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PyPSA-Eur: An open optimisation model of the European transmission system

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ABSTRACT

PyPSA-Eur, the first open model dataset of the European power system at the transmission network level to cover the full ENTSO-E area, is presented. It contains 6001 lines (alternating current lines at and above 220 kV voltage level and all high voltage direct current lines), 3657 substations, a new open database of conventional power plants, time series for electrical demand and variable renewable generator availability, and geographic potentials for the expansion of wind and solar power. The model is suitable both for operational studies and generation and transmission expansion planning studies. The continental scope and highly resolved spatial scale enables a proper description of the long-range smoothing effects for renewable power generation and their varying resource availability. The restriction to freely available and open data encourages the open exchange of model data developments and eases the comparison of model results. A further novelty of the dataset is the publication of the full, automated software pipeline to assemble the load-flow-ready model from the original datasets, which enables easy replacement and improvement of the individual parts. This paper focuses on the description of the network topology, the compilation of a European power plant database and a top-down load time-series regionalisation. It summarises the derivation of renewable wind and solar availability time-series from re-analysis weather datasets and the estimation of renewable capacity potentials restricted by land-use. Finally, validations of the dataset are presented, including a new methodology to compare geo-referenced network datasets to one another.

1. Introduction

The energy system in Europe is undergoing a far-reaching transformation on multiple fronts: generation from variable renewable energy sources, such as wind and solar power, is growing due to the imperative of tackling climate change; electricity provision has been unbundled and liberalised, raising complex challenges for the efficient design and regulation of electricity markets; the need to decarbonise heating and transport is driving electrification of these sectors; and finally energy markets are being integrated across the continent [1].

To study this transformation, accurate modelling of the transmission grid is required. The need to take account of international electricity trading and the possibility of smoothing variable renewable feed-in over large distances (wind generation has a typical correlation length of around 600 km [2]) mean that models should have a continental scope. At the same time, high spatial detail is required, since national grid bottlenecks are already hindering the uptake of renewable energy today [3], and given persistent public acceptance problems facing new transmission projects [4], severe grid bottlenecks will remain a feature of the energy system for decades to come.

Currently there is no openly-available model of the full European transmission network with which researchers can investigate and compare different approaches to the energy transformation. The transmission grid dataset provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) for the 2016 Ten Year Network Development Plan (TYNDP) [5] is rendered unusable by restrictive licensing, the exclusion of Finland, Norway and Sweden, and a lack of geographical localisation of the represented substations. The lack of geo-data means that the crucial weather system correlations and dynamics cannot be mapped onto the network. In 2005 in Ref. [6] an openly-available model of the continental European transmission network (i.e. excluding the UK, Ireland, Scandinavia and the Baltic states) was presented using a manual matching of buses and lines to the raster graphic of the ENTSO-E map, along with an open power plant database based on the Global Energy Observatory [7]; this model was updated to the network of 2009 in Ref. [8]. Apart from not covering the

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full ENTSO-E area, this dataset has the problem that much of the data was extracted manually, which is potentially error-prone and hard to repeat as new data becomes available, the buses are missing geo-coordinates and the power plant database is incomplete. In Refs. [9,10] geo-coordinates and data for wind and solar plants were added to the dataset. Open datasets based on OpenStreetMap [11], such as the SciGRID network [12] and the osmTGmod [13] network, are of high quality in Germany, where data is well organised, but are not yet accurate for the rest of Europe. Similarly the open electricity model provided by the German Institute for Economic Research (DIW), ELMOD-DE [14], only covers Germany.

In this paper we present a model of the European power system at the transmission network level which remedies these many deficiencies: it is not only open but also contains a high level of detail for the full ENTSO-E area. Grid data is provided by an automatic extraction of the ENTSO-E grid map; a power plant database is presented using a sophisticated algorithm that matches records from a wide range of available sources and includes geo-data; other data, such as time series for electrical load and wind, solar and hydro-electric availability, and geographic potentials for the expansion of wind and solar power, are also described. A new technique for comparing network datasets is presented and used to validate the grid data. The dataset and all code used to generate it from the raw data are available online [15,16], as a model for the Python for Power System Analysis (PyPSA) framework version 0.13.1 [17,64].

In Section 2 the data sources and processing methods are presented; the data is validated in Section 3; limitations of the dataset are discussed in Section 4; conclusions are drawn in Section 5.

2. Data sources and methods

2.1. Network topology

The network topology and geography of substations and transmission lines have been extracted from the geographical vector data of the online ENTSO-E Interactive Map [18] by the GridKit toolkit [19]. We did not use the published extract at [20], since several errors like inadvertently duplicated alternating current (AC) lines and missing transformers and lines between substations of short distances below 1 km have been identified.

Instead we extended the GridKit toolkit[1]:

1. A python script was added to stitch the vector tiles from the ENTSO-E map according to the identifier attribute 'oid' before importing the line structures into GridKit, since the toolkit previously often mislabeled the overlapping parts of the same line as two separate circuits.
2. The tolerance for connecting dangling high-voltage direct current (HVDC) lines and their converter stations with the next high-voltage alternating current (HVAC) substations has been increased and the new connections have been manually verified.
3. AC lines carrying circuits of several voltage levels had to be split by inspecting the descriptive text tag and are split into several lines.
4. The columns and format of the extracted CSV lines have been aligned closer with PyPSA to simplify the subsequent import.

The electrical parameters are derived by assuming the standard AC line types in Table 1 for the length and number of circuits. The DC line capacities are assigned from the table in Ref. [21]. No transformer information is contained in the map, so a single transformer of capacity 2 GW (i.e. equivalent to four 500 MW transformers) is placed between buses of different voltage levels at the same location, with a reactance of 0.1 per unit. The transformer capacity assumption is on the high side to avoid introducing constraints where none exist in reality.

[1] The modified toolkit has been published at https://github.com/PyPSA/GridKit/.

Table 1
Standard line types for overhead AC lines [22].

Volt. level (kV)	Wires	Series resist. (Ω/km)	Series ind. reactance (Ω/km)	Shunt capacit. (nF/km)	Current therm. limit (A)	App. power therm. limit (MVA)
220	2	0.06	0.301	12.5	1290	492
300	3	0.04	0.265	13.2	1935	1005
380	4	0.03	0.246	13.8	2580	1698

The restriction to buses and transmission lines of the voltage levels 220 kV, 300 kV, and 380 kV in the landmass or exclusive economic zones of the European countries and the removal of 23 disconnected stub sub-networks (of less than 4 buses) produces the transmission network in Fig. 1 of all current transmission lines plus several ones which are already under or close to construction (these are marked in the dataset). In total the model contains 6001 HVAC lines with a volume of 345.7 TW km (of which 17 TW km are still under construction), 46 HVDC lines with a volume of 6.2 TW km (of which 2.3 TW km are still under construction). The buses are composed of 3657 substations and 1320 auxiliary buses, like joints and power plants.

The countries are partitioned into Voronoi cells as catchment areas, each of which is assumed to be connected to the substation by lower voltage network layers. These Voronoi cells are used to link power plant capacities and determine feed-in by potential renewable energy generation, as well as the share of demand drawn at the substation.

2.2. Conventional power plants

Official sources often only report on country-wide capacity totals keyed by fuel-type and year like the Eurostat nrg_113a database [23], the ENTSO-E net generation capacity [24] or the ENTSO-E Scenario Outlook and Adequacy Forecast (SO&AF) [25,26], while only seven countries[2] have official power plant lists collected and standardised by the Open Power System Data (OPSD) project [27].

This gap has been gradually closing since ENTSO-E started maintaining a power plant list (ENTSO-E PPL) on their Transparency Platform [28]. Unfortunately, it is still far from complete, for instance even after excluding solar and wind generators, the total capacity represented in Germany amounts only to about 57 GW, while the SO&AF reports 111 GW, 107 GW of which are also covered as operational in the German BNetzA Kraftwerksliste [29].

The powerplantmatching (PPM) tool and database [30] we present in this section achieves good coverage by (1) standardising the records of several freely available databases, (2) linking them using a deduplication and record linkage application and (3) reducing the connected claims about fuel type, technology, capacity and location to the most likely ones.

PPM incorporates several power plant databases that are either published under free licenses allowing redistribution and reuse or are at least freely accessible. In the order of approximate reliability, there are OPSD [27], ENTSO-E PPL [28], DOE Energy Storage Exchange [31], Global Energy Observatory (GEO) [7], Carbon Monitoring for Action (CARMA) from 2009 [32,33], DOE Energy Storage Exchange [31] (ESE) and the WRI Powerwatch project [34]. All of them are brought into the standardised tabular structure outlined in Table 2 by explicit maps between the various naming schemes and additional heuristics identifying common fuel-type or technology keywords like *lignite* or *CHP* in

[2] BE, DE, FR, HU, IE, IT, LT as listed by the Open Power System Data project at http://open-power-system-data.org/data-sources#23_National_sources.

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