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PyPSA-GB: An open-source model of Great Britain's power system for simulating future energy scenarios

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ABSTRACT

This paper presents PyPSA-GB, a dataset and model of Great Britain's (GB) power system encompassing historical years and the future energy scenarios developed by National Grid. It is the first fully open-source model implementation of the future GB power system with high spatial and temporal resolution, and data for future years up to 2050. Two power dispatch formulations can be optimised: (i) single bus unit commitment problem, and (ii) network constrained linear optimal power flow. The model is showcased through an example analysis of quantifying future wind curtailment in Scotland. PyPSA-GB provides an open-source basis for GB operational and planning studies, e.g., sector coupling and flexibility options.

1. Introduction

In recent years there has been a global policy trend towards setting net zero targets. In 2019 the UK government legislated a binding target to reach net zero by 2050 [1]. This was driven by, and further motivated, the development of net zero transition pathways. The Climate Change Committee carried out a detailed analysis of each sector of the UK economy, and recommended net-zero greenhouse gases by 2050 [2]. Net Zero Britain is a report on the modelling of pathways to net zero for the UK where it is concluded that the necessary tools and technology exist to power the UK with 100% renewable energy [3]. The outputs from these types of studies often rely on energy systems modelling, and are in turn used to inform further modelling studies. However, these studies often do not make underlying models and data openly available.

There is growing awareness of the benefits of making energy system models and underlying data openly available, as seen with the expansion of open energy modelling initiatives [4]. Pfenninger et al. [5] set out four reasons why energy models and data should be open: enable transparency, peer review, reproducibility, and traceability; improved collaboration between modellers and policy makers; improved collaboration between researchers; and more prominent role in wider public debate. These reasons have motivated the authors of this paper to ensure the work described is made openly available.

Energy system models are important for analysing and understanding the performance of future, increasingly complex, energy systems highly reliant on renewable energy sources (RES) [6]. Electricity generation using RES is variable and dependent on both spatial factors, due to varying resource availability in different geographical locations, and temporal factors, such as weather conditions which are stochastic and uncertain. Energy system modelling studies are tackling challenges related to these factors, such as the spatial distribution of RES generators [7] and complementarity of different types of RES [8]. Additionally, studies are exploring the role of the expansion of electricity networks [9]; various types of storage [10]; sector coupling [11]; and demand side management [12]. Addressing these challenges benefit from using energy system models with high spatial and temporal resolution.

There are a wide range of energy system models, both commercial and open-source, which can be applied to different sectors and scales, and at different spatial and temporal resolutions (see [13, 14] for model reviews). Many models are only applicable to a single sector such as power system tools, e.g., DIgSILENT PowerFactory [15], MATPOWER [16], and were developed before the challenges of energy system integration. More recent open-source energy system models are applicable to multiple sectors, e.g., Calliope [17], OSeMOSYS [18]. These use linearised models and can simulate systems at a high temporal resolution, but they use simplified models for energy networks.

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Whole system optimisation tools, e.g., TIMES [19], can represent all sectors of an energy system [20] but use limited number of time slices to represent a whole year which makes storage modelling less accurate. TIMES is not open-source and is built in GAMS, which uses a mix of commercial and open source software components. Often multi-sector energy system models with low spatial and temporal resolution are soft-linked with detailed power system tools [21, 22].

PyPSA is an open-source Python based package that can simulate and optimise modern energy systems over multiple time steps based on marginal costs [23], and can perform analyses at high spatial and temporal resolution. It was developed to bridge the gap between power system models and whole energy system models. It can be used to tackle power system problems such as dispatch modelling, unit commitment, and power flow, while having a flexible framework such that other energy vectors such as heat and hydrogen can also be modelled. It can be used for both operational studies (it can calculate optimal linear, non-linear, and security-constrained power flow) and investment studies (it can calculate total energy system least-cost investment optimisation). Model implementations of PyPSA include the European transmission system [24], transmission expansion in the northern sea [25], and global coverage models [26]. PyPSA is suited to modelling studies aiming for open-source and requiring high spatial and temporal resolution.

The transmission network operator for the UK, the National Grid, publish an annual report, Future Energy Scenarios (FES) [27], on their modelling of the UK's pathway to net zero based on four scenarios: a steady progression or falling short scenario, and three net zero scenarios. The modelling used to inform the FES involves numerous modelling methods applied to different sections of the energy system. For the net zero scenarios a cost-optimisation model, the UK TIMES Model [28], is used to determine the evolution of the whole energy system to 2050. The outputs from this model are validated using a more detailed electricity generation model, BID3 [29]. This is an electricity dispatch model which is pan-European and is used with hourly timesteps. Energy demand modelling is undertaken on a sector basis and collated together to calculate annual electricity demand, peak and minimum electricity demand, and system losses. Electricity supply modelling includes dispatchable and non-dispatchable electricity generators, interconnectors and storage. All scales from household generation (e.g., rooftop PV) to large generators directly connected to the transmission network are considered. BID3 is not open-source, but PyPSA can replicate it's functionality in the FES development.

There are limitations to the current FES modelling approach. It does not include transmission or distribution networks or grid-service operational constraints in the step using TIMES. This approach is oversimplified because it means generation and demand can be transported through the limited capacity network freely, and they are not required to provide system services (e.g., reserve and frequency response), both these limitations mean the model is not representative of a future system with increasing constrained flows and constraint management needs. The openly available outputs are limited to annual metrics, and higher temporal resolution input or output data (e.g., hourly generation or load outputs from the BID3 model) are not available. The outputs from the FES would benefit from implementation in a transparent, open-source high spatial and temporal resolution dispatch model such as PyPSA.

UK-specific energy system model implementations have been developed and utilised in recent years. The UK TIMES model covers all aspects of the energy system, all steps between fuel extraction and trading to final energy demands [30]. It is used to generate long-term transition pathways (such as National's Grid FES discussed above) using a cost minimisation approach and contains 16 distinct timeslices to represent four typical days for the four seasons. While the UK TIMES models does not incorporate high spatial or temporal resolution aspects, it has been linked with the dispatch model highRES [31] which is capable of capturing transmission network constraints and hourly timestep modelling. Zeyringer et al. [32] used highRES to simulate a future year, 2050, using outputs from a UK TIMES model run. They found that spatial aspects such as reinforcing the transmission system can decrease system costs while the spatial deployment of electricity storage and flexible generation is optimal when installed close to high demand areas. This study only simulated a single future year, 2050, the data is only available from the author on request, and the model is not open-source.

An example of an open-source, UK-specific model implementation is Calliope-UK. The Calliope energy modelling framework is a linear, cost optimisation model which is capable of high spatial (transmission network representation) and high temporal (hourly timesteps) resolutions [33]. Operation and installed capacities are simultaneously solved, removing the need for soft-linking to a long-term pathway energy system model. Calliope-UK [34] incorporates traditional thermal power plants and RES electricity generators, a 20-node representation of the transmission network, historical National Grid demand data, and 25 years of hourly weather data from the MERRA reanalysis dataset [35]. This study highlights the importance of modelling inter-year variability introduced by solar and wind power generation.

Table 1: UK energy system models. Spatial resolution refers to fidelity of network modelling; temporal resolution is the simulation/optimisation timestep; future data refers to exogenous datasets representing components of a future power system; and open-source is used to refer to availability of model/data on an accessible repository.

UK Model	Institute	Description	Spatial resolution	Temporal resolution	Future data	Open-source
UK TIMES [36]	University College London (Formerly developed by BEIS)	Integrated partial equilibrium energy systems model for least cost optimization	Not included (UK single region)	4 seasons, 4 intraday (day, evening peak, late evening, night)	Endogenous	Closed source - discussions around open sourcing
Ember-PyPSA [37]	Ember	Merit-order style dispatch model for UK and EU, but can be run as a capacity expansion model.	12 nodes representing the UK, 29 for rest of Europe	Hourly	2030 only. Use FES2022 pathways, Falling short and Leading the Way	Open source (MIT Licence)
BID3 [29]	AFRY	Electricity market dispatch model	Transmission network	Hourly renewable generation based on detailed historical windspeed and solar radiation data; Sub-hourly possible	User input; Scenario generation for optimal new-build, retiral and mothballing	Closed source
ESME [38]	Energy Technologies Institute (ETI) & Energy Systems Catapult	National energy system design and planning Monte Carlo model to identify investment in technology innovation and strategic policy	12 onshore and 12 offshore regions	2 seasons (Summer, Winter), 5 intraday time slices (Morning, Mid-day, Early Evening, Late Evening, Overnight)	Endogenous	Closed source
highRES [31]	University College London	Electricity system planning and dispatch model	20-zone transmission network	Hourly	Wind and solar data from 1983-2017 at 0.25 degrees x 0.25 degrees (~28 x 17 km)	Open source - but uses GAMS which has limited open features
UK-Calliope [34]	TUDelft, ARUP, & ETH Zürich	Power system model based on the open-source Calliope high-resolution modeling framework	20-zone model of the power system of Great Britain	20 years of validated hourly wind and PV generation data	No future data included, model used to generate endogenous scenarios	Open source
Integrated Whole Energy System (IWES) [39]	Imperial College London	Large, linear-programming-based optimisation problem to minimise overall system costs	14 regions + interconnectors	Hourly	Endogenous	Closed source - only documented through literature
Combined Gas and Electricity Network (CGEN) [40]	Cardiff University	High-resolution system-of-systems modelling framework	Transmission + distribution scale; Wind/solar = 10 km x 10 km; "Local authority district level"	Wind/solar = daily, "down-scaled to hourly"; Hourly	Uses Future Energy Scenarios (2019)	Closed source with "workflows, code and data used are available from the corresponding author upon reasonable request"
DECC Dynamic Dispatch Model [41]	UK Government - DECC	Comprehensive fully integrated power market model covering the GB power market over the medium to long term.	Not included (UK single region)	Half hourly basis for sample days, not full year	Does not have future data but relies on input assumptions of the costs and characteristics of all generation types	Closed source - not openly available
Unit commitment dispatch model of the GB electricity market [42]	University of Cambridge	A calibrated unit commitment dispatch model of the GB electricity market.	UK transmission not included, however, interconnector flows are included	Hourly for full year	Single year, 2025, from National Grid's Five Year Forecast of supply mix	Closed source - paper states model is on GitHub but authors did not find repository
PyPSA-GB	University of Edinburgh	Open dataset and power dispatch model of the GB transmission network using country-specific data over historical years and National Grid's Future Energy Scenarios for future years	29 node transmission network or zonal model	Half hourly and hourly	National Grid Future Energy Scenario data incorporated 2021 to 2050	Open source with full documentation

This model implementation does not consider explicit power flows, instead Calliope approximates power flow to energy flows, and does not incorporate data from whole energy system long-term pathway models (such as outputs from FES), instead optimising installed capacities in the same framework.

Table 1 displays relevant information on 11 UK-specific energy system models with focus on spatial resolution, temporal resolution, future data, and open-source. The table shows that PyPSA-GB is the only UK-specific model implementation of a high spatial and temporal resolution dispatch model including exogenous open-source data to readily simulate future years.

Accordingly, this paper presents PyPSA-GB, an open dataset and power dispatch model of the Great Britain (GB) power system encompassing both historical years (2010-2020) and future years (up to 2050) based on National Grid's FES. It is the first model implementation of the GB power system which is: high spatial resolution, high temporal resolution, contains exogenous data for future years, and open-source. The dataset covers the GB electrical power system and excludes Northern Ireland which is operated by an independent system operator and only connected to the GB power system through an interconnector which is included in this dataset. The collection of data sources into a model implementation of the UK in PyPSA is a contribution to knowledge for the following reasons.

PyPSA-GB can be used as a dispatch model using the FES data for future years, and it can also be used as a capacity expansion model which optimises simultaneously with detailed power flow constraints. Furthermore, it can also be used solely as a capacity expansion model by removing power flow constraints. This flexibility in usage is a key reason for using PyPSA as the backend for this UK model. PyPSA-GB is a highly flexible implementation of linking between long-term energy transition pathway outputs and high spatial and temporal resolution operational/dispatch functionality. It is the authors intention that PyPSA-GB can form a basis for future GB energy system modelling in directions such as sector coupling and flexibility options.

This paper is structured as follows: Section 2 provides an overview of PyPSA-GB and motivates the need to simulate historical and the FES projections for future years in high spatial and temporal resolution; Section 2.1 describes the linear optimal power flow and unit commitment power dispatch functionality; Section 2.2 explores the underlying data covering network, demand, generators and marginal prices, renewable power, storage, and greenhouse gas emissions; Section 3.1 provides a comparison to historical data; Section 3.2 describes an example study using PyPSA-GB to investigate future wind curtailment in Scotland; and Sections 4 and 5 are the discussions and conclusions respectively.

2. Methodology

PyPSA-GB has been developed to simulate the GB power system in high spatial and temporal resolution for both historical and future years. This section will describe the methodology focusing on the power dispatch functionality and the underlying data. The data included in the model has been sourced from openly available datasets found online. This data is processed in a format suitable for use within the PyPSA framework. Additionally, this dataset can be converted into formats suitable for use within other energy model frameworks (interoperability of open source frameworks is an ongoing area of research [43]). Code for PyPSA-GB is written in Python and Jupyter Notebooks are used to showcase data, functionality, and analysis. PyPSA-GB v1.0.0, is available on a public GitHub repository `https://github.com/andrewlyden/PyPSA-GB`.

The default optimisation solver in the example notebooks is Gurobi which is currently available for free to academics, however, is not free for non-academics. Use of the open-source solver HIGHS [44] (and others) is integrated in PyPSA, and HIGHS is emerging as a promising alternative to closed-source solvers. While new open-source solvers are closing the performance gap, the use of a closed-source solver may be required for ensuring solutions with large-scale optimisation problems. With PyPSA-GB aiming for high spatial and temporal resolution there may be limitations to being able to solve these large-scale problems.

For the historical years, 2010-2020 inclusive, PyPSA-GB includes data on generators, marginal prices, demand, renewable power, and storage. Simulating historical years can provide insight into the operation of the GB power system, e.g., dispatch of thermal power plants and curtailed renewable generation. It is also useful in order to compare to historical data and build confidence in the model (see Section 3.1).

For future years, PyPSA-GB includes data to simulate future years based on National Grid's FES21 [45] and FES22 [46] for all four scenarios which go up to 2050. Steady Progression (FES21) or Falling Short (FES22) represents business as usual with low level of both societal change and speed of decarbonisation, and is the only scenario which fails to meet the net zero target. Leading the Way represents the highest speed of decarbonisation coupled with a high level of societal change. Consumer Transformation and System Transformation represent the same speed of decarbonisation, but Consumer Transformation requires higher level of societal change than System Transformation.

Many studies which are focussed on a single, or subset, of technologies are interested in the wider energy system integration. Research is increasingly interested in whole energy system analysis in order to identify overall optimal energy systems, as discussed in detail in the smart energy systems concept [47]. Often studies develop simple representations of the entire GB energy system to analyse this wider system integration. However, these are often not further developed and do not get reused. One of the aims of PyPSA-GB is to provide a robust basis for these types of studies to more easily incorporate a whole energy system element of analysis. The FES scenarios included as the dataset in PyPSA-GB provide a whole energy system view which can be used as the starting point for these types of analysis, and individual sectors can then be modified to investigate the wider system impacts.

2.1. Power Dispatch

PyPSA-GB can readily solve two power dispatch formulations: (i) single bus unit commitment problem, and (ii) network constrained linear optimal power flow. The power dispatch functionality utilises the open-source PyPSA (Python for Power Systems Analysis) to perform unit commitment and network-constrained linear optimal power flow calculations. PyPSA is extensively documented in literature [23] and by the developers [48].

PyPSA offers a simulation platform for various components like loads, generators, and storage units linked to buses. Loads signify fixed power demands, generators optimize power dispatch, and stores shift power with efficiency losses. Storage units behave similarly but have additional charging and discharging limits. Shunt impedances exhibit voltage-dependent power consumption when using AC optimal power flow functionality.

Lines and transformers connect two buses, facilitating power transmission based on imbalances and network impedances, and represent passive branches. Links connect two buses with controllable active power dispatch, representing processes like high voltage DC lines or import-export capacities. Networks of links adhere to Kirchhoff's Current Law, while Kirchhoff's Voltage Law applies to passive branch networks.

Unit commitment is formulated as a single bus (i.e., ignoring the network constraints which may occur) optimisation with continuous and binary variables which include ramping constraints and start-up costs. The optimisation minimises total system cost by dispatching generators and storage to meet demand under various constraints. The unit commitment functionality in PyPSA is an implementation of the Taylor [49] formulation. In PyPSA-GB the constraints imposed on generators under the unit commitment formulation are 'commitable', which indicates on/off status of generator, 'minimum up time', 'minimum down time', 'ramp limit up', 'ramp limit down', 'minimum power output', 'maximum power output', and 'start up cost'. See the extensive existing PyPSA documentation for the mathematical equations, and the PyPSA-GB documentation for an example implementation.

The Linear Optimal Power Flow (LOPF) functionality in PyPSA optimises the dispatch of generation and storage to meet demand which must be met in all timesteps. All optimisation variables are linear and continuous. Four formulations of linear power flow calculations can be selected [50]: 'angles' which formulates the problem in terms of the voltage phase angles; 'PTDF', Power Transfer Distribution Factor formulation [51]; the 'Kirchhoff' formulation where the linear load flow is expressed as explicit linear constraints on the flows themselves; and 'Cycle formulation' where the flows are decomposed into a superposition of the flows on a spanning tree of the network. While all of these formulations are included in PyPSA, the Kirchhoff formulation was fastest for 92% of the problems with distributed generation solved by Hörsch et al. [50], where all formulations gave identical results.

The objective function of the LOPF is to minimise the total system cost. The optimisation can be extended to include the capacities of generation and storage, both with capital and marginal cost, along with parameters of the transmission network, with capital cost.

2.2. Data

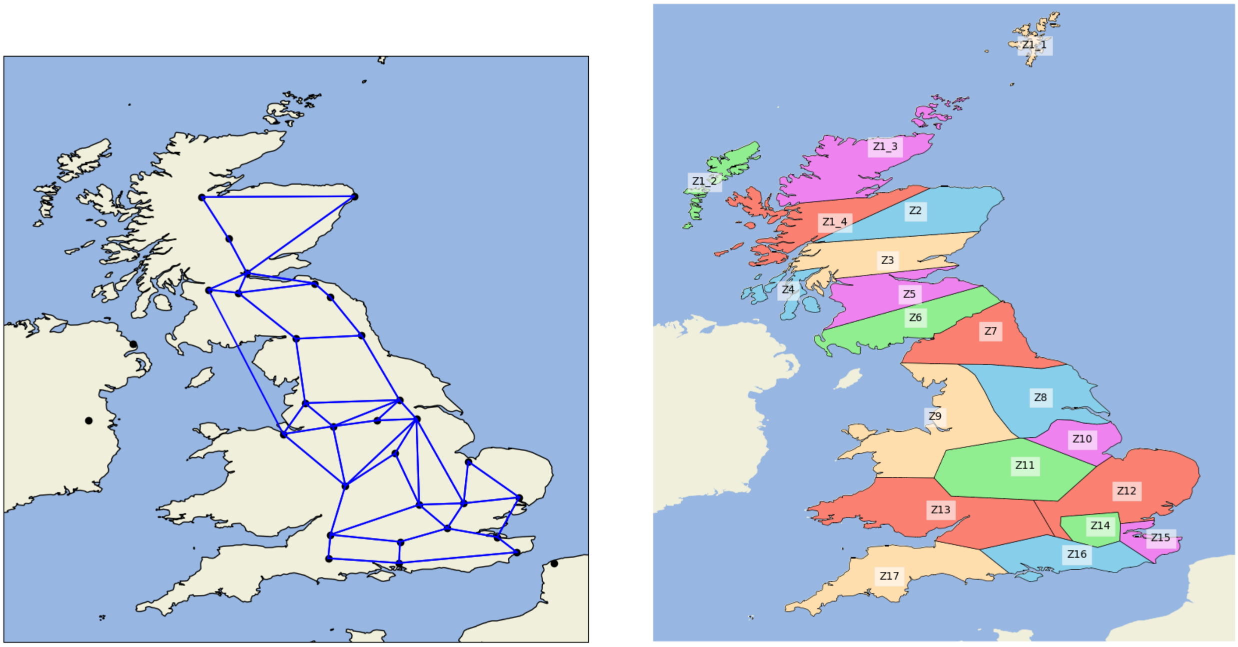
This section details the data included in PyPSA-GB for representing the network, demand, marginal prices, thermal power plants, renewable power, storage, and emissions. See Table 3 in the Appendix for a detailed overview of these data types.

2.2.1. Network

The current GB transmission network consists of high voltage (HV) AC transmission power lines, one internal HVDC line (Western HVDC link [52]), and HVDC interconnectors to other countries. PyPSA-GB represents this with two formulations: the 'reduced network model', which is a 29 bus and 99 line representation of the high voltage AC transmission network of the Great Britain (GB) electricity system developed in 2010 [53], and the 'zonal model' which is based on National Grid's ETYS reports [54] and utilises the link PyPSA component. Due to the network upgrades since the release of this model, additions have been made - the Western HVDC link, which strengthens the connection between Scotland and England, and upgrades of various lines. All modelled lines in England are 400kV, while in Scotland a combination of 275kV and 400kV are included. The network model data, shown in Figure 1 has been compared to the ENTSO-E Grid Map [55] and Openinframap [56].

The main difference between the network models is their data source and the way they are implemented in PyPSA. The 'reduced network model' is built on an outdated source from 2013 which has not been periodically updated and uses passive lines for power flow between buses. The 'zonal model' uses the ETYS report which is updated every year, meaning that it is easier to update the model in line with network upgrades and uses links for power flow between buses. Networks of links adhere to Kirchhoff's Current Law, while Kirchhoff's Voltage Law applies to networks of passive lines.

Generators, demands, and storage units are connected to the buses of the network by calculating the nearest bus by distance, or identifying the zone in which they are located. For the 'reduced network model', see Figure 1, Voronoi cells can be generated to illustrate the areas which correspond to the nearest bus, see `https://pypsa-gb.readthedocs.io/en/latest/notebooks/1%20-%20Network.html`. Voronoi cells show regions where all the points in one region are closer to one bus than any other bus.



(a) Reduced network model

(b) Zonal network model

Figure 1: Network models available in PyPSA-GB

The historical years model the 6 existing interconnectors (as of 2020) as fixed import/export from historical data sourced from the ESPENI (Elexon Sum Plus Embedded Net Imports) dataset (see Section 2.2.2 for more details on this dataset). Interconnectors which have only recently become operational, such as IFA2 which began operation in January 2021, will not be operational before that date in the model and will have fixed zero imports/exports.

Future interconnectors are modelled as bi-directional controllable links with fixed marginal costs based on assumptions on the connected countries (these simplistic inputs can easily be changed by users). A pipeline of interconnector projects with GB regulatory approval exists up to 2030 [57] and these are scaled to match projected interconnector capacities from FES21 and FES22.

2.2.2. Demand

PyPSA-GB uses the ESPENI dataset [58] to represent the system demand. This is a cleaned dataset using both National Grid and Elexon data to develop a historical half hourly electricity profile which represent the total system demand of the GB power system. The EPSENI dataset takes system view data (from Elexon [59]) and adds both embedded generation (distribution-connected solar and wind) and interconnector imports and exports (both from National Grid [60]). In PyPSA-GB both embedded generation and interconnectors are modelled to account for this. National Grid's FES21 and FES22 data include a regional breakdown of projected demand by grid supply point which can be mapped to the nearest bus. The 2020 data for these regional breakdown is used to distribute the load across the buses for the historical years 2010-2020.

Future demand profiles are generated by scaling historical demand profiles or the load demand profile for 2050 (see [61] for more details) to match the projected annual load from the FES21 and FES22 datasets. Different demand profiles from 2010-2020 years can be chosen. Distributions across buses are obtained from FES21 and FES22, where data is available for distributions across gird supply points (which are mapped to buses), for the years 2020-2050 and all four scenarios. Scaling the load profile according to solely the annual energy demand results in overestimation of peak demands.

Historical demand data is openly available through Elexon and National Grid, and the ESPENI dataset offers a clean and comprehensive dataset combining these sources. Future demand profiles are generated using historical profiles and projected annual loads from FES, however a mismatch was found with the FES peak demand projections. Alternative methods for synthesising future demand profiles have been developed and could be implemented in PyPSA-GB to better represent future demand. Bobmann and Staffell [61] used two models, capable of synthesising future demand, to explore load curves in the UK and Germany, and found there will be significant change to the future shape of load curves.

2.2.3. Marginal Prices

Marginal costs for thermal power plants are calculated in PyPSA-GB using a combination of fuel costs and carbon-related costs (EU Emissions Trading Scheme (ETS) and Carbon Price Support). The EU-ETS has recently been replaced by a GB specific ETS, but is not included in this dataset. Quarterly fuel costs for coal, gas, and oil were sourced using BEIS [62]. Historical daily futures EU-ETS prices were sourced from Ember Climate [63], and Carbon Price Support (a top up to the EU-ETS price by the UK government) historical prices were from Hirst [64]. Nuclear marginal prices were based on variable O&M from Harris et al. [65]. Biomass electricity generation fuel cost were estimated based on assumptions in McIlveen-Wright et al. [66], and combined with Renewable Obligation Certificate subsidies [67] to calculate a marginal price.

Predicting marginal prices for the future is highly uncertain, particularly for future thermal power plants such as hydrogen power plants and carbon capture and storage power plants. In PyPSA-GB, marginal prices for future fossil fuels are extracted from FES21 and FES22. As with all data in PyPSA-GB these default marginal costs can be changed by the user.

The method used for calculating marginal prices for thermal power plants is simple, but is capable of representing the primary dispatch costs of fuel and carbon related costs. Market mechanisms such as the capacity market, contracts for difference, and ancillary services will impact on the power dispatch of the generators, however, these are not included in this model.

2.2.4. Thermal Power Plants and Hydropower

The data source used for historical data on regional location, fuel, type, and installed capacity of thermal power stations is the DUKES dataset from BEIS [62]. Fuel data extracted from this database are for: coal, diesel, natural gas, nuclear, sour gas, and waste (e.g., anaerobic digestion and waste to energy). The coordinates of each power station has been obtained from a combination of OpenStreetMap [68], Global Energy Monitor [69], and manual searches using Google Maps for missing data.

Technical characteristics (minimum up/down time, ramp limit up/down, minimum/maximum power output) and economic characteristics (start up and shut down costs), are important for power dispatch of thermal power plants, particularly for unit commitment problems. Coal, oil, CCGT, OCGT, and nuclear assumptions are based on Schröder et al. [70] and Angerer et al. [71]. Hydropower (non-pumped hydro) is not modelled as a dispatchable generator, instead historical Elexon generation data is used, and is therefore fixed. Biomass is assumed to have the same technical characteristics as coal.

For future years the projected installed capacities of thermal power plants uses a combination of short-term predictions and long-term predictions based on FES21 and FES22. Short-term phase out of coal power plants and nuclear power plants coming to the end of their lifespans is specifically included in the dataset, and long-term projections of installed capacities for remaining thermal power plants up to 2050 uses the FES21 and FES22 data. Spatial distributions of thermal power plants, including nuclear power plants, uses FES21 and FES22 data.

2.2.5. Renewable Power

Data on renewable power generation units is collated to determine installed capacities, technology type, and location. Additionally, this data is required to generate power output timeseries calculated using the open-source Python tool Atlite [72]. This tool retrieves global historical weather data (the ERA5 reanalysis dataset [73] is used in PyPSA-GB) and converts it to power generation potentials for renewable power generation technologies such as wind turbines and PV panels based on detailed mathematical models. While these weather datasets typically use a grid structure, Atlite contains functions for interpolating between grid points.

For historical years, 2010-2020, data on operational solar photovoltaics (PV), onshore wind, and offshore wind sites is sourced from the Renewable Energy Planning Database (REPD) [74]. However, this only includes renewable projects with an installed capacity >150kW. Therefore, an additional scaling step is included where annual generation is scaled to historical annual generation reported by BEIS [62]. This results in significant scaling up for solar PV which have a high proportion of small-scale installations.

For modelling future energy scenarios, the FES21 and FES22 data is used to extract projected capacities. The spatial distributions of PV, onshore wind, and offshore wind are projected by the FES21 and FES22 Regional Breakdown data. For offshore wind in the near future (to 2030), the pipeline (from the REPD) and Sectoral Marine Plan [75] (planning sites around Scotland) are used to update the spatial distribution from 2020 as it is anticipated that there will be a large expansion of offshore wind in the next 10 years, which will significantly impact the current spatial distribution. Tidal lagoon and tidal stream site installed capacity and locations were developed by inspection of the FES21 and FES22 data and Mackie et al. [76]. Their power output time series are modelled directly by extracting harmonic tidal constituents for the years 2025, 2030, 2040, 2045 and 2050 using the Thetis coastal ocean model [77]. Tidal lagoon power is modelled directly [78], and tidal stream uses a nominal 2 MW device power curve [79]. Wave power sites were similarly interpreted from FES21 and FES22 data, Pennock et al. [80], Struthers et al. [79], and the UK Marine Energy Database (MED) [81], using a publicly available 750 kW wave energy converter power matrix [82].

2.2.6. Storage

PyPSA-GB includes explicit models of historical and future electrical storage technologies. The only historical storage units for 2010-2020 included are large-scale pumped hydro stations. The future storage technologies represented are pumped hydro, batteries, liquid air storage and compressed air storage. The energy capacities and nominal power for the years 2021-2050 are extracted from the FES21 and FES22 workbook, and can be obtained for the four different scenarios. Charging/discharging efficiency and standing losses data were sourced from Moseley and Garche [83], and the spatial distributions of the storage types are projected by the FES21 and FES22 Regional Breakdown data.

There are flexibility measures which are included in FES21 and FES22 which are not included in PyPSA-GB such as thermal storage and vehicle-to-grid. In FES21 and FES22 these are treated as demand side measures which influence the electrical demand distribution. PyPSA-GB does not currently modify the electrical demand to represent these flexibility measures, and development of this area is left to further work.

2.2.7. Emissions

PyPSA-GB can calculate time series of the direct carbon dioxide emissions of each generation technology at the same resolution as the power dispatch model, by use of direct emissions intensity data from the BID3 developers who aided the FES21 and FES22 analysis [29], Staffell [84], and IPCC AR5 Annexx III [85]. Instantaneous and total emissions from the generation dispatch over the considered time period can be calculated at both a whole network and a single bus scale. For this release of PyPSA-GB, these values are stationary, where the effects of thermal plant ramp up/ramp down are not modelled.

3. Results

This section will showcase the functionality of these for both historical years and the future energy scenarios, and then detail a illustrative case study for wind curtailment in Scotland.

To illustrate the LOPF for future electricity system figures are shown for power dispatch of generators and of a storage unit. Figure 2 shows the power dispatch of 2050 under the FES22 Leading the Way scenario, with much higher proportion of demand being met by solar and wind power. Figure 3a shows the charging/discharging and state of charge of the pumped hydroelectricity storage units which are being dispatched to minimise system costs. Figure 3b shows the future behaviour of pumped hydroelectricity storage units, and highlights the greater role of storage in balancing the future system with higher penetration of wind and solar power.

3.1. Comparison to Historical Data

This section compares the generation outputs from a LOPF simulation to historical data. This provides confidence in the model that it is producing expected output, but is not intended to form a fully validated model because of the sensitivity to user inputs. This is particularly important for modelling the future energy scenarios which introduce numerous user assumptions. A fully validated model of the future energy scenarios is not possible since there are a number of assumptions, therefore, these models should be seen as tools to expand understanding of future system operation, as opposed to trying to replicate future systems exactly. More on the limitations of PyPSA-GB can be found in the Discussion section.

Figure 4 shows the annual energy output of all of the different power generation types for a LOPF simulation (hourly timestep) compared to the 2018 data published by BEIS from the DUKES dataset [62] (see Table 2 in the

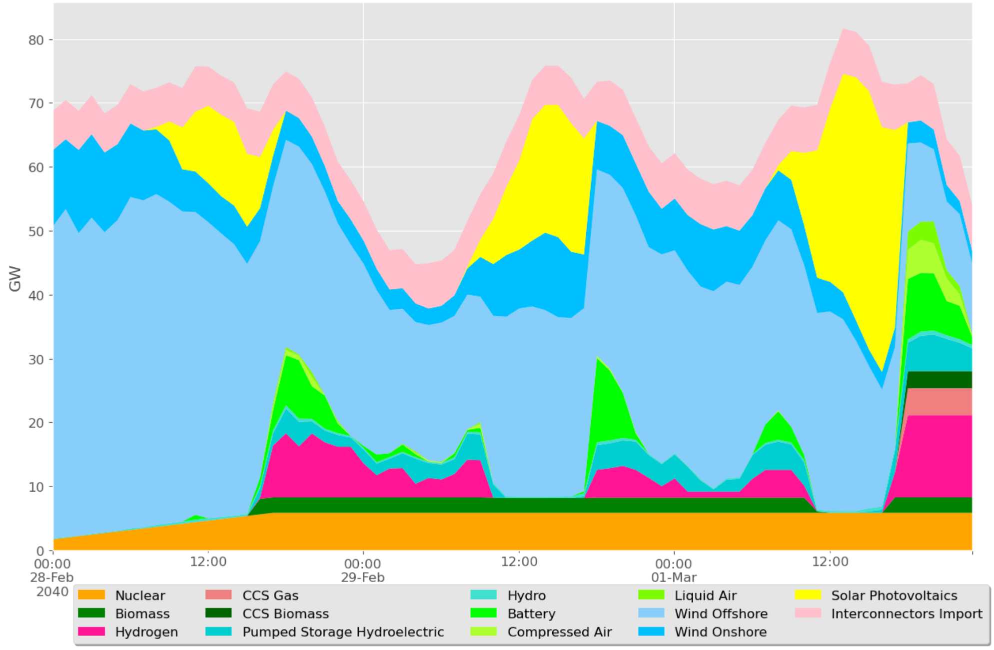
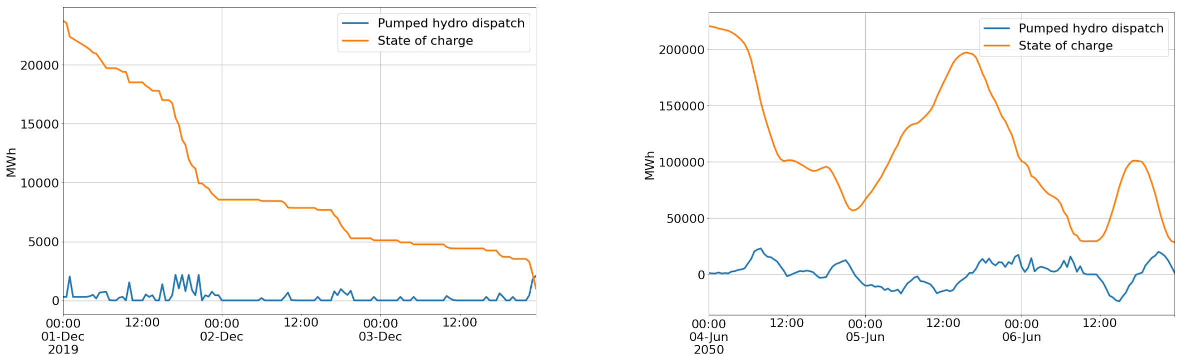


Figure 2: Future LOPF over a three day period in December 2050 under Leading the Way.



(a) Pumped hydroelectric storage over 2019 three day period.

(b) Pumped hydroelectric storage over 2050 three day period.

Figure 3: Pumped storage hydroelectric. State of charge is the MWh stored in each timestep, and dispatch is MWh charged or discharged in hourly timesteps (equivalent to MW).

Appendix for numerical data). The figure shows most generation types have similar power outputs. The generation types which are not similar are coal and natural gas. The input marginal prices for the simulation are always higher for coal than natural gas, and therefore very little coal generation can be seen. It is likely that additional electricity market factors such as capacity markets are influencing the higher production of coal over natural gas. The assumptions for calculating the marginal price for natural gas and coal does not wholly reflect market prices. Additionally, coal power stations use coal blending schemes to introduce coal slurry referred to as pond fines into their fuel mix as this lower grade coal isn't subject to carbon tax. In 2016, Ratcliffe had pushed their pond fines content to 25% of their total coal input. This is not accounted for in the model [86] and is likely a contributing factor for the under-prediction of coal generation.

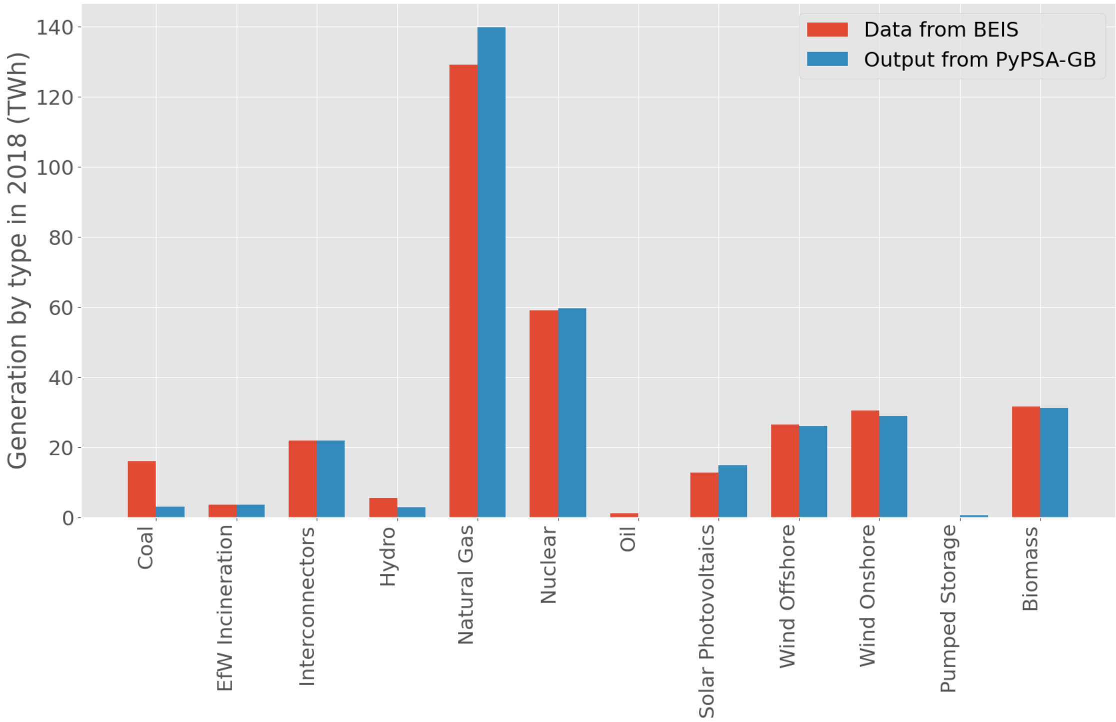


Figure 4: Comparison of LOPF simulation of 2018 to historical data published by BEIS.

3.2. Illustrative Case Study: Wind Curtailment in Scotland in 2035

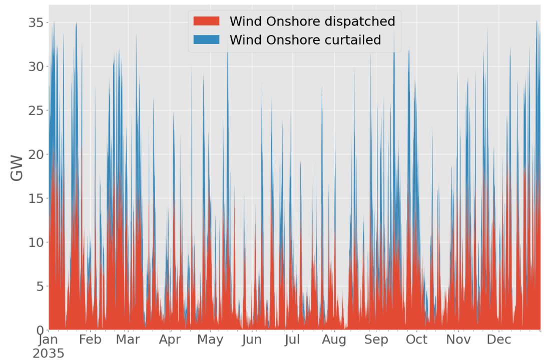
Wind curtailment in Scotland in 2035 was chosen as as an illustrative case study to highlight the use of PyPSA-GB in planning studies. This is a relevant case study because there are targets for a net zero power system by 2035. There is also expected to be a high proportion of installed capacity of onshore wind farms located in Scotland whose generation will be exported to the rest of GB. This may lead to frequent curtailment due to constraints in the network. This problem is already occuring with constraint payments to wind farms in the UK rising between 2015 and 2021 from £90 to £140 million [87]. An LOPF simulation was run for the whole of GB over 2035 under the FES22 Leading the Way scenario, and network has been scaled to projected levels in the Leading the Way scenario.

This scenario contains larger renewable generation than is currently on the system, for example, the installed offshore wind generation is 83GW and the demand peak is 80GW (see Table 4 in the Appendix for all installed capacities). Network constraints occur over the Scotland-England boundary due to these large scale installation of renewables in Scotland which has better wind resource.

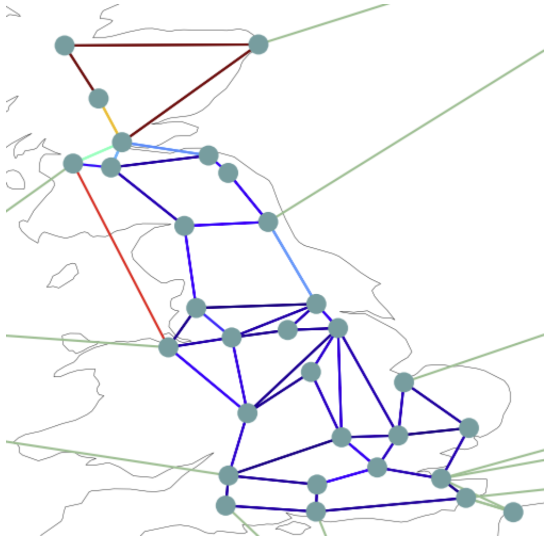
Figure 5a shows the profiles of onshore wind generation which is dispatched and used to meet demand, and curtailed where the potential generation is reduced, and Figure 5b shows the relative line loading with higher relative loading seen for this snapshot in Scotland than England, which is indicative of closer to constrained areas in Scotland.

High levels of curtailment can be seen, and while there is energy storage in this case study it may reflect a requirement for network expansion or additional flexibility measures (e.g., large-scale thermal energy storage [88]) as more renewables are built in Scotland which needs to transported to the higher demands in England. This analysis results in 36.6 TWh of wind dispatched and 29.4 TWh of wind curtailed; meaning that 44.5% of potential wind generation is curtailed. For comparison, running the model with the same assumptions but with no network constraints results in 51.2 TWh of wind dispatched and 14.9 TWh of wind curtailed; meaning that 22.5% of potential wind generation is curtailed. Around half the curtailment is not included when using the model without network constraints.

This illustrative case study shows the potential of using PyPSA-GB in vital questions such as renewable energy curtailment in future energy scenarios.



(a) Dispatch and curtailment of onshore wind for 2035.



(b) Relative line loading for snapshot in 2035, with red indicating high loading and blue low loading.

Figure 5: Curtailment of onshore wind farm generation in 2035 under FES scenario Leading the Way.

4. Discussion

PyPSA-GB builds upon the power systems analysis functionality of PyPSA with a model implementation of high spatial and temporal resolution to represent the GB power system for both historical years (2010-2020) and future years (2021-2050). Combining PyPSA with the collated relevant historical and future GB-specific energy system data provides an open-source basis for future studies. This section discusses the data implemented, future developments, and the reusability of the model to be used and developed by other researchers.

The reduced network model representation of the current transmission network was developed more than 10 years ago and has been updated in this model. This network can capture the constraints between buses, in particular the Scotland-England border constraint where high renewable generation from wind farms in Scotland are often constrained and unable to connect to the higher demand found in England. The zonal model allows for easier integration of the network upgrades planned by National Grid in their Electricity Ten Year Statement studies [54]. There is scope for utilising other network models, such the network model included in the OATS power system modelling tool which is similar to the reduced network model but with more buses [89].

Interconnectors are currently included as HVDC links with fixed marginal costs based on user input assumptions. However, this fails to capture the marginal cost dynamics in the connected countries. A Europe-wide model or dataset, such as a clustered PyPSA-Eur model [24], Euro-Calliope [90], JRC TIMES model [91], IIASA scenario explorer [92] could be used to generate import/export interconnector flows or marginal costs, which could then be used as exogenous inputs to PyPSA-GB. PyPSA-GB only includes connections which are in the current pipeline, while connections to countries further away (see the Britain-Morocco proposed interconnector [[93]) may be installed in the future.

For future energy scenarios there is data on the future of fuel and emission trading scheme costs for coal, natural gas, and oil but this has not been scrutinised in terms of uncertainty. Meanwhile, the model relies on speculative data input for future marginal costs for future dispatchable power plants such as hydrogen and CCS gas and biomass. Predicting these costs is beyond the scope of this work, but an interesting avenue for future consideration, particularly in the field of whole energy system modelling.

Hydrogen is included as a generator type and electrolysers as storage at each bus. Future extension could include hydrogen pipes with links between nodes to represent transport. It would then be useful to differentiate types of hydrogen based on how they are produced (e.g., green hydrogen is made from renewable energy sources, and blue hydrogen is made from splitting natural gas with carbon capture and storage), this would enable endogenous marginal costs for electricity production form hydrogen. Additionally, many existing gas turbines could be retrofitted to run on hydrogen which will influence the spatial distribution of hydrogen power plants.

Modelling of power generation from renewable power generation has relied primarily on Atlite (see 2.2.5 for introdudction and references related to Atlite) Renewable Power with weather data from the ERA5 reanalysis dataset, historical installed capacities from the Renewable Energy Planning Database, and future projected installed capacities from FES21 and FES22. Historical profiles required scaling in order to make up for the missing small-scale, <150kW, generators, while future profiles required additional data sources to project the spatial distribution. The ERA5 dataset has been shown to be one of the best for energy system modelling, but an advantage of Atlite is the integration of multiple weather datasets. Examples illustrated in the PyPSA-GB documentation focus on year (or sub-year) simulations, whereas the importance on storage requirements when simulating multiple weather years has been highlighted in a recent study [94]. Further, use of future climate change adjusted data could be instructive, as done in other studies [95].

Interpretation has been necessary to discretise the technology of aggregated 'Marine' into installed capacities of tidal stream, tidal lagoon and wave power FES2021 and FES2022, based on grid supply points and Struthers et al. [79]. However, the relatively small proportion of installed capacity by generation type makes it likely that the results would be relatively insensitive to this interpretation.

PyPSA-GB currently only includes electrical storage, and does not include demand-side flexibility measures such as electric vehicle to grid, demand response, and thermal storage. A wider range of storage and flexibility options are to be implemented in the model in future work.

In terms of software, workflow management tools such as *snakemake* [96], as for instance PyPSA-Eur, greatly enhances reproducibility while giving the model flexibility to react to new data and parametric inputs. PyPSA-GB currently does not use such a tool. Incorporating *snakemake* is a target of future model updates, in particular as the model iterates through research projects, and gains traction with the community.

A central contribution of PyPSA-GB is reusability to enable future development and application by other energy system modellers. This discussion section has highlighted a number of areas where further development can be made, however, the model is also mature enough to be applied by others looking to undertake GB operational and planning studies, such as analysing the role of sector coupling in future energy scenarios. The current model includes the FES21 and FES22 data and National Grid publish an annual report with updated modelling every year, and is robust to future updates in the FES data.

The modular and extensible nature of PyPSA-GB allows for the incorporation of new technologies, market structures, and policy scenarios. This can foster innovation and facilitate the exploration of diverse pathways for the evolution of the power system. PyPSA-GB's practical applications extend to the realm of policy-making. Policymakers can utilise the model to assess the implications of different policy interventions on the energy system. By simulating various policy scenarios, decision-makers can make informed choices that align with broader energy transition goals, such as decarbonisation and sustainability. The transparency and flexibility of PyPSA-GB also facilitate stakeholder engagement in the policy-making process. The model can serve as a communication tool, enabling policymakers to convey complex energy system dynamics to diverse audiences. This transparency fosters a shared understanding among stakeholders, ultimately leading to more effective and widely accepted policy measures.

5. Conclusions

This paper has presented PyPSA-GB which is a model implementation of the GB power system consisting of data and power flow functionality encompassing historical years and the future energy scenarios developed by National Grid. It is the first fully open-source model implementation of GB with high spatial and temporal resolution, and data for future years up to 2050, and analysis in this paper shows good agreement with historical data.

PyPSA-GB is openly available which has benefits such as: enabling transparency, peer review, reproducibility, and traceability; improved collaboration between modellers and policy makers; improved collaboration between researchers; and a more prominent role in wider public debate. Many countries are facing similar challenges in developing open-source energy models to provide transparent and evidence-proven energy system development decision for decarbonisation, the method and approach provided in this work can be generally applicable.

PyPSA-GB provides an open-source basis for GB operational and planning studies, as illustrated in the wind curtailment in Scotland case study, and for future studies e.g., whole system analysis, sector coupling, flexibility options such as large-scale thermal energy storage, and evolving electricity markets such as locational pricing. PyPSA-GB is reusable which enables future development and application by other energy system modellers.

6. Supplementary Material and Acknowledgements

Please see the GitHub repository - https://github.com/andrewlyden/PyPSA-GB - in addition to the documentation - https://pypsa-gb.readthedocs.io/ - for more details on PyPSA-GB.

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References

[1] BEIS, Net Zero Strategy: Build Back Greener, October, 2021. URL: https://www.gov.uk/government/publications/net-zero-strategy.

[2] CCC, Net Zero Technical Report (2019) 304 pp.

[3] P. Allen, P. James, Zero carbon Britain: rising to the climate emergency, 2019. URL: https://cat.org.uk/info-resources/zero-carbon-britain/research-reports/zero-carbon-britain-rising-to-the-climate-emergency/.

[4] S. Pfenninger, L. Hirth, I. Schlecht, E. Schmid, F. Wiese, T. Brown, C. Davis, M. Gidden, H. Heinrichs, C. Heuberger, S. Hilpert, U. Krien, C. Matke, A. Nebel, R. Morrison, B. Müller, G. Pleßmann, M. Reeg, J. C. Richstein, A. Shivakumar, I. Staffell, T. Tröndle, C. Wingenbach, Opening the black box of energy modelling: Strategies and lessons learned, Energy Strategy Reviews 19 (2018) 63–71.

[5] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, I. Staffell, The importance of open data and software: Is energy research lagging behind?, Energy Policy 101 (2017) 211–215.

[6] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renewable and Sustainable Energy Reviews 33 (2014) 74–86.

[7] F. Cebulla, T. Naegler, M. Pohl, Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch, Journal of Energy Storage 14 (2017) 211–223.

[8] W. Sun, G. P. Harrison, Wind-solar complementarity and effective use of distribution network capacity, Applied Energy 247 (2019) 89–101.

[9] M. Sun, F. Teng, I. Konstantelos, G. Strbac, An objective-based scenario selection method for transmission network expansion planning with multivariate stochasticity in load and renewable energy sources, Energy 145 (2018) 871–885.

[10] J. Haas, F. Cebulla, W. Nowak, C. Rahmann, R. Palma-Behnke, A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply, Energy Conversion and Management 178 (2018) 355–368.

[11] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy 160 (2018) 720–739.

[12] A. Zerrahn, W. P. Schill, On the representation of demand-side management in power system models, 2015. doi:10.1016/j.energy.2015.03.037.

[13] M. Chang, J. Z. Thellufsen, B. Zakeri, B. Pickering, S. Pfenninger, H. Lund, P. A. Østergaard, Trends in tools and approaches for modelling the energy transition, Applied Energy 290 (2021) 116731.

[14] A. Lyden, R. Pepper, P. G. Tuohy, A modelling tool selection process for planning of community scale energy systems including storage and demand side management, Sustainable Cities and Society 39 (2018) 674–688.

[15] DigSILENT, PowerFactory - DIgSILENT, 2019. URL: https://www.digsilent.de/en/powerfactory.html.

[16] MATPOWER, MATPOWER - Free, open-source tools for electric power system simulation and optimization, 2019. URL: https://matpower.org/.

[17] S. Pfenninger, B. Pickering, Calliope: a multi-scale energy systems modelling framework, Journal of Open Source Software 3 (2018) 825.

[18] T. Niet, A. Shivakumar, F. Gardumi, W. Usher, E. Williams, M. Howells, Developing a community of practice around an open source energy modelling tool, Energy Strategy Reviews 35 (2021).

[19] R. Loulou, M. Labriet, Etsap-tiam: the times integrated assessment model part i: Model structure, Computational Management Science 5 (2008) 7–40.

[20] H. Teichgraeber, A. R. Brandt, Clustering methods to find representative periods for the optimization of energy systems: An initial framework and comparison, Applied Energy 239 (2019) 1283–1293.

[21] J. P. Deane, A. Chiodi, M. Gargiulo, B. P. Ó Gallachóir, Soft-linking of a power systems model to an energy systems model, Energy 42 (2012) 303–312.

[22] W. Sun, G. P. Harrison, P. E. Dodds, A multi-model method to assess the value of power-to-gas using excess renewable, International Journal of Hydrogen Energy 47 (2022) 9103–9114.

[23] T. Brown, J. Hörsch, D. Schlachtberger, PyPSA: Python for power system analysis, Journal of Open Research Software 6 (2018) 4.

[24] J. Hörsch, F. Hofmann, D. Schlachtberger, T. Brown, Pypsa-eur: An open optimisation model of the european transmission system, Energy Strategy Reviews 22 (2018) 207–215.

[25] J. G. Dedecca, R. A. Hakvoort, P. M. Herder, Transmission expansion simulation for the european northern seas offshore grid, Energy 125 (2017) 805–824.

[26] M. Parzen, H. Abdel-Khalek, E. Fedotova, M. Mahmood, M. M. Frysztacki, J. Hampp, L. Franken, L. Schumm, F. Neumann, D. Poli, A. Kiprakis, D. Fioriti, Pypsa-earth. a new global open energy system optimization model demonstrated in africa, Applied Energy 341 (2023) 121096.
[27] National Grid, FES document | National Grid - Future Energy Scenarios, 2016. URL: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021.
[28] P. E. Dodds, The UK TIMES Model, Technical Report, 2013.
[29] BID3: AFRY's Power Market Modelling Suite | AFRY, 2022. URL: https://afry.com/en/service/bid3-power-market-modelling.
[30] H. E. Daly, B. Fais, UK TIMES MODEL OVERVIEW (2014).
[31] highRES | UCL ENERGY INSTITUTE MODELS - UCL – University College London, 2022. URL: https://www.ucl.ac.uk/energy-models/models/highres.
[32] M. Zeyringer, J. Price, B. Fais, P. H. Li, E. Sharp, Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather, Nature Energy 3 (2018) 395–403.
[33] S. Pfenninger, B. Pickering, Calliope: a multi-scale energy systems modelling framework, Journal of Open Source Software 3 (2018) 825.
[34] S. Pfenninger, Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability, Applied Energy 197 (2017) 1–13.
[35] M. M. Rienecker, M. J. Suarez, R. Gelaro, R. Todling, J. Bacmeister, E. Liu, M. G. Bosilovich, S. D. Schubert, L. Takacs, G.-K. Kim, et al., Merra: Nasa's modern-era retrospective analysis for research and applications, Journal of climate 24 (2011) 3624–3648.
[36] Ucl, Uk times, 2020. URL: https://www.ucl.ac.uk/energy-models/models/uk-times.
[37] Ember-Climate, Ember-climate/ember-pypsa, 2020. URL: https://github.com/ember-climate/ember-pypsa.
[38] ETI, ESC, 2020. URL: https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2014/04/ESME_Modelling_Paper.pdf.
[39] D. Pudjianto, G. Strbac, Whole system value of long-duration electricity storage in systems with high penetration of renewables, iEnergy 1 (2022) 114–123.
[40] M. Chaudry, L. Jayasuriya, J. W. Hall, N. Jenkins, N. Eyre, S. Eggimann, Simulating flexibility, variability and decentralisation with an integrated energy system model for great britain, Scientific Reports 13 (2023) 4772.
[41] D. of Energy Climate Change, The Dynamic Dispatch Model: a fully integrated power market model — gov.uk, https://www.gov.uk/government/statistics/the-dynamic-dispatch-model-a-fully-integrated-power-market-model, 2012. [Accessed 14-12-2023].
[42] C. K. Chyong, D. Newbery, A unit commitment and economic dispatch model of the gb electricity market – formulation and application to hydro pumped storage, Energy Policy 170 (2022) 113213.
[43] S. Berendes, S. Hilpert, S. Günther, C. Muschner, S. Candas, K. Hainsch, J. van Ouwerkerk, S. Buchholz, M. Söthe, Evaluating the usability of open source frameworks in energy system modelling, Renewable and Sustainable Energy Reviews 159 (2022) 112174.
[44] Q. Huangfu, J. J. Hall, Parallelizing the dual revised simplex method, Mathematical Programming Computation 10 (2018) 119–142.
[45] National Grid ESO, National Grid ESO: Future Energy Scenarios (FES) 2021, Technical Report, 2021. URL: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021.
[46] National Grid ESO, National Grid ESO: Future Energy Scenarios (FES) 2022, Technical Report, 2022. URL: https://www.nationalgrideso.com/future-energy/future-energy-scenarios.
[47] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Ostergaard, B. Möller, S. Nielsen, I. Ridjan, P. KarnOe, K. Sperling, F. K. Hvelplund, Smart Energy Systems for coherent 100% renewable energy and transport solutions, 2015. URL: https://www.sciencedirect.com/science/article/pii/S0306261915001117. doi:10.1016/j.apenergy.2015.01.075. arXiv:arXiv:1011.1669v3.
[48] PyPSA, PyPSA: Python for Power System Analysis — PyPSA 0.19.2 documentation (2022).
[49] J. A. Taylor, Convex optimization of power systems, Cambridge University Press, 2015.
[50] J. Hörsch, H. Ronellenfitsch, D. Witthaut, T. Brown, Linear optimal power flow using cycle flows, Electric Power Systems Research 158 (2018) 126–135.
[51] A. J. Wood, B. F. Wollenberg, G. B. Sheblé, Power generation, operation, and control, John Wiley & Sons, 2013.
[52] SP Energy Networks, Western HVDC Link - SP Energy Networks, 2020. URL: https://www.spenergynetworks.co.uk/pages/western_hvdc_link.aspx.
[53] UoE, Reduced GB Network, 2013. URL: https://www.maths.ed.ac.uk/optenergy/NetworkData/reducedGB/.
[54] National Grid, Electricity Ten Year Statement (ETYS) (2013) | National Grid, 2013. URL: https://www.nationalgrideso.com/research-publications/etys.
[55] ENTSO-E, Grid Map, 2021. URL: https://www.entsoe.eu/data/map/. doi:10.4135/9781529776713.
[56] Openinframap, Open Infrastructure Map, 2018. URL: https://openinframap.org/#2/26/12.
[57] Ofgem, Interconnectors, 2022. URL: https://www.ofgem.gov.uk/energy-policy-and-regulation/policy-and-regulatory-programmes/interconnectors.
[58] I. G. Wilson, S. Sharma, J. Day, N. Godfrey, Calculating Great Britain's half-hourly electrical demand from publicly available data, Energy Strategy Reviews 38 (2021) 100743.
[59] ELEXON, Electricity industry Data, 2022. URL: https://www.elexon.co.uk/data/.
[60] National Grid, ESO Data Portal: Demand - Dataset| National Grid Electricity System Operator, 2020. URL: https://data.nationalgrideso.com/demand/historic-demand-data.
[61] T. Bobmann, I. Staffell, The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain, Energy 90 (2015) 1317–1333.
[62] BEIS, Digest of UK Energy Statistics 2021 (2021).

[63] E. Climate, Ember - Coal to clean energy policy, 2021. URL: https://ember-climate.org/.

[64] D. Hirst, Carbon Price Floor (CPF) and the price support mechanism, Technical Report Briefing Paper 05927, 8 January 2018, 2018. URL: https://researchbriefings.files.parliament.uk/documents/SN05927/SN05927.pdf.

[65] G. Harris, P. Heptonstall, R. Gross, D. Handley, Cost estimates for nuclear power in the UK, Energy Policy 62 (2013) 431–442.

[66] D. R. McIlveen-Wright, Y. Huang, S. Rezvani, D. Redpath, M. Anderson, A. Dave, N. J. Hewitt, A technical and economic analysis of three large scale biomass combustion plants in the UK, Applied Energy 112 (2013) 396–404.

[67] Ofgem, Renewables Obligation (RO), 2021. URL: https://www.ofgem.gov.uk/environmental-and-social-schemes/renewables-obligation-ro.

[68] OSM, OpenStreetMap Wiki, 2015. URL: http://wiki.openstreetmap.org/.

[69] GEM, Global Energy Monitor, 2021. URL: https://www.gem.wiki/Main_Page.

[70] A. Schröder, F. Kunz, J. Meiss, R. Mendelevitch, C. von Hirschhausen, Current and prospective costs of electricity generation until 2050, Technical Report 68, 2013. URL: https://www.diw.de/documents/publikationen/73/diw_01.c.424566.de/diw_datadoc_2013-068.pdf.

[71] M. Angerer, S. Kahlert, H. Spliethoff, Transient simulation and fatigue evaluation of fast gas turbine startups and shutdowns in a combined cycle plant with an innovative thermal buffer storage, Energy 130 (2017) 246–257.

[72] F. Hofmann, J. Hampp, F. Neumann, T. Brown, J. Hörsch, atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series, Journal of Open Source Software 6 (2021) 3294.

[73] ECMWF Reanalysis v5 — ecmwf.int, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5, ???? [Accessed 14-12-2023].

[74] E. &. I. S. Department for Business, Renewable Energy Planning Database quarterly extract - GOV.UK, 2018. URL: https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract.

[75] The Scottish Government, Sectoral marine plan for offshore wind energy - gov.scot, 2020. URL: https://www.gov.scot/publications/sectoral-marine-plan-offshore-wind-energy/.

[76] L. Mackie, S. C. Kramer, M. D. Piggott, A. Angeloudis, Assessing impacts of tidal power lagoons of a consistent design, Ocean Engineering 240 (2021) 109879.

[77] T. Kärnä, S. C. Kramer, L. Mitchell, D. A. Ham, M. D. Piggott, A. M. Baptista, Thetis coastal ocean model: discontinuous galerkin discretization for the three-dimensional hydrostatic equations, Geoscientific Model Development 11 (2018) 4359–4382.

[78] D. Coles, A. Angeloudis, D. Greaves, G. Hastie, M. Lewis, L. Mackie, J. McNaughton, J. Miles, S. Neill, M. Piggott, et al., A review of the uk and british channel islands practical tidal stream energy resource, Proceedings of the Royal Society A 477 (2021) 20210469.

[79] I. A. Struthers, G. P. Harrison, D. Coles, A. Angeloudis, R. C. Thomson, Future scenarios and power generation of marine energy deployment around great britain, in: 11th International Conference on Renewable Power Generation - Meeting net zero carbon (RPG 2022), volume 2022, 2022, pp. 223–227. doi:10.1049/icp.2022.1831.

[80] S. Pennock, D. Coles, A. Angeloudis, S. Bhattacharya, H. Jeffrey, Temporal complementarity of marine renewables with wind and solar generation: Implications for gb system benefits, Applied Energy 319 (2022) 119276.

[81] RenewableUK, UK Marine Energy Database - RenewableUK, 2017. URL: https://www.renewableuk.com/page/UKMED2.

[82] C. Kalogeri, G. Galanis, C. Spyrou, D. Diamantis, F. Baladima, M. Koukoula, G. Kallos, Assessing the european offshore wind and wave energy resource for combined exploitation, Renewable Energy 101 (2017) 244–264.

[83] P. T. Moseley, J. Garche, Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Elsevier, 2014. URL: http://www.sciencedirect.com/science/article/pii/B9780444626165000085. doi:10.1016/C2012-0-01253-7.

[84] I. Staffell, Measuring the progress and impacts of decarbonising british electricity, Energy Policy 102 (2017) 463–475.

[85] S. Schlömer, T. Bruckner, L. Fulton, E. Hertwich, A. McKinnon, D. Perczyk, J. Roy, R. Schaeffer, R. Sims, P. Smith, et al., Annex iii: Technology-specific cost and performance parameters, in: Climate change 2014: Mitigation of climate change: Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2014, pp. 1329–1356.

[86] H. R. &. Customs, Excise Notice CCL1/6: a guide to carbon price floor, Technical Report, 2016. URL: https://www.gov.uk/government/publications/excise-notice-ccl16-a-guide-to-carbon-price-floor/excise-notice-ccl16-a-guide-to-carbon-price-floor.

[87] National Grid ESO, ESO Data Portal: Monthly Balancing Services Summary (MBSS) - Dataset, 2021. URL: https://data.nationalgrideso.com/balancing/mbss.

[88] A. Lyden, C. Brown, I. Kolo, G. Falcone, D. Friedrich, Seasonal thermal energy storage in smart energy systems: District-level applications and modelling approaches, Renewable and Sustainable Energy Reviews 167 (2022) 112760.

[89] W. Bukhsh, C. Edmunds, K. Bell, Oats: Optimisation and analysis toolbox for power systems, IEEE Transactions on Power Systems 35 (2020) 3552–3561.

[90] T. Tröndle, J. Lilliestam, S. Marelli, S. Pfenninger, Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in europe, Joule 4 (2020) 1929–1948.

[91] S. Simoes, W. Nijs, P. Ruiz, A. Sgobbi, D. Radu, P. Bolat, C. Thiel, S. Peteves, The jrc-eu-times model, Assessing the long-term role of the SET Plan Energy technologies (2013).

[92] D. Huppmann, Iiasa as a fair data hub for energy systems modeling & integrated assessment (2020).

[93] Xlinks, Morocco-UK Power Project - Xlinks, 2022. URL: https://xlinks.co/morocco-uk-power-project/.

[94] O. Ruhnau, S. Qvist, Storage requirements in a 100% renewable electricity system: Extreme events and inter-annual variability, Environmental Research Letters 17 (2022) 044018.

[95] M. Schlott, A. Kies, T. Brown, S. Schramm, M. Greiner, The impact of climate change on a cost-optimal highly renewable european electricity network, Applied Energy 230 (2018) 1645–1659.

[96] F. Mölder, K. P. Jablonski, B. Letcher, M. B. Hall, C. H. Tomkins-Tinch, V. Sochat, J. Forster, S. Lee, S. O. Twardziok, A. Kanitz, et al., Sustainable data analysis with snakemake, F1000Research 10 (2021).

[97] K. Bell, A. Tleis, Test system requirements for modelling future power systems, in: IEEE PES General Meeting, 2010, pp. 1–8. doi:10.1109/PES.2010.5589807.

[98] W. Bukhsh, C. Edmunds, K. Bell, Oats: Optimisation and analysis toolbox for power systems, IEEE Transactions on Power Systems 35 (2020) 3552–3561.

7. Appendix

Table 2: Comparison between the generation outputs from the LOPF simulation to historical data

	Simulated	Historical	Simulated - Historical	Simulated (%)	Historical (%)	Simulated (%) - Historical (%)
Coal	2.9	16	-13.1	0.9	4.7	-3.8
EfW Incineration	3.5	3.5	0	1.1	1	0.1
Interconnectors Import	21.9	21.9	0	6.6	6.5	0.1
Hydro	2.8	5.4	-2.6	0.8	1.6	-0.8
Natural Gas	139.8	129.1	10.7	42.1	38.3	3.8
Nuclear	59.6	59.1	0.5	18	17.5	0.5
Oil	0	1	-1	0	0.3	-0.3
Solar Photovoltaics	14.7	12.7	2	4.4	3.8	0.6
Wind Offshore	26	26.5	-0.5	7.8	7.9	-0.1
Wind Onshore	28.9	30.4	-1.5	8.7	9	-0.3
Pumped Storage Hydroelectric	0.6	0	0.6	0.2	0	0.2
Biomass	31.1	31.5	-0.4	9.4	9.3	0.1
Total	331.8	337.1	-5.3	100	99.9	0.1

Table 3: This table shows all of the data sources used in PyPSA-GB. Note license only named if data is released with explicit license, journals use various licences and are not included here.

Type	Data	Data processing	Source and License
Network	Reduced network model	Matpower file converted to buses and lines	Bell and Tleis [97], Bukhsh et al. [98] GPL-3.0 license
	Zonal model	Excel data converted to buses and links	National Grid's ETYS [54] NG ESO Open Data Licence v1.0
Electrical demand	ESPENI	Excel file converted to loads	Wilson et al. [58] Creative Commons Attribution Non Commercial 4.0 International
Marginal prices	Fuel costs from FES	Excel data converted to marginal price with addition of EU-ETS and CPS	National Grid's FES [46] NG ESO Open Data Licence v1.0
	EU-ETS	Excel data converted to marginal price in addition to fuel costs and CPS	Ember Climate [63] Creative Commons Attribution Licence (CC-BY-4.0)
	Carbon Price Support (CPS)	Excel data converted to marginal price in addition to fuel costs and EU-ETS	UK Gov (at time BEIS) [64] Open Government Licence v3.0
Thermal power plants and hydropower	Historical data on regional location, fuel, type, and installed capacity	Conversion from Excel data to generators	DUKES dataset [62] Open Government Licence v3.0
	Coordinates	Coordinate data converted to generators attributes - latitude and longitude	OpenStreetMap [68] - Open Data Commons Open Database License (ODbL), Global Energy Monitor [69] - Creative Commons Attribution 4.0 International Public License, Google Maps
	Technical characteristics	Data from papers converted to generators attributes	Schröder et al. [70] and Angerer et al. [71]
	Hydropower power output timeseries	Excel data converted to generators power time series	Elexon [59] with BSC Open Data licence
	Future installed capacities and regional location data	Excel data converted to generators attributes	National Grid's FES [46] NG ESO Open Data Licence v1.0
Renewable power	Renewable power time series	ERA5 weather data converted to generators power time series using Atlite	ERA5 [73] - CC BY 4.0 DEED, and Atlite [72] - MIT license
	Historical data on regional location, type, and installed capacity	Excel data converted to generators attributes	Renewable Energy Planning Database (REPD) [74] Open Government Licence v3.0
	Historical annual generation of renewables	Data from report used to scale REPD data (above) to account for <150kW installations	UK Gov (at time BEIS) [62] Open Government Licence v3.0
	Future installed capacities and regional location data	Excel data converted to generators attributes	National Grid's FES [46] NG ESO Open Data Licence v1.0
	Offshore wind in near-term future	Data from reports used for near-term spatal distributionof offshore wind as generators attribute	Pipeline in REPD [74] and Sectoral Marine Plan [75] Open Government Licence v3.0
	Tidal lagoon and stream power generation	Generators power time series using the Thetis coastal ocean model	Thetis [77] - MIT license
	Wave power generation	Wave climate data from ERA5 converted to generators power time series using power matrix	ERA5 [73] - CC BY 4.0 DEED, and power matrix [82]
Storage	Historical pumped hydro	Data from Excel converted to storage units attributes	DUKES dataset [62] Open Government Licence v3.0
	Future storage installed capacities and locations	Data from Excel converted to storage units attributes	National Grid's FES [46] NG ESO Open Data Licence v1.0
	Charging/discharging efficiency and standing losses data	Data from reports converted to storage units attributes	Moseley and Garche [83]
Emissions	Direct emissions data	Data from various sources converted to carbon factors for use in PyPSA-GB emission calculations	Staffell [84], Schlömer et al. [85]

Table 4: Installed generation and demand for 2035 Leading the Way scenario used in illustrative case study. Storage includes battery, compressed air, liquid air, and pumped hydro.

Type	**Capacity (MW)**
Biomass	973
Hydro	2,127
Marine	441
Offshore Wind	82,574
Onshore Wind	35,763
Solar	60,208
Waste	2,141
Storage	37,928
Gas	7,080
Hydrogen	7,642
Interconnectors	24,550
CCS	5,510
Nuclear	7,180
Demand peak (excludes electrolysis)	80,407