Modelling the future GB power system

A dissertation submitted to The University of Manchester for the degree of

Master of Science in Electrical Power Systems Engineering

in the Faculty of Science and Engineering

Year of submission

2025

Student ID

11610796

School of Engineering

Contents

Word count: X

Abstract

This is abstract text.

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci. Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

Declaration of originality

I hereby confirm that this dissertation is my own original work unless referenced clearly to the contrary, and that no portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Intellectual property statement

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made **only** in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trademarks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://documents.manchester.ac.uk/DocuInfo.aspx?DocID=24420), in any relevant Dissertation restriction declarations deposited in the University Library, and The University Library’s regulations (see http://www.library.manchester.ac.uk/about/regulations/_files/Library-regulations.pdf).

Acknowledgements

No need to include, but can if want to.

1 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.

1.1 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.

1.2 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.

1.3 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.

1.4 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.

1.5 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.

1.6 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.

.

2 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.

2.1 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.

2.2 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.

2.3 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

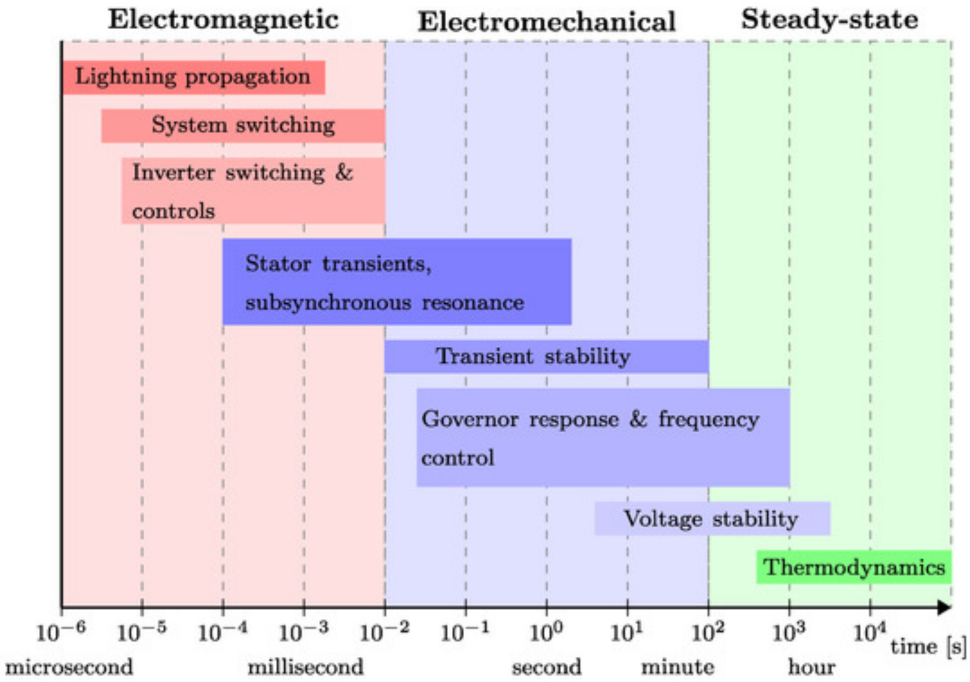

Figure 2.1: Timescales in power system studies (adapted from [15]).

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.

2.3.1 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:

$$P_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} - B_{ij} \sin\theta_{ij}\right)$$

where P_i and Q_i are the active and reactive power injections at bus i, V_i is the voltage magnitude, θ_{ij} is the angle difference between buses, and G_{ij}, B_{ij} 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.

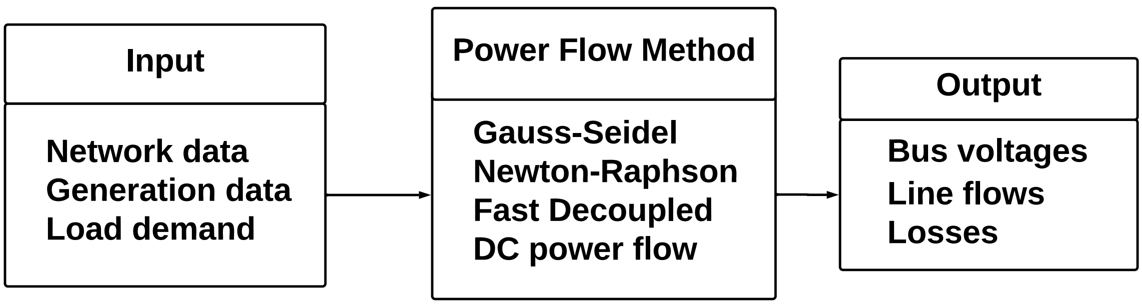

Figure 2.2: Power flow workflow

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.

2.3.2 AC and DC Power Flow

AC power flow uses the full set of nonlinear equations for P_i and Q_i 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 linearised 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:

$$P_i = \sum_{j=1}^{n} \frac{\theta_i - \theta_j}{X_{ij}}$$

where X_{ij} is the line reactance and θ_i is the phase angle at bus i [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.

2.3.3 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.

2.3.4 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].

2.3.5 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.

2.4 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.

2.4.1 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.

2.4.2 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.

2.4.3 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.

2.5 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.

2.6 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.

2.7 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.

2.8 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.

2.9 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.

References

[1] “National Electricity Transmission System Performance Report”.

[2] “Britain’s reliance on coal-fired power set to end after 140 years.” Accessed: Aug. 20, 2025. [Online]. Available: https://www.ft.com/content/5164185d-b0d6-40d1-99b4-59f8039111c2

[3] Molly Lempriere and Simon Evans, “Q&A: How the UK became the first G7 country to phase out coal power,” CarbonBrief. Accessed: Aug. 20, 2025. [Online]. Available: https://interactive.carbonbrief.org/coal-phaseout-UK/index.html

[4] “Flexibility in the GB Power System,” 2025.

[5] “£58bn plan to rewire Great Britain expected to spark tensions along route | Energy industry | The Guardian.” Accessed: Aug. 20, 2025. [Online]. Available: https://www.theguardian.com/business/2024/mar/19/58bn-plan-rewire-great-britain-spark-tensions-route

[6] “UK regulator fast tracks $5.2 billion energy grid investment | Reuters.” Accessed: Aug. 20, 2025. [Online]. Available: https://www.reuters.com/business/energy/uk-regulator-fast-tracks-52-billion-energy-grid-investment-2025-03-20/

[7] N. Energy System Operator, “Future Energy Scenarios 2025: Pathways to Net Zero – Executive Summary,” 2025.

[8] A. Lyden *et al.*, “PyPSA-GB: An open-source model of Great Britain’s power system for simulating future energy scenarios,” *Energy Strategy Reviews*, vol. 53, May 2024, doi: 10.1016/j.esr.2024.101375.

[9] A. F. Lyden *et al.*, “An Open-Source Model of Great Britain’s Power System for Simulating Future Energy Scenarios,” 2023, doi: 10.2139/SSRN.4509311.

[10] A. B. Birchfield *et al.*, “A Metric-Based Validation Process to Assess the Realism of Synthetic Power Grids,” *Energies 2017, Vol. 10, Page 1233*, vol. 10, no. 8, p. 1233, Aug. 2017, doi: 10.3390/EN10081233.

[11] L. Franken *et al.*, “Power system benefits of simultaneous domestic transport and heating demand flexibility in Great Britain’s energy transition,” *Appl*

Energy, vol. 377, p. 124522, Jan. 2025, doi: 10.1016/J.APENERGY.2024.124522.

[12] “Electricity Ten Year Statement,” 2024, Accessed: Aug. 21, 2025. [Online]. Available: https://www.neso.energy/document/352001/download

[13] Chris Owens, “National Grid’s Summer Outlook 2023 | the Blackout report.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.theblackoutreport.co.uk/2023/04/20/national-grid-summer-outlook-2023/?

[14] “Britain’s Electricity Explained: 2023 Review | National Energy System Operator.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.neso.energy/news/britains-electricity-explained-2023-review?

[15] L. Meegahapola, A. Sguarezi, J. S. Bryant, M. Gu, E. R. Conde D., and R. B. A. Cunha, “Power System Stability with Power-Electronic Converter Interfaced Renewable Power Generation: Present Issues and Future Trends,” *Energies 2020, Vol. 13, Page 3441*, vol. 13, no. 13, p. 3441, Jul. 2020, doi: 10.3390/EN13133441.

[16] H. Konara, U. D. Annakkage, and R. Wierckx, “Co-simulation of real-time electromagnetic transient and transient stability simulations using dynamic phasor T-Line model,” *Electric Power Systems Research*, vol. 223, p. 109611, Oct. 2023, doi: 10.1016/J.EPSR.2023.109611.

[17] T. Xu, W. Jang, and T. Overbye, “Location-Dependent Impacts of Resource Inertia on Power System Oscillations”, doi: 10.24251/HICSS.2018.342.

[18] J. J. Grainger and W. D. Stevenson, “POWER SYSTEM ANALYSIS,” 1994.

[19] B. Stott and O. Alsac, “Fast decoupled load flow,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-93, no. 3, pp. 859–869, 1974, doi: 10.1109/TPAS.1974.293985.

[20] B. Stott, J. Jardim, and O. Alsaç, “DC power flow revisited,” *IEEE Transactions on Power Systems*, vol. 24, no. 3, pp. 1290–1300, 2009, doi: 10.1109/TPWRS.2009.2021235.

[21] Allen J. Wood, Bruce F. Wollenberg, and Gerald B. Sheblé, “Power Generation, Operation, and Control, 3rd Edition | Wiley.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.wiley.com/en-us/Power+Generation%2C+Operation%2C+and+Control%2C+3rd+Edition-p-9780471790556

[22] S. Frank, I. Steponavice, and S. Rebennack, “Optimal power flow: a bibliographic survey I,” *Energy Systems 2012 3:3*, vol. 3, no. 3, pp. 221–258, Apr. 2012, doi: 10.1007/S12667-012-0056-Y.

[23] H. W. Dommel and W. F. Tinney, “Optimal Power Flow Solutions,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-87, no. 10, pp. 1866–1876, 1968, doi: 10.1109/TPAS.1968.292150.

[24] D. K. Molzahn and I. A. Hiskens, “A Survey of Relaxations and Approximations of the Power Flow Equations,” *Foundations and Trends® in Electric Energy Systems*, vol. 4, no. 1–2, pp. 1–221, Feb. 2019, doi: 10.1561/3100000012.

[25] E. Press *et al.*, “Renewable Power Generation Costs in 2020,” 2021, Accessed: Aug. 23, 2025. [Online]. Available: www.irena.org

[26] “Projected Costs of Generating Electricity,” 2015, Accessed: Aug. 23, 2025. [Online]. Available: www.iea.org/t&c/

[27] “PSS®E – transmission planning and analysis.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.siemens.com/global/en/products/energy/grid-software/planning/pss-software/pss-e.html

[28] “PowerFactory - DIgSILENT.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.digsilent.de/en/powerfactory.html

[29] “Overview | PSCAD.” Accessed: Aug. 21, 2025. [Online]. Available: https://www.pscad.com/software/pscad/overview

[30] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, “MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, Feb. 2011, doi: 10.1109/TPWRS.2010.2051168.

[31] L. Thurner *et al.*, “Pandapower - An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6510–6521, Nov. 2018, doi: 10.1109/TPWRS.2018.2829021.

[32] “Future Energy Scenarios: Pathways to Net Zero.” Accessed: Aug. 22, 2025. [Online]. Available: https://www.neso.energy/document/364541/download

[33] A. Lyden *et al.*, “PyPSA-GB: An open-source model of Great Britain’s power system for simulating future energy scenarios,” *Energy Strategy Reviews*, vol. 53, p. 101375, May 2024, doi: 10.1016/j.esr.2024.101375.

[34] L. Franken *et al.*, “Power system benefits of simultaneous domestic transport and heating demand flexibility in Great Britain’s energy transition,” 2024, doi: 10.1016/j.apenergy.2024.124522.

[35] T. Brown, J. Hörsch, and D. Schlachtberger, “PyPSA: Python for power system analysis,” *J Open Res Softw*, vol. 6, no. 1, 2018, doi: 10.5334/jors.188.

[36] L. P. Kunjumuhammed, B. C. Pal, and N. F. Thornhill, “A Test System Model for Stability Studies of UK Power Grid”.

[37] J. F. DeCarolis, K. Hunter, and S. Sreepathi, “The case for repeatable analysis with energy economy optimization models,” *Energy Econ*, vol. 34, no. 6, pp. 1845–1853, Nov. 2012, doi: 10.1016/j.eneco.2012.07.004.

[38] A. M. Foley, B. P. Ó Gallachóir, J. Hur, R. Baldick, and E. J. McKeogh, “A strategic review of electricity systems models,” *Energy*, vol. 35, no. 12, pp. 4522–4530, Dec. 2010, doi: 10.1016/J.ENERGY.2010.03.057.

[39] J. F. DeCarolis, K. Hunter, and S. Sreepathi, “The case for repeatable analysis with energy economy optimization models,” *Energy Econ*, vol. 34, no. 6, pp. 1845–1853, Nov. 2012, doi: 10.1016/J.ENECO.2012.07.004.

[40] H. Li *et al.*, “Building Highly Detailed Synthetic Electric Grid Data Sets for Combined Transmission and Distribution Systems,” *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 478–488, 2020, doi: 10.1109/OAJPE.2020.3029278.

[41] A. B. Birchfield, T. Xu, and T. J. Overbye, "Power flow convergence and reactive power planning in the creation of large synthetic grids," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6667–6674, Nov. 2018, doi: 10.1109/TPWRS.2018.2813525.

[42] A. B. Birchfield *et al.*, "A Metric-Based Validation Process to Assess the Realism of Synthetic Power Grids," *Energies 2017, Vol. 10, Page 1233*, vol. 10, no. 8, p. 1233, Aug. 2017, doi: 10.3390/EN10081233.

[43] A. B. Birchfield, T. Xu, K. S. Shetye, and T. J. Overbye, "Building Synthetic Power Transmission Networks of Many Voltage Levels, Spanning Multiple Areas," *Proceedings of the Annual Hawaii International Conference on System Sciences*, vol. 2018-January, pp. 2766–2774, Jan. 2018, doi: 10.24251/HICSS.2018.349.

[44] K. M. Gegner, A. B. Birchfield, T. Xu, K. S. Shetye, and T. J. Overbye, "A methodology for the creation of geographically realistic synthetic power flow models," *2016 IEEE Power and Energy Conference at Illinois, PECI 2016*, Apr. 2016, doi: 10.1109/PECI.2016.7459256.

[45] T. Xu, A. B. Birchfield, K. M. Gegner, K. S. Shetye, and T. J. Overbye, "Application of Large-Scale Synthetic Power System Models for Energy Economic Studies," *Proceedings of the Annual Hawaii International Conference on System Sciences*, vol. 2017-January, pp. 3123–3129, Jan. 2017, doi: 10.24251/HICSS.2017.386.

[46] A. B. Birchfield, "The creation of synthetic power grids: preliminary considerations," Nov. 2016, Accessed: Aug. 25, 2025. [Online]. Available: https://hdl.handle.net/2142/95328

[47] A. B. Birchfield, "Inertia Adequacy in Transient Stability Models for Synthetic Electric Grids," Jul. 2022, Accessed: Aug. 25, 2025. [Online]. Available: https://arxiv.org/pdf/2207.03396

[48] H. Li *et al.*, "Building Highly Detailed Synthetic Electric Grid Data Sets for Combined Transmission and Distribution Systems," *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 478–488, 2020, doi: 10.1109/OAJPE.2020.3029278.

3 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.

3.1 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.

3.2 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.

3.3 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

3.4 NGET NETWORK

3.4.1 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.

3.4.2 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.

3.4.3 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.

3.4.4 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.

3.4.5 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.

3.4.6 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.

3.5 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) |

3.6 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,

3.7 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.

3.8 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.

3.9 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.

3.10 Summary

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

4 Results and discussion

4.1 Introduction

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

4.2 Detail

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

4.3 More detail

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

4.4 Summary

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

5 Conclusions and future work

5.1 Conclusions

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

5.2 Future work

Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Maecenas porttitor congue massa. Fusce posuere, magna sed pulvinar ultricies, purus lectus malesuada libero, sit amet commodo magna eros quis urna.

Nunc viverra imperdiet enim. Fusce est. Vivamus a tellus.

Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Proin pharetra nonummy pede. Mauris et orci.

Aenean nec lorem. In porttitor. Donec laoreet nonummy augue.

Suspendisse dui purus, scelerisque at, vulputate vitae, pretium mattis, nunc. Mauris eget neque at sem venenatis eleifend. Ut nonummy.

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.