, as it cannot capture voltage profiles, reactive power behaviour, or system losses. Despite this drawback, its main advantage lies in being highly efficient, scalable, and requiring less system data, which makes it practical for large-scale analyses.

For this study, which requires repeated evaluations of active power flows across the Great Britain network under different scenarios, computational efficiency is critical. DC power flow is therefore selected as the more appropriate method, as it captures the active power flows of the network while requiring far less computation, making it suitable for large interconnected systems.

### Optimisation-based Approach

The drawback of standard power flow methods is that they depend on a slack bus to absorb mismatches and ignore operating constraints such as generator limits and thermal line ratings, meaning they do not fully capture real-world conditions [19]. To overcome these shortcomings, optimisation-based approaches extend the power flow framework to include both physical limits and operational objectives.

The simplest of these approaches is Economic Dispatch (ED), which determines the least-cost generator outputs required to meet demand. ED considers generator cost functions and operating limits but does not account for the physics of the transmission network. As a result, a solution that appears economical in theory may be infeasible in practice, since power cannot always be delivered across congested or capacity-limited lines [21].

To address this issue, Optimal Power Flow (OPF) was developed. OPF builds upon ED by combining the economic objective with the physical and operational constraints of the network. In addition to generator cost and output limits, OPF incorporates the power flow equations, thermal line ratings, and in the AC formulation, voltage and reactive power limits. This ensures that OPF produces dispatch schedules that are both economical and physically feasible [22], [23]. The key advantage of OPF is therefore its ability to jointly consider system economics and network security. However, the main drawback is complexity: OPF problems are much more computationally demanding than ED, particularly when based on the full nonlinear AC equations [22].

When incorporating the power flow model, two main variants are considered: AC OPF and DC OPF. AC OPF uses the full nonlinear AC power flow formulation, providing the most accurate results by capturing reactive power flows, voltage magnitudes, and losses. This level of detail is valuable in studies where voltage stability and reactive support are critical. The limitation, however, is that AC OPF is nonconvex and often difficult to solve reliably at scale. Convergence can be slow or even fail under stressed conditions, and the computational burden becomes significant for repeated large-scale analyses [24].

DC OPF, by contrast, applies the simplifying assumptions of DC power flow within the OPF framework. By fixing voltages at 1 pu, neglecting line resistance, and assuming small angle differences, the nonlinear AC equations reduce to a linear form [20]. This makes DC OPF a convex optimisation problem that can be solved quickly and reliably using standard linear programming techniques.

### Cost Modelling with LCOE

To represent generation costs within the OPF, this study adopts the Levelised Cost of Electricity (LCOE), a widely used metric that expresses the average lifetime cost of electricity per unit of output, incorporating capital, operational, and fuel costs [25], [26].

### Selection of DC Optimal Power Flow

DC OPF is adopted in this study because it provides a scalable and reliable way to model active power transfers across a large interconnected system. Its linear formulation ensures fast and robust solutions, avoiding the convergence issues and computational burden of nonlinear approaches. This makes it particularly well suited for repeated scenario analysis, where the network must be evaluated many times under varying conditions. While it does not capture voltage magnitudes or reactive power, these details are not central to the objectives here. Instead, the ability of DC OPF to represent active power flows and congestion patterns with high computational efficiency makes it the most appropriate modelling framework for this work.

## Power System Modelling Tools

Power system studies rely on specialised software to apply power flow and optimisation methods to real networks. These tools implement the numerical solvers, handle system data, and provide the framework for analysing network behaviour. Choosing the right tool is therefore essential to ensure that the modelling approach matches the objectives of the study.

### General Modelling Environments

A wide range of software platforms exist for power system studies, supporting applications from steady-state analysis to dynamic and transient simulations. Widely used examples include **PSS®E**, which has long been applied to transmission planning and power flow studies using Newton–Raphson and fast-decoupled solvers [27]. **DIgSILENT PowerFactory** extends beyond power flow into dynamic and stability analysis, with modules for protection coordination and electromagnetic transients [28]. **ETAP** integrates generation, industrial, and monitoring capabilities within a single environment, while **PSCAD/EMTDC** specialises in electromagnetic transient studies at very short timescales [29].

Most commercial platforms implement both AC and DC power flow, and many also provide **optimal power flow (OPF)** functions. These implementations are primarily designed for operational decision support, typically emphasising AC OPF with limited flexibility to modify formulations. While reliable for routine analysis, they are less suited to research applications where repeated OPF runs and customised formulations are required.

For this study, a critical requirement is the ability to **automate network creation and analysis**. Commercial platforms often rely on graphical interfaces and manual input of network data, which becomes inefficient and error-prone when scaling to large datasets or many scenarios. Scripting-based environments that support automated model generation and batch processing are therefore more suitable, as they allow networks to be constructed and solved consistently across hundreds of scenarios.

### Tools for Optimal Power Flow

Given the need for automation and repeated evaluations, tools developed in research contexts are particularly relevant for optimal power flow studies. Among these, **MATPOWER** and **pandapower** are the most widely used and form the basis of much current academic and applied work.

**MATPOWER** is a MATLAB-based package developed specifically for steady-state operations, planning, and OPF research [30]. It implements AC and DC OPF formulations using Newton-based solvers for nonlinear problems and linear programming for DC cases. Its strength lies in being transparent and extensible, making it a benchmark platform for testing new OPF algorithms. However, its dependence on MATLAB, a proprietary environment, limits scalability and integration with modern data handling workflows. Running large numbers of scenarios or coupling OPF with external optimisation routines can become cumbersome, especially when compared with modern scripting environments.

**Pandapower** was developed to address these limitations by providing a Python-based framework for power system analysis [31]. Like MATPOWER, it supports AC and DC OPF, but its design emphasises automation and integration with data science tools. Networks can be created directly from tabular datasets using the Pandas data structure, which is particularly valuable when handling large interconnected systems. The framework supports repeated OPF evaluations with minimal manual intervention, enabling efficient large-scale scenario analysis. Pandapower also integrates with widely used optimisation solvers: linear programming solvers for DC OPF, and nonlinear solvers such as IPOPT (Interior Point OPTimizer) for AC OPF, giving it both flexibility and scalability [31].

In summary, MATPOWER remains a reference platform for OPF research but is constrained by its reliance on MATLAB. Pandapower extends the same philosophy into Python, offering a modern, data-driven framework that supports automated model creation, scripting, and large-scale analysis. These features make it particularly suitable for studies such as this.

### Selection of Modelling Tool

For this study, pandapower is selected as the modelling environment. Its Python-based framework is designed around automation, allowing networks to be generated directly from data tables and evaluated repeatedly with minimal manual input [31]. This is particularly important for the Great Britain transmission system, where the analysis involves large datasets and multiple scenarios.

Pandapower natively supports DC optimal power flow (DC OPF) through linear programming solvers, making it well suited to studies that require fast and scalable evaluation of active power transfers. Its integration with Python’s numerical libraries enables efficient data handling and scripting, ensuring that results can be reproduced consistently across hundreds of cases.

While commercial tools remain strong in industry applications, the combination of automation, scalability, and reproducibility makes pandapower the most appropriate choice for implementing DC OPF in this study.

## Data-Driven DC OPF Modelling of Transmission Systems

Accurate data is fundamental for meaningful transmission system modelling. For Great Britain, the National Energy System Operator (NESO) Data Portal provides detailed appendices alongside the Future Energy Scenarios (FES), including generation capacities, regional demand profiles, and locational breakdowns essential for realistic network representation. Complementary sources such as the ENTSO-E Transparency Platform offer cross-border exchanges and operational statistics, enabling analysis of the GB system in the wider European context.

In this study, DC Optimal Power Flow (DC OPF) is implemented using the pandapower framework, which integrates structured datasets with computationally efficient modelling. This approach allows large-scale scenario analysis of active power flows, congestion, and system adequacy to be performed consistently and reproducibly. By embedding DC OPF within a Python-based environment, the workflow remains adaptable to evolving datasets and scalable for testing hundreds of FES-driven scenarios with reduced computational burden compared to AC formulations.

## Future Energy Scenarios

The Future Energy Scenarios (FES), published annually by the National Energy System Operator (NESO), present different possible pathways for how the GB energy system might develop under varying policies, technologies, and consumer behaviours [32]. They are not forecasts, but rather structured scenarios that are widely used in policy and academic work to explore long-term challenges. The supporting datasets include projections of generation capacity, regional demand, fuel mixes, and assumptions about electrification, making them an important resource for examining future system conditions.

In this study, the modelling framework is used to bring FES data into transmission system analysis, showing how these scenarios can be explored in a structured and transparent way [33], [34]. However, given the scope of this project, only selected aspects of the FES are analysed, serving primarily to demonstrate the applicability of the modelling approach rather than to provide an exhaustive scenario comparison.

## Critical Comparison of Previous Work on GB Modelling

Although power system modelling has a long history, relatively few studies have focused on openly available, high-resolution modelling of the Great Britain (GB) transmission system. Existing work tends to fall into three broad categories: simplified zonal models, detailed but proprietary models, and synthetic test systems.

One of the most notable open-source contributions is **PyPSA-GB**, developed by Lyden et al. [33], [35] which provides a 29-bus zonal representation of the GB system. Its strength lies in accessibility and ease of use for policy and scenario studies, but its zonal structure inevitably masks detailed network constraints, such as congestion on specific transmission corridors. The model is therefore more appropriate for long-term strategic planning than for operationally relevant analysis.

By contrast, **Imperial College London** and other academic institutions have developed detailed models of GB transmission for specific studies, often focusing on renewable integration or flexibility requirements [36]. These models typically use data from the National Grid ESO (NGESO) and employ AC power flow or OPF methods [36]. However, they are usually developed for one-off studies, remain proprietary, and are not released in a form that can be reproduced or automated by others [37].

The **NGESO itself** maintains proprietary planning and operational models, which are the most detailed representations of the GB system [38], [39]. While these form the basis of network planning decisions, they are not openly available and require commercial licences to access. As such, they cannot serve as a basis for reproducible academic research.

A third category is represented by **synthetic systems**, such as those of Birchfield et al. [40], [41], [42], [43], [44], [45], [46], [47], [48], which construct large test networks with realistic statistical properties. These are openly available and valuable for benchmarking algorithms, but they are generic in design and do not reflect the specific characteristics of the GB system, such as strong north–south flows or the rapid expansion of offshore wind.

Table 2.1:High-level comparison of representative GB models:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model / Source** | **Resolution** | **Openness & Data Basis** | **Reproducibility** | **FES Scenario Use** |
| **PyPSA-GB** | Zonal  (29-bus) | Open-source, ESO/FES public | Reproducible, manual updates | Good for policy, not detailed flows |
| **Imperial models** | Bus-level (detailed) | Proprietary,  ESO data | Limited, one-off | Scenario-focused, not repeatable |
| **NGESO tools** | Full bus-level | Proprietary, internal ESO | Not reproducible | Official planning, not research |
| **Synthetic systems** | Bus-level (generic) | Open-source, synthetic | Fully reproducible | Benchmarking only, not GB-specific |
| **This study** | Bus-level (GB-specific) | Open-source, ESO appendices | Automated, fully reproducible | GB-specific, high-resolution analysis |

This study holds a distinct position among existing approaches. Like PyPSA-GB, it is open and reproducible, but unlike zonal models it develops a bus-level representation of GB. NGESO’s proprietary tools are the most detailed but remain inaccessible, and synthetic systems, while useful for benchmarking, are not GB-specific. The novelty lies in combining automation with high resolution to enable repeated and consistent scenario analysis.

## Summary

This chapter reviewed the literature on GB transmission system modelling and the need for automation. It outlined the characteristics and challenges of the GB network, including north–south flows, high renewable penetration, and reduced inertia. Key modelling approaches were introduced, from power flow and OPF methods to DC OPF, with pandapower identified as the most suitable tool for automated, reproducible studies. A critical comparison of existing models showed that zonal, proprietary, and synthetic approaches each have limitations. This study addresses the gap by developing an open, bus-level GB model from public datasets, combining automation with high resolution to enable consistent scenario analysis.

# Methodology

This chapter describes the methodology used to develop a reproducible, high-resolution model of the Great Britain (GB) transmission network using Python and pandapower. The approach is programming-based rather than graphical, meaning that code snippets and pseudo-code are used to illustrate the workflow instead of screenshots or GUI elements. Additional Python libraries, notably pandas, are also employed for data handling. The snippets provided are simplified representations of the actual implementation; the full codebase is documented separately.

## Methodological Framework

The purpose of this methodology is to produce an automated model of the National Grid Electricity Transmission (NGET) portion of the GB transmission system, which can later be scaled to cover the full network. At a high level, the framework:

* Takes structured datasets as inputs.
* Produces a pandapower network object as output.
* Is modular and adaptable for updates or scenario variations.
* Demonstrates reproducibility: the same model can be regenerated by simply providing the source files.

The outputs of this chapter are:

1. A functioning bus-level model of the NGET transmission system.
2. A clear strategy for validation.
3. A framework that demonstrates applicability to scenario exploration.

## Methodological Workflow

The modelling process follows a structured sequence, which is summarised in the workflow presented in Figure 3.1. This flowchart outlines the key stages from dataset selection to validation, providing a high-level overview of how the network model is created.

A screenshot of a computer

Description automatically generated

Figure 3.1: Methodological Workflow for Network Model Creation

Each stage of this workflow is explained in detail in the following subsections, beginning with the selection of suitable datasets and progressing through data preparation, model construction, and validation.

### Data Selection

For this study, the primary data source is the **National Energy System Operator (NESO) Data Portal**, with emphasis on the **Electricity Ten Year Statement (ETYS) appendices**, which provide generation, demand, and network information. Table 3.1 summarises the relevant appendices and their contents.

Table 3.1: ETYS Appendices and Data Used

|  |  |  |
| --- | --- | --- |
| **Appendix** | **Content** | **Key Data Provided** |
| B | Network Data | Substation codes, transmission circuits (lines, cables, series devices), transformers (shunts ignored for DC studies) |
| F | Generation Data | Connection sites, project names, installed capacity (MW), project status (built/unbuilt), plant type |
| G | Demand Data | Node identifiers (bus IDs) and corresponding MW demand values |

To represent interconnections, the **NESO Interconnector Register** is also used, as these assets are essential for validation of cross-border flows. Together, these datasets provide the necessary foundation for constructing a **bus-level model of the GB transmission network.**

### Data Preparation

The ETYS appendices provide the core datasets for this study. Since the methodology is programming-based, the structure of each appendix is important, as column headings determine how data are extracted in pandas (data extraction tool).

**Appendix B – Network Data**

Includes substations, transmission circuits, and transformers (shunt data ignored as not relevant for DC). Examples of each are shown below.

Table 3.2: Transmission Circuit Data

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Node 1** | **Node 2** | **OHL (km)** | **Cable (km)** | **Circuit Type** | **X (% on 100 MVA)** | **Winter Rating (MVA)** | **Summer Rating (MVA)** |
| ABHA4A | EXET41 | 48.785 | 0.000 | OHL | 0.9831 | 2078 | 2078 |
| WTHU4C | WTHU4E | 0.000 | 0.000 | Series Reactor | 1.0000 | 2400 | 2400 |
| BIRK21 | LISD2A | 0.000 | 12.891 | Cable | 0.2978 | 817 | 817 |

Table 3.3: Transformer Data

|  |  |  |  |
| --- | --- | --- | --- |
| **Node 1** | **Node 2** | **X (% on 100MVA)** | **Rating (MVA)** |
| ABHA4A | ABHA11 | 8.4025 | 275 |

Table 3.4: Substation Data

|  |  |  |
| --- | --- | --- |
| **Site Code** | **Site Name** | **Voltage (kV)** |
| ABBA | ABERDEEN BAY WINDFARM | 132 |

**Appendix G – Load Data**

Contains a single sheet listing bus IDs and their demand values in MW, with an example shown below in table 3.5.

Table 3.5: Load Data

|  |  |
| --- | --- |
| **Node** | **24/25 MW** |
| ABHA4A | 41 |

**Appendix F – Generation Data**

Provides generator connection information, including site, capacity, project status, and plant type (important for cost and scenario analysis). An example is given with table 3.6.

Table 3.6: Generation Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Project Name** | **Connection Site** | **MW Connected** | **Project Status** | **HOST TO** | **Plant Type** |
| 17 Acres and BESS | Tealing 275/33kV Substation | 0.00 | Scoping | SHET | Energy Storage System |
| A'Chruach Wind Farm | A'Chruach Wind Farm 275kV Substation | 43.00 | Built | SHET | Wind Onshore |
| Abedare | Upperboat 132kV Substation | 10.00 | Built | NGET | CCGT (Combined Cycle Gas Turbine) |

All data must be structured this way for automated modelling.

### Data Cleaning and Extraction

Once the datasets are identified and structured, the next stage is to prepare them for use in pandapower. This involves extracting the relevant sheets, cleaning the data, and handling missing data to ensure consistency across files.

#### Extraction with pandas

Using pandas, Excel and CSV files can be read directly into Python, with each sheet becoming a dataframe.

# Import the pandas library

import pandas as pd

# Define the file and sheet to be read

document\_name = "ETYS\_B.xlsx"

sheet\_name = "Transformers"

# Read the selected sheet into a dataframe

df\_trafo = pd.read\_excel(document\_name, sheet\_name)

# Columns can be accessed directly, e.g., transformer ratings:

df\_trafo["Rating"]

#### Standard Cleaning Functions

Helper functions are used to harmonise units and prepare data for OPF analysis. All values are converted to a 100 MVA, 400 kV system base.

As pandapower requires line ratings in kA but ETYS provides them in MVA, a conversion function is applied.

# This function converts MVA ratings to kA.

def convert\_mva\_to\_ka(mva\_rating):

ka\_rating = (mva\_rating \* 1000) / (math.sqrt(3) \* 400)

return ka\_rating

# Example

line\_rating\_ka = convert\_mva\_to\_ka(500)

Similarly, a helper function converts reactances from p.u. to ohm/km for use in pandapower.

# Convert reactance from p.u. to ohm/km

def convert\_x\_from\_pu\_to\_ohm\_per\_km(x\_pu, length\_km):

z\_base = (400e3 \*\* 2) / 100e6 # base impedance at 400 kV, 100 MVA

x\_ohm = (x\_pu / 100) \* z\_base # convert from percent to ohms

return x\_ohm / length\_km

Plant types are grouped into broader LCOE categories to ensure consistent cost modelling; the example shown here is not exhaustive.

# mapping plant types for LCOE category

def map\_to\_lcoe\_category(plant\_type):

if plant\_type in ["Onshore Wind", "Offshore Wind"]:

return "Wind"

elif plant\_type == "Solar PV":

return "Solar"

else:

return "Other"

#### Handling Missing Nodes

Not all values are directly available in the raw appendices.

For load allocation, if demand is only given at the regional or substation level, it is distributed evenly across the associated buses. This ensures each bus receives a share of the total demand. The code below illustrates this process.

# Distribute regional/substation load evenly across buses

for substation, total\_load in regional\_load:

number\_of\_buses = len(substation.buses)

load\_per\_bus = total\_load / number\_of\_buses

for bus in substation.buses:

pp.create\_load(net, bus, p\_mw=load\_per\_bus)

Generator nodes are more complex to allocate. In cases where generator buses are not explicitly listed, connection sites are matched against substation names using fuzzy matching, requiring at least an 80% match. Once the substation is identified, the generator capacity is divided evenly among its buses. The pseudo-code below illustrates this process.

# Match generator connection sites to substations using fuzzy matching

for generator in generators:

substation = fuzzy\_match(generator.site\_name, substation\_names, threshold=80)

if substation:

number\_of\_buses = len(substation.buses)

gen\_per\_bus = generator\_capacity / number\_of\_buses

for bus in buses:

pp.create\_gen(net, bus, p\_mw=gen\_per\_bus)

This ensures that generators without explicit bus IDs are mapped to the most likely connection site, preserving network integrity.

### Applying the Network Model

The model is designed to be modular, meaning changes such as adding new generators or updating line ratings can be made without altering the workflow. This modularity mirrors the dataset structure, where generation, demand, and network assets are provided in separate files. It also allows flexibility to handle multiple files of the same type, for example, combining several transformer files into the model automatically.

To implement this, a dedicated script (network.py) was created. The script **initialises an empty pandapower network** and **populates it with buses, lines, transformers, loads, and generators** based on user-provided datasets. In practice, the user only needs to supply the dataset as input; the script automates the creation of the full model, which can subsequently be analysed, as shown in the code snippet below.

import pandapower as pp

from buses import create\_buses

from lines import create\_lines

from transformers import create\_transformers

from loads import create\_loads

from generators import create\_gens

# --- User Inputs ---

network\_file = "ETYS\_B.xlsx"

demand\_file = "ETYS\_G.xlsx"

generator\_file = "ETYS\_F.xlsx"

substation\_sheet = "substations"

transformer\_sheet = "transformers"

line\_sheet = "lines"

load\_sheet = "loads"

gen\_sheet = "generators"

# --- Create Empty Network ---

net = pp.create\_empty\_network()

# --- Build Network Elements ---

create\_buses(net, network\_file, substation\_sheet)

create\_lines(net, network\_file, line\_sheet)

create\_transformers(net, network\_file, transformer\_sheet)

create\_loads(net, demand\_file, load\_sheet)

create\_gens(net, generator\_file, gen\_sheet, substation\_sheet)

# --- Export Results ---

pp.to\_excel(net, "results/network\_results.xlsx") # network res

pp.to\_excel(net, "results/dc\_opf\_results.xlsx") # dc opf res

Running the network.py script executes the full workflow.

The results are exported to Excel files: a network file (network\_results.xlsx) and a DC OPF file (dc\_opf\_results.xlsx), which can then be used for further studies and analysis. The stepwise construction process is reflected in the following subsections, where each function is introduced in detail.

### Creation of Network Elements

This section explains how each element of the network is created from the input datasets.

#### Buses

Create bus nodes from the substation table

**What it does:**

* Reads substation codes/names and nominal voltage.
* Creates pandapower buses and stores a lookup (i.e., bus → id) for later use.

# create\_buses(net, network\_file, substation\_sheet)

def create\_buses(net, xlsx\_path, sheet):  
 v\_base = 400\_000

df\_sub = pd.read\_excel(xlsx\_path, sheet\_name=sheet)

bus\_lookup = {}

for \_, bus in df\_sub.iterrows():  
 # Create buses

bus\_id = pp.create\_bus(net, v\_base, bus\_name)

bus\_lookup[“bus\_substation\_code”] = bus\_id

return bus\_lookup

#### Lines

Add transmission circuits using electrical parameters and end-points.

**What it does:**

* Matches from\_bus and to\_bus to bus IDs.
* Converts ratings to kA where needed.
* Creates transmission elements with X parameters.
* Preserves zero-length connections by assigning a small length.

def create\_lines(net, file, sheet, bus\_lookup):

df\_lines = pd.read\_excel(file, sheet\_name=sheet)

for \_, line in df\_lines():

from\_bus = bus\_lookup.get(line["from\_bus"])

to\_bus = bus\_lookup.get(line["to\_bus"])

length = line["Length\_km"] or 0.01 # Handle zero length

x = convert\_x\_pu\_to\_ohm\_per\_km(x\_pu, length\_km)

ka\_rating = convert\_mva\_to\_ka(line["mva\_rating"])

# Add line to pandapower

pp.create\_line\_from\_parameters(net, from\_bus, to\_bus, length, x, ka\_rating)

#### Transformers

Model transformers between buses as impedances.

**What it does:**

* Creates trafo elements.

# create\_transformers(net, network\_file, transformer\_sheet)

def create\_transformers(net, xlsx\_path, sheet, bus\_lookup):

df\_trafos = pd.read\_excel(xlsx\_path, sheet\_name=sheet)

for trafo in df\_trafos:

x\_pu = trafo["x"] / 100

mva\_rating = trafo["rating\_mva"]

# Add transformer as impedance element

pp.create\_impedance(net, from\_bus, to\_bus, x\_pu, mva\_rating)

#### Loads

Assign demand to buses.

**What it does:**

* Reads node/bus demand (MW).
* Where only substation totals exist, distributes across buses.

# create\_loads(net, demand\_file, load\_sheet)

def create\_loads(net, xlsx\_path, sheet, bus\_lookup, subs\_to\_buses):

df\_loads = pd.read\_excel(xlsx\_path, sheet\_name=sheet)

# Case A: demand per bus directly

if bus\_name in df\_loads.columns:

for loads in df\_loads):

bus = bus\_lookup.get(bus\_name

if bus is not None:

pp.create\_load(net, bus, demand\_mw)

# Case B already described earlier – distribute substation demand across buses

#### Generators

Allocate generation by connection site/plant type.

**What it does:**

* Matches connection sites to substations (using fuzzy matching)
* Splits site capacity across buses at the matched substation.
* Creates generator elements for DC OPF active power.
* Assigns each generator a cost function based on its LCOE category.

# create\_gens(net, generator\_file, gen\_sheet, substation\_sheet)

def create\_gens(net, xlsx\_path, sheet):

df\_gens = pd.read\_excel(xlsx\_path, sheet\_name=sheet)

for gen in df\_gens ():

# Substation identified via fuzzy matching (see earlier section)

# Map plant type to LCOE category (done earlier)

for bus in buses:

pp.create\_gen(net, bus, p\_mw, slack=False)

# Assign linear cost function to generator

pp.create\_poly\_cost(net, element=gen, cp1\_eur\_per\_mw=gen\_cost)

## Validation

The model is validated to ensure it produces plausible results and to demonstrate that it can be applied to FES analysis, generating outputs that can support research and decision-making.

### Validation Requirements

Validation requires a set of reference points against which the model outputs can be assessed. **It begins with a review of the network and DC OPF results to confirm overall plausibility. Additional requirements are then applied:**

* **Using Reference Data:** Validate model outputs by comparing dispatch and boundary flows under comparable loading.
* **Scenario Applicability:** Demonstrate the model in base cases (e.g., winter/summer loading) and standard security studies (N-1).
* **High Resolution:** Use bus-level detail to identify lines which are fully loaded lines, showcasing the model’s fine-grained capability.

### Implementation of Validation

**To implement the validation strategy, two additional elements are introduced:**

**Interconnectors:** Data are taken from the **NESO Interconnector Register** [49], which provides technical and operational details of GB’s main links (e.g., France–IFA, Belgium–Nemo, Netherlands–BritNed, Norway–NSL, and Ireland–EWIC). These are modelled as short line elements with ratings to capture transfer capacity. The operating **mode** can be set manually but does not participate in the DC OPF optimisation.

create\_interconnectors(net, mode=”import”)

**Scottish Power Transmission (SPT) Assets:** A reduced representation of the Scottish network is included for validation. Here, demand and generation are aggregated and connected as single loads and equivalent generators (by plant type) which take part in the DC OPF optimisation. This simplification enables comparison against UK-published boundary flow data while keeping the focus on the NGET portion of the network.

**Running the Program** The validation workflow proceeds as follows:

1. **Run DC OPF**
   1. Execute the optimisation (pp.runopp) to produce generator dispatch and line flows.
   2. Results are collected from net.res\_line and net.res\_gen.
2. def run\_dc\_opf(net):
3. pp.runopp(net, calculate\_voltage\_angles=True, delta=1e-8)
4. return net.res\_line, net.res\_gen
6. **Reference Data Comparison**
   1. net.load is scaled to replicate published operating conditions.
   2. net.load
   3. **Dispatch** is compared against reference generation patterns.
   4. **Boundary transfers** are aggregated and checked against published ESO boundary flows.
7. **Scenario Analysis**
   1. **Base cases:** Winter high demand and summer light demand are applied to confirm model performance.
   2. **Load growth:** net.load is scaled (e.g., +X%) to simulate increasing electrification.
   3. **Renewables growth:** Renewable generation is increased (e.g., +Y%) to simulate higher penetration.
   4. These adjustments are consistent with near-term expectations from FES datasets.
8. def apply\_scenario\_scalers(net, load\_scale=1.10, wind\_scale=1.20):
9. net.load["p\_mw"] \*= load\_scale
10. net.gen.loc[net.gen["name"].str.contains("Wind"), "p\_mw"] \*= wind\_scale
12. **N-1 Security**
    1. A winter base case is used as reference.
    2. Load is incrementally increased to determine the maximum level that can be supported without violations under current network capacity.
    3. For each contingency, the affected line is set out of service, and flows are recalculated. Violations are identified when line loading reaches 100%.
13. def n\_minus\_1\_screen(net, line\_ids):
14. results = []
15. for lid in line\_ids:
16. net.line.at[lid, "in\_service"] = False
17. pp.runpp(net, calculate\_voltage\_angles=True)
18. max\_loading = net.res\_line["loading\_percent"].max()
19. results.append({"outage\_line": lid, "max\_loading\_%": max\_loading})
20. net.line.at[lid, "in\_service"] = True
21. return pd.DataFrame(results)

**Constraint Identification** Across all scenarios, constraints are identified by highlighting lines that become fully loaded. This allows the study to document which corridors are most critical and under what conditions. By working at bus-level detail, the model provides a fine-grained view of network bottlenecks—a key novelty of this study.

### Note on scope

This chapter **demonstrates applicability** using **selected scenarios** to show the framework works with FES-style inputs. Full scenario exploration is outside scope and reserved for future work.

**Some bugs and fixes for the methodology**

**3.6 Summary of Methodology**

This methodology develops a reproducible, programming-based framework for modelling the GB transmission network. Using Python, pandapower, and pandas, public datasets are transformed into a validated bus-level model through a modular, automated workflow. Validation focuses on dispatch patterns, boundary flows, and the model’s adaptability to scenario inputs. While limitations exist, the framework demonstrates that automated, reproducible modelling of the GB system is feasible, laying the foundation for the results presented in Chapter 4.

✅ This gives you a clean skeleton + populated content, with the right level of detail for Chapter 3.

Do you want me to also **draft the flowchart textually** (step-by-step so you can later convert it into a diagram), or just leave it as “Figure 3.1 (flowchart)” placeholder?

# Results and discussion

* **Scenario Applicability:** Demonstrate the model in base cases (e.g., winter/summer loading) and standard security studies (N-1).
* **High Resolution:** Use bus-level detail to identify lines which are fully loaded lines, showcasing the model’s fine-grained capability.

For different cases – identify the loaded lines, the ones which are repeated are the most critical ones

Limitations is that plants like nuclear which do not ramp up are reflected to ramp up explicitly but based on cost functions which does not reflect show a fix for this limitation - temp fix - code snippet

## Limitations and Challenges of the Approach

While DC OPF in pandapower enables efficient and reproducible scenario analysis, several limitations must be acknowledged:

* **Simplifications of DC OPF:** Reactive power, voltage magnitudes, and losses are neglected, while linearised flow assumptions can misrepresent stressed conditions. Stability aspects such as inertia, frequency response, and transients are also excluded.
* **Data-Driven Challenges:** Public datasets (e.g., NESO appendices) often lack full technical detail, requiring assumptions. Aligning generation and demand data to network nodes is non-trivial, and preprocessing large datasets can become the main bottleneck.
* **Economic Representation:** LCOE-based cost functions capture long-term averages but ignore short-term dynamics, ancillary services, and market bidding, limiting realism in operational contexts.
* **Practical Considerations:** High renewable penetration introduces flexibility and reserve issues not represented by DC OPF. Interconnector flows and policy-driven operations are simplified, meaning results reflect least-cost dispatch rather than actual market behaviour.

**In summary**, DC OPF with pandapower is best viewed as an approximation for analysing active power flows and congestion, requiring careful interpretation and, where necessary, complementary detailed studies.

### Network summary

**2. Tables**

1. **Dataset Summary Table (already included)**
   * Could add **number of elements** per type: e.g., 350 buses, 450 lines, 120 transformers.
   * Helps quantify the network’s scale for readers.

## Interconnectors

Interconnectors are represented as controllable injections at dedicated buses within the network. Each interconnector is assigned a maximum transfer capacity based on ETYS ratings, with import flows modelled as generators and export flows as loads. Where specific terminal connections cannot be mapped directly to a known bus, the interconnector capacity is aggregated and distributed across the nearest relevant buses to preserve total system transfer capability. Thermal limits are calculated from the rated capacity to ensure realistic operational constraints. Each interconnector is also assigned a cost function reflecting the economic value of imported or exported power, supporting subsequent optimal power flow and dispatch analyses.

**Interconnector Summary Table**

* Include: | Interconnector | Connected Regions | Max Transfer (MW) | Typical Flow (MW) |

## SPT Assets

SPT assets, representing a mix of generation and storage technologies, are modelled as controllable elements at a dedicated SPT bus. The total SPT load is calculated as the sum of shore-side (SHE) load and SPT-specific load, and applied as a fixed, uncontrollable load at the SPT bus. This ensures that the model accurately captures total demand while preserving network topology for power flow analyses.

**Load Aggregation Table**

* Show **NGET loads vs aggregated SPT/SHE loads** by MW.
* Helps demonstrate your simplification method visually.

Generation within the SPT system includes dispatchable technologies such as CCGT, CHP, Nuclear, Hydro, and Pumped Storage, as well as non-dispatchable sources like Wind, and storage resources including Battery Storage. Each generator is assigned a maximum and minimum output, with non-dispatchable generators limited to their available capacity. Offshore wind generation connected via the OFTO is treated as non-controllable, representing physical generation constraints. A slack bus is defined at the SPT bus to balance the network and accommodate external interactions.

**Generator Capacity Table**

* For SPT separately,

## Validation Strategy

Validation ensures that the constructed network and DCOPF results are consistent with historical and reference data. Boundary flows across the B6 interface are compared for summer and winter conditions. Dispatch patterns are validated against GridWatch Templar data to confirm alignment of load and generation across NGET.

## Scenario Analysis

Future energy scenarios are simulated using FES data. Load is scaled to represent electrification and increased demand projections for 2030 and 2040. The model tracks line loadings and congestion, highlighting potential bottlenecks under different seasonal conditions. Visualization maps are produced to show stress levels for each line.

## N-1 Security Assessment

Contingency analysis is performed by simulating single line or transformer outages. The model evaluates overload conditions and potential loss-of-load scenarios, highlighting critical network elements. This assessment demonstrates the network’s resilience under increased stress.

*Figure 3.4*: Example N-1 contingency and resulting line flows.

## Summary

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# Results and discussion

## Introduction

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## Summary

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# Conclusions and future work

## Conclusions

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## Future work

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References

Put references here.

Appendicies

A Project outline

Project outline as submitted at the start of the project is a required appendix. Put here.

B Risk assessment

Risk assessment is a required appendix. Put here.