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 9](#_Toc146539478)

[1.3 Report structure 10](#_Toc146539479)

[2 Literature review 10](#_Toc146539480)

[2.1 Introduction 10](#_Toc146539481)

[2.2 Detail 11](#_Toc146539482)

[2.3 More detail 11](#_Toc146539483)

[2.4 Summary 12](#_Toc146539484)

[3 Methods 12](#_Toc146539485)

[3.1 Introduction 12](#_Toc146539486)

[3.2 Detail 12](#_Toc146539487)

[3.3 More detail 13](#_Toc146539488)

[3.4 Summary 13](#_Toc146539489)

[4 Results and discussion 14](#_Toc146539490)

[4.1 Introduction 14](#_Toc146539491)

[4.2 Detail 14](#_Toc146539492)

[4.3 More detail 14](#_Toc146539493)

[4.4 Summary 15](#_Toc146539494)

[5 Conclusions and future work 15](#_Toc146539495)

[5.1 Conclusions 15](#_Toc146539496)

[5.2 Future work 16](#_Toc146539497)

[References 16](#_Toc146539498)

[Appendicies 16](#_Toc146539499)

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Abstract

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Acknowledgements

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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 representing 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 presents the methodology. It describes how the chosen modelling approach was implemented, the data used, and the steps taken to build and validate the network model. The approach for scenario and security studies is also outlined.

Chapter 4 presents the results and discussion. The findings from the modelling are set out and interpreted, with attention to their meaning for the GB transmission system. The chapter highlights key insights from the analysis and reflects on their implications for system operation and long-term planning.

Chapter 5 concludes the thesis. It summarises the main findings, reflects on the effectiveness of the modelling approach, and places the results in the wider context of energy system development. Finally, it provides recommendations for future work, including possible extensions of the study and opportunities for collaboration with industry and research.

# 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.

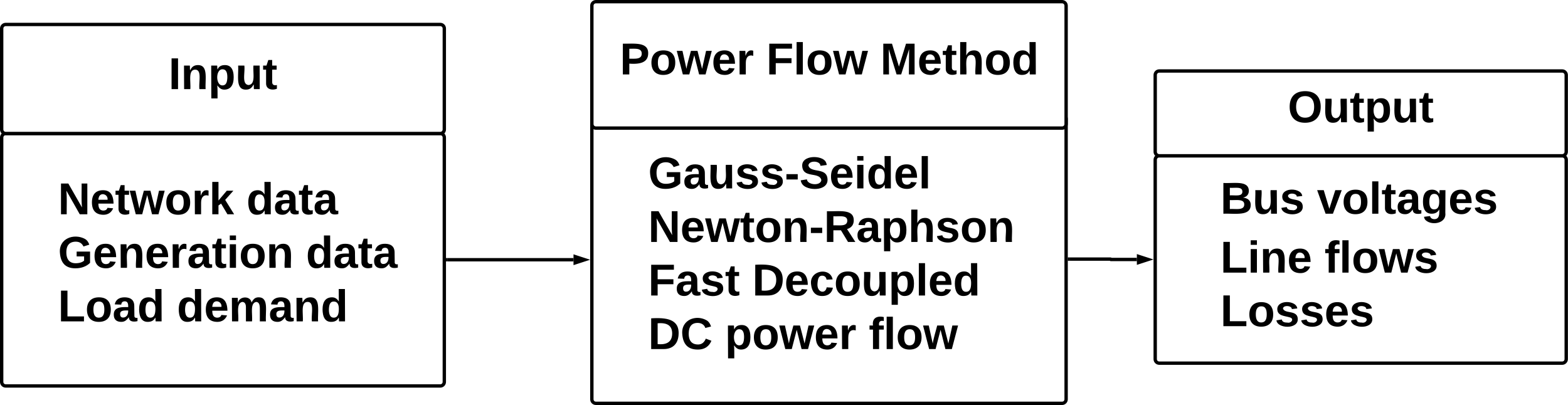


Figure 2.2: Power flow workflow

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.

## Role of Data in Transmission System Modelling

Accurate data is essential for representing a transmission system and ensuring that modelling results are meaningful. For Great Britain, the main source is the **National Energy System Operator (NESO) Data Portal**, which publishes detailed appendices alongside the **Future Energy Scenarios (FES)**. These appendices contain information on generation capacities by technology, regional demand profiles, and locational breakdowns that are necessary for constructing realistic models of the GB network.

Additional data can be obtained from the **ENTSO-E Transparency Platform**, which provides cross-border exchanges, generation mixes, and operational statistics for European systems. This allows the GB system to be studied not only in isolation but also in the context of its interconnections with neighbouring networks.

Although this study is based on the NESO appendices, the modelling approach is not limited to this dataset. Any structured source of information on generation, demand, and network parameters can be used to recreate the workflow, making it applicable to other systems as well.

## Application of DC OPF with pandapower

In this study, DC OPF is implemented using the pandapower framework. This approach combines the computational tractability of DC OPF with the automation and data integration capabilities of a Python-based environment. Pandapower enables networks to be constructed directly from structured datasets and solved repeatedly with minimal manual input, which is particularly valuable for testing multiple scenarios based on the National Grid ESO Future Energy Scenarios (FES).

By embedding DC OPF within a scripting environment, large-scale scenario analysis can be carried out consistently and reproducibly. This makes it possible to evaluate active power transfers, congestion patterns, and system adequacy across hundreds of scenarios with significantly reduced computational burden compared to AC formulations. The ability to interface with Python’s numerical and optimisation libraries further enhances efficiency and flexibility, allowing the modelling framework to be adapted as new datasets or assumptions become available [31].

## Limitations and Challenges of the Approach

While DC OPF in pandapower provides an efficient and reproducible framework for large-scale scenario analysis, several limitations must be acknowledged.

**Simplifications of DC OPF**

* **Neglect of reactive power and voltage magnitudes:** DC OPF assumes all voltages are fixed at 1 pu and ignores reactive power flows. This prevents analysis of voltage stability, reactive power adequacy, and losses [19], [20].
* **Linearisation of power flows:** By assuming small angle differences and negligible resistance, the model may under- or overestimate flows in stressed conditions, particularly on long or heavily loaded lines [21].
* **Limited insight into system stability:** Operational concerns such as inertia, frequency response, and transient stability cannot be assessed with DC OPF [22].

**Challenges of Data-Driven Automation**

* **Incomplete or aggregated data:** Public datasets such as the NESO appendices often lack full technical details (e.g., transformer parameters, line impedances, dynamic models), requiring approximations or synthetic assumptions. This introduces uncertainty into the automated modelling process.
* **Data harmonisation:** Aligning generation and demand data with network nodes is non-trivial, especially when datasets are published in different regional or zonal formats. Automated mapping risks misallocation without careful preprocessing.
* **Scalability of preprocessing:** Although pandapower handles repeated OPF runs efficiently, the main bottleneck often lies in parsing, cleaning, and harmonising large public datasets for each scenario.

**Economic Representation with LCOE**

* **Simplification of costs:** Using LCOE as the basis for generator cost functions captures long-term average costs but ignores short-term dynamics such as fuel price fluctuations, ancillary services, or balancing costs [IEA & NEA, 2015; IRENA, 2020].
* **No market mechanisms:** The DC OPF formulation with LCOE represents least-cost dispatch in physical terms but does not capture market bidding strategies, reserve requirements, or redispatch actions used in real GB operation [23].

**Practical Considerations for GB Modelling**

* **High renewable penetration:** DC OPF cannot represent operational flexibility issues (ramping, intermittency, reserve margins) that are critical under high levels of wind and solar generation.
* **Interconnector flows:** While cross-border transfers can be represented as line, DC OPF does not capture the market-driven dynamics of interconnectors, such as price coupling with continental Europe.
* **Policy and operational decisions:** Outputs from DC OPF are a technical least-cost dispatch; they should not be interpreted as forecasts of actual operational schedules.

In summary, while DC OPF with pandapower offers computational efficiency and transparency, it should be viewed as an approximation that provides insight into active power transfers and congestion under different scenarios. Its limitations in representing voltage behaviour, dynamic stability, and market operations mean that results must be interpreted with caution and complemented by more detailed analyses where necessary.

## Future Energy Scenarios

The **Future Energy Scenarios (FES)** are developed annually by the National Energy System Operator (NESO, formerly National Grid ESO) to describe alternative pathways for the future of the GB energy system. They are not forecasts, but structured explorations of possible system developments under different combinations of policy ambition, technological change, and consumer behaviour [32].

Each scenario is supported by detailed **data appendices**, which include projected generation capacities by technology, regional demand forecasts, fuel mixes, and assumptions on electrification of heat and transport. These datasets provide a quantitative foundation that can be used to model the transmission system under a range of future conditions. The FES are widely applied in both policy and academic contexts as a consistent basis for long-term planning and analysis of the GB electricity system [33], [34].

### Relevance to This Study

For this work, the FES are particularly valuable because they provide **structured, openly available data** that can be directly integrated into the modelling framework established in Chapter 2. By covering a wide spectrum of possible system futures, they enable the analysis to capture uncertainty around renewable deployment, demand growth, and regional imbalances.

Previous research has demonstrated the usefulness of FES for exploring future system challenges. FES data have been widely used in research, for example in [33] to investigate flexibility requirements under high electrification, and in [34] to assess renewable integration impacts on GB transmission planning.. Building on this, the present study uses the FES datasets to stress-test the GB transmission network under different future pathways, ensuring that the results are both technically robust and directly relevant to national planning discussions.

## 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. [8], [9], 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 [11]. These models typically use data from the National Grid ESO (NGESO) and employ AC power flow or OPF methods. 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.

The **NGESO itself** maintains proprietary planning and operational models, which are the most detailed representations of the GB system. 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. [10], 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.X provides a high-level comparison of representative GB models:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Model / Source** | **Resolution** | **Openness** | **Data Source** | **Automation / Reproducibility** | **Suitability for FES-type Scenario Analysis** |
| PyPSA-GB (Lyden et al.) | Zonal (29-bus) | Open-source | Public (ESO, FES) | Reproducible but manual updates | Good for high-level policy, not detailed flows |
| Imperial College models | Bus-level (detailed) | Proprietary | ESO proprietary | Limited, one-off studies | Scenario-focused but not openly repeatable |
| NGESO proprietary tools | Full bus-level | Not public | Internal ESO data | Not reproducible | Used for official planning, not research |
| Synthetic test systems | Bus-level (generic) | Open-source | Synthetic | Fully reproducible | Benchmarking only, not GB-specific |
| **This study** | Bus-level (GB-specific) | Open-source (pandapower scripts) | Public ESO appendices (FES) | Automated and fully reproducible | High-resolution, GB-specific scenario analysis |

This comparison highlights the distinct position of the present study. Like PyPSA-GB, it is designed to be open and reproducible, but unlike zonal approaches, it develops a **bus-level representation** of GB. Unlike proprietary models, it relies only on public datasets (NESO appendices, FES), and unlike synthetic systems, it directly reflects the characteristics of the GB transmission network. The novelty lies in combining **automation** with **high resolution** to enable repeated and consistent scenario analysis.

## Research Gap and Link to This Study

The review above shows that while useful tools exist, no previous work has demonstrated a fully automated, high-resolution, reproducible model of the GB transmission system based on public data. Existing models are either:

* **Simplified (zonal)** – useful for policy but not detailed enough for transmission-level analysis.
* **Proprietary** – detailed but inaccessible and not reproducible.
* **Synthetic** – openly available but not GB-specific.

This study addresses that gap by:

* **Automating the ingestion of public datasets**, particularly the NESO appendices, to create a reproducible bus-level representation of the GB network.
* **Implementing DC Optimal Power Flow (DC OPF) in pandapower**, ensuring scalability for large-scale scenario analysis.

By bridging the gap between data availability and practical usability, the framework developed in this work provides a novel contribution: it enables the GB system to be modelled at scale, across many scenarios, with transparency and reproducibility.

## Summary of Chapter 2

This chapter reviewed the literature relevant to automated modelling of the GB transmission system. It first outlined the **need for automation**, noting that existing studies often rely on proprietary or simplified models. It then described the **characteristics of the GB system**, including strong regional imbalances and growing operational challenges due to renewable integration.

The chapter introduced the main **power system modelling approaches**, from transient analysis to steady-state methods, and discussed **power flow techniques** (AC and DC) and their optimisation-based extensions (ED and OPF). DC OPF was identified as the most suitable approach for this study due to its scalability and efficiency.

A review of **modelling tools** highlighted the limitations of commercial software for automation, and compared research-oriented platforms, with pandapower selected for its Python-based, data-driven design. The role of data was then discussed, particularly the NESO appendices and the FES datasets, which provide the foundation for scenario analysis.

Finally, the chapter conducted a **critical comparison of previous GB models**, showing that existing approaches are either high-level, proprietary, or synthetic, and therefore cannot meet the dual need for detail and reproducibility. The research gap was clearly identified: the absence of an **automated, reproducible, bus-level model of the GB system based on public datasets**.

The chapter concludes by establishing the **novelty of this study**, which is to fill that gap by automating model creation from NESO appendices, implementing DC OPF in pandapower, and applying the framework to FES scenarios. This sets the stage for the next chapter, which describes the methodology in detail.

# Methodology

This chapter describes the methodology used to model the Great Britain transmission network through DC Optimal Power Flow (DC-OPF) studies. The model was developed in Python using the open-source package PandaPower. The workflow, illustrated in Figure 3.1, begins with data collection and preparation, followed by network construction, DC-OPF formulation, model validation, and finally scenario and security studies.

## Overview of the Network Model

The network model developed in this study is designed to provide a detailed representation of the Great Britain transmission system, with particular focus on the NGET network. The NGET region is modelled in high detail, capturing all major buses, lines, transformers, generators, and loads, along with their electrical parameters, line ratings, transformer ratings, and generation capacities. This detailed representation ensures that the internal connectivity of the NGET network is fully preserved, allowing for accurate studies of power flows, congestion, and operational constraints. In contrast, the surrounding Scottish networks, including SPT, SHE, and OFTO assets, are represented as simplified aggregated systems.

***Figure 3.1: the model***

As illustrated in Figure 3.1, the Scottish network is modelled as a boundary bus with equivalent generation and load. The aggregated generation reflects the mix of technologies present in the region, including wind, open-cycle gas turbines, nuclear, and other types, while the total load represents the net demand of the network.

***Figure 3.2: aggregated generation?***

This approach provides an interface between the high-detail NGET model and the external networks, enabling computational efficiency while maintaining sufficient accuracy for operational studies.

Interconnectors linking NGET to Ireland and continental Europe are also included in the model. These are implemented as controllable power injections at dedicated buses, allowing the study of both import and export scenarios. The interconnectors are manually integrated based on their reported capacities and typical flows, providing flexibility to test different operating and stress scenarios.

By integrating a detailed NGET core with simplified surrounding networks and carefully modelled interconnectors, the model maintains accuracy while remaining computationally efficient. This hybrid approach allows detailed analysis of NGET operations, including DC Optimal Power Flow (DCOPF) studies, while efficiently capturing the influence of external regions and cross-border exchanges.

## Dataset Preparation

The model construction relies on data from the National Electricity System Operator (NESO) ETYS appendices, which provide detailed information on the electrical equipment and operational conditions of the GB transmission system across different seasons, including summer and winter. Table 3.1 summarises the datasets used to construct the network model, including key parameters and their source in the NESO ETYS appendices.

|  |  |  |  |
| --- | --- | --- | --- |
| Data Type | Description | Parameters / Details | Appendix |
| Substations | Network connection points | Bus ID, Substation name | B |
| Transmission Circuits | Overhead lines, underground cables, series compensation | Reactance (X), Ratings (MW), Line type (OHL/Cable/etc.) | B |
| Transformers | Power transformers in the network | Reactance (X), Ratings (MW) | B |
| Generators | Generation units connected to the network | Connection site, Capacity (MW), Generator type | F |
| Loads | Demand points connected to buses | Node, Connected load (MW) | G |

Prior to model construction, data preprocessing is conducted to ensure consistency and usability. All buses are verified against substation data to ensure consistency and accuracy in the network model. Buses that are not part of the high-detail NGET network are aggregated into a single representative bus to simplify the peripheral network. Electrical parameters, including line reactances and transformer impedances, are checked and converted into suitable units for the DCOPF formulation, with the specific conversion process described later in this chapter. Missing or incomplete data points are estimated based on typical values from similar assets, ensuring the model remains accurate.

## Network Construction in PandaPower

The PandaPower model is assembled in a structured sequence, beginning with an empty network. From the processed ETYS datasets, buses, lines, transformers, loads, and generators are progressively added. NGET is represented in full electrical detail, while SPT, SHE, and OFTO are modelled as single aggregated boundary buses with equivalent total generation and demand. Interconnectors to Ireland and continental Europe are incorporated as dedicated buses with defined transfer capacities.

The overall workflow is illustrated in the pseudo-code below:

* INITIALISE empty network
* DEFINE buses:
  + Create detailed NGET buses from processed data
  + Create aggregated bus for SHE, SPT, OFTO
* ADD transmission circuits:
* Create lines linking NGET buses with parameters from ETYS.
* Create series compensation devices such as series reactors and capacitors.
* Create connections from NGET buses to the boundary bus.
  + Assign all transmission elements to the appropriate buses.
* Add transformers
* Create transformers linking NGET buses according to ETYS data.
* Include transformer parameters such as reactance (X) and ratings (MW).
* Assign transformers to the appropriate buses.
* ADD demand:
  + Create NGET loads with assigned MW values.
  + Assign to their respective buses with respect to ETYS data.
* ADD generation:
  + Create NGET generators with capacity in MW.
  + Specify generator type (e.g., nuclear, OCGT, wind).
  + Assign generator to their respective buses.
* ADD interconnectors:
  + Create Ireland connection at dedicated bus
  + Create Europe connection at dedicated bus
* ADD SPT assets:
  + Add aggregated Scottish generation from SPT/SHE/OFTO
  + Add aggregated Scottish loads

## NGET NETWORK

### Buses

Each bus in the NGET network corresponds to nodes listed in the ETYS dataset. To represent the Scottish networks (SPT, SHE, and OFTO) in a simplified manner, a single aggregated Scottish boundary bus is created. This bus combines all Scottish generation and demand into one node and connects to the NGET system at the main connection point between Scotland and England, capturing the net power flow across this boundary.

### Transmission Circuits

Transmission circuits are built using the processed ETYS dataset, which provides detailed information about the NGET network. Each line is defined by its sending and receiving buses, circuit type such as overhead line, cable, series reactor, or series capacitor, its length, and per-unit reactance. The per-unit reactance from ETYS is converted to ohms per kilometer to be compatible with the DC power flow model.

***eqtn***

Thermal ratings from ETYS are also converted into current limits to ensure that lines operate safely.

***eqtn***

Series compensation devices, including series reactors and series capacitors, are incorporated into the model to capture their effect on network reactance, while parallel reactors are excluded because they do not influence the DC power flow. Line lengths are determined according to the circuit type, with zero-length or series devices assigned a minimal length to avoid numerical issues. Each line is then assigned to the appropriate buses, which can be detailed NGET buses or aggregated boundary buses representing SPT, SHE, and OFTO networks, preserving the connectivity of the network.

### Transformers

Transformers are represented as series impedances consistent with the DC power flow formulation. Tap-changing transformers are not considered, and all bus voltages are assumed to be 1 per unit. Both the model and the ETYS data are defined on a system base of 100 MVA, so the per-unit reactances from ETYS are applied directly without conversion.

Each transformer connects to a sending and a receiving bus, which can be either a detailed NGET bus or an aggregated boundary bus for SPT. Thermal ratings are taken from ETYS and applied as the apparent power limit for each transformer.

### Demands

Loads are added to the network according to the ETYS demand data. Each load is associated with a specific bus, and if the bus exists in the network, the load is directly assigned. For buses that are not individually modelled, the total load for the substation is aggregated and distributed evenly across the available buses within that substation in the NGET network. Loads from SHE and SPT are handled as aggregated values assigned to dedicated buses. This approach ensures that the total demand is represented in the network while maintaining realistic connectivity and distribution across the available buses.

### Generators

Generators are mapped to their corresponding substations based on the TEC register and ETYS substation data. Each generator is assigned a minimum and maximum output (Pmin and Pmax), with non-dispatchable sources such as wind and solar represented by their maximum available output. Where a generator cannot be matched to a specific bus, its capacity is aggregated and evenly distributed across the buses of the nearest substation to preserve total system capacity. Each generator is also assigned a fixed cost based on its technology type, supporting subsequent optimal power flow analyses. This ensures that the network model accurately represents both the physical location and the operational characteristics of all generation assets.

### 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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# 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.