Modelling the high-voltage grid using open data for Europe and beyond

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ABSTRACT

This paper provides the background, methodology and validation for constructing a representation of the European high-voltage grid (AC 220 kV to 750 kV) based on public data provided by OpenStreetMap. Grid components include commissioned substations, AC and DC transmission lines and cables, transformers, and converters as well as their respective technical parameters based on standard types. The data is provided as easy-to-access comma-separated values files. Hence, the dataset is suitable for model-independent, large-scale electricity and energy system modelling. For further ease-of-use, an interactive map is included to allow for visually inspecting the highly geospatially resolved data and its parameters. To assess the data quality, this paper compares the dataset with official statistics and representative model runs using PyPSA-Eur based on different electricity grid representations. The dataset and workflow are provided as part of PyPSA-Eur, an open-source, sector-coupled optimisation model of the European energy system. By integrating with the codebase for initiatives such as PyPSA-Earth, the value of open and maintainable high-voltage grid data extends to the global context. The dataset is published under the Open Data Commons Open Database (ODbL 1.0) licence.

Background & Summary

Energy system models are indispensable tools in today's world in order to understand the complex interactions between energy sources, technologies, policies, and markets. They are used by researchers, industry and policy makers to enable informed decision-making in the transition to a net-zero energy system. However, conclusions drawn from such models are only as good as the underlying data and assumptions. Especially the representation of existing energy infrastructure, such as the electricity grid, can have a deciding impact on future investments derived from such models.[?] While Transmission System Operators (TSOs) have their own information on the high-voltage grid, this data is often not publicly available to the level of detail needed for academic research purposes. Official institutions like the European Network of Transmission System Operators for Electricity (ENTSO-E) provide an online map[?] of the European high-voltage grid. There are however, several limitations typical for these sources: i) there is no underlying, topologically connected dataset, ii) it is not released under an open licence, iii) nor updated frequently, and iv) its geographic detail is limited or highly stylised.

There are previous projects that have modelled the European high-voltage grid or its parts based on OpenStreetMap (OSM) data. Some institutions provide data for particular regions, however all of them come with their individual limitations: While the most trustworthy data comes from TSOs themselves, they are — with few regional exceptions[?] — not georeferenced[?] or do not cover the entirety of Europe. Datasets from previous academic projects[?,?,?] are either very complex to reproduce or have not been updated for close to a decade. An overview of notable projects and datasets is listed in Table **??**. Proven to be a reliable public data source, we make use of OSM to introduce a transparent workflow in order to create a representation of the European high-voltage grid. On the lack of updates of existing datasets, there are two main advantages of our work compared to previous initiatives. First, our approach uses the OSM Overpass turbo Application Programming Interface (API)[?] that always allows to retrieve the latest OSM data. Second, an active OSM community as well as a large user base of PyPSA-Eur and integration into automated workflows mean frequent updates and validation of processed data. Debugging can be easily done with the help of the open source project OpenInfraMap[?] ~~which renders the OSM energy infrastructure on an interactive map~~ and the interactive map included in our dataset. Both tools render the electricity infrastructure in a JavaScript-based map which can be accessed with any modern browser. Finally, the entire workflow is developed in Python and may hence be more accessible than other implementations which require external dependencies (e.g. SQL databases, commercial software, Java).[?]

Compared to previous implementations in the global modal PyPSA-Earth,[?] we significantly improve the work in speed and data quality by taking advantage of the topological, electrical and geographical information available for Europe in OSM. Given the generic structure of the developed workflow, it can be easily applied to other regions and fed back to the global

PyPSA-Earth project. However, the output will directly depend on the OSM data quality for a particular region (e.g. whether data on the substation's geometric footprint is available). To fill in missing data, we introduce cleaning process that yields a representation of the European high-voltage grid. We benchmark the processed data against country-level statistics provided by ENTSO-E, concluding that OSM data coverage of the European high-voltage grid is high or even close to complete. These improvements will also contribute to the quality of transmission grids modelled on a global scale in PyPSA-Earth.

Methods

PyPSA-Eur is a spatially and temporally highly resolved, open-source, sector-coupled linear optimisation model that covers the European continent.[?] The model is build on top of the open-source toolbox PyPSA[?] and is suited for operational as well as expansion studies (transmission, generation, and storages). The model includes a stock of existing power plants (processed with the tool powerplanmatching[?]) as well as renewable potentials and availability time series (processed with atlite[?]). Throughout the last decade, PyPSA-Eur has gained a large user base from academia, industry, and policy makers alike and has been used in a variety of studies.[?,?,?,?,?,?,?,?] Other open-source models exist ~~, one notable being OSeMOSYS Global,~~ — notable and widely-used ones include the *open energy modelling framework (oemof)*[?] and *OSeMOSYS Global*.[?] ~~however it lacks~~ However both models lack the detailed geographical as well as electrical representation of the transmission grid that PyPSA-Eur provides. With the integration into PyPSA-Eur, we also enable compatibility with additional functions already implemented into the model, such as, but not limited to, the option to enable dynamic line rating[?] and adding projects under planning (e.g. European Ten-Year Network Development Plan[?] and the German Network Development Plan[?]).

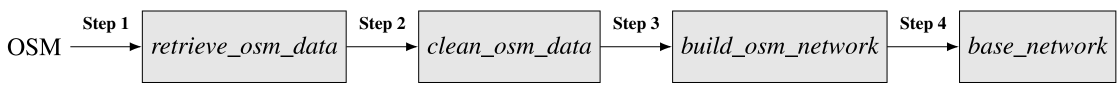

Figure 1. Process diagram for creating the European high-voltage grid from OSM data, representing the snakemake rules.

PyPSA-Eur is managed by a workflow management system called Snakemake.[?] Its modular structure enables the addition of new model functionalities and data sources, these can then be toggled using a configuration file. We split the construction of the high-voltage grid into four steps and add them into the existing workflow. We also use the model for validation purposes (see section Technical Validation). While the dataset and its reconstruction is built into PyPSA-Eur, it has the potential to be used in other energy system models, too. For this purpose, we release the entire dataset, including their original and mapped technical parameters. To obtain a functioning, topologically connected representation of the European high-voltage grid based on OSM data, we take the following steps (see Figure **??** for an application to an example region).

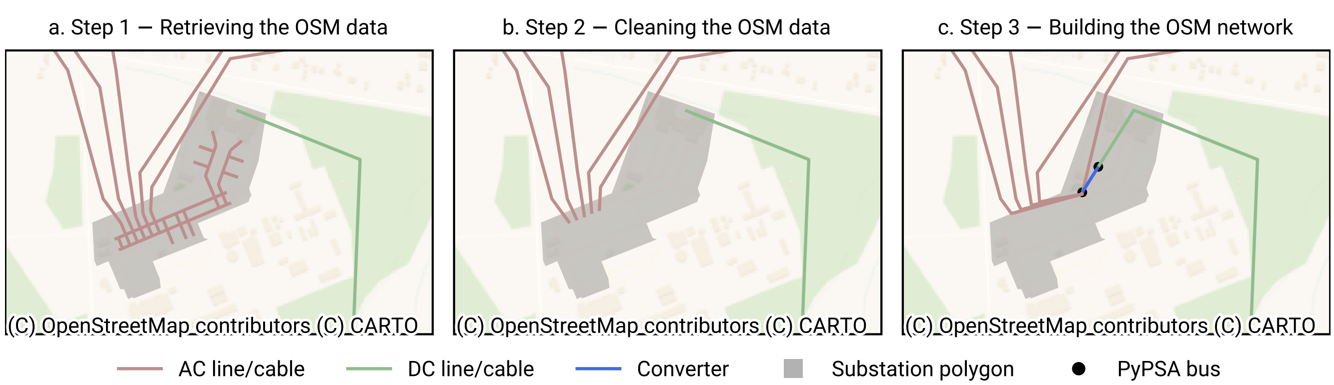

Figure 2. Illustration of the steps to create a PyPSA-ready network from OSM data. *Note that Step 4 does not make changes to the topology and is hence omitted from this illustration.*

Step 1 — Retrieving the ~~OSM~~ OSM data

In OSM, geographical data is stored in 'nodes', 'ways', and 'relations'. Being the simplest data type, nodes are defined by coordinates and associated parameters. Ways are geometric line strings that connect a set of nodes. Relations can contain nodes, ways, a combination of either or other relations.[?] For the purpose of this work, we extract ways for obtaining the outline of substations~~and AC power lines and cables.~~. For AC lines we use both ways and relations data to build the dataset. To harness the highest data quality available, we use relational data AC lines whenever available. To avoid for duplicates in the representation of an AC line, all members (ways) of a relation are removed from the dataset, respectively. This hybrid approach allows us to make use of relations, if they are complete and exist, and fall back to ways if relations are incomplete or missing.

To obtain DC projects (usually cables, hereafter refered to as DC links), we use relations. There are two main reasons for this differentiation: i) relations are the more complex data type, coverage for AC lines and cables is still scarce for Europe, whereas for DC links, given that there are much fewer of them in Europe, ~~coverage is close to~~ we consider the coverage of commissioned DC links complete (see Table **??**); ii) Some DC links contain multiple components, accessing relations allows us to efficiently aggregate and simplify the links for the purpose of static energy system modelling.

First, we retrieve the raw data using the Overpass turbo API[?] (Figure **??**.a). Specifically, we query the OSM database for electricity grid related features (see Table **??**). Note that Overpass turbo has a limit on the size and number of requests for each query and provides the API under a fair use policy. To avoid unnecessary load and re-use of data, we provide a prepared transmission grid for for download via Zenodo (0.6 is tge latest version at the time of publication).[?]

Step 2 — Cleaning the ~~OSM~~ OSM data

While OSM provides a rich dataset, it is not directly usable for energy system modelling. Next to geospatial coordinates, OSM includes tags that provide feature-specific additional information. Depending on the individual feature, data may however contain noise, be incomplete, or inconsistent. After importing the retrieved raw data into a pandas dataframe,[?] we apply a series of steps including heuristics to clean and fill in the missing information (see example in Table **??**). We then use the power of geopandas[?] to perform geospatial operations (including but not limited to spatial joins, intersections, buffering, etc.).

Substations and transformers

To obtain the set of substations, we filter for substations with a voltage level within the scope of interest, i.e. between AC ~~200 kV~~ 220 kV and 750 kV. Where available, we extract the polygon shape of the substations, stored in the element's geometry. This allows us to differentiate between internal and external grid components. Note that information on transformers are not extracted from OSM, as i) we cannot adequately evaluate their coverage and ii) this data is not sufficient to create a topologically connected network. Instead, we use a needs-based approach, i.e. adding a single transformer ~~of 2000 MW~~ between buses of different voltages within the perimeter of the same substation. The nominal capacity of the transformer is determined by the maximum of the sum of connected AC lines and cables on either side. This is in line with previous approaches to obtain the ENTSO-E map based transmission grid.[?]

~~AC~~ AC lines and cables

In a first step, we clean the tag columns to only contain the correct data type and unit, as shown in Table **??** for AC power lines and cables. The minimum parameters that need to be given for a particular line or cable are 'voltage' (in V) and 'power' (string: 'line' or 'cable').

Tag	Data type	Example
cables	numeric	9
circuits	numeric	3
frequency	numeric	50 Hz
power	string	line
voltage	numeric	380 000 V

Table 1. Key tags/parameters for AC power lines and cables.

We filter for the entries with a voltage level including and above AC 200 kV. While data for the mid- to low-voltage grid is also partially available in OSM, public statistics are scarce, making validation of such data difficult. As not all entries contain clean or complete data, we make heuristic assumptions to fill in the gaps, as illustrated in Tables **??** and **??**.

For each line or cable we use the most specific information available that the data provides. In a three-phase AC high-voltage system, we assume three cables to form an AC circuit (e.g. way/2).[?] If a way contains multiple data points split by semicolons (i.e. transmission lines sharing overhead line routes), we split the entries into individual lines, accordingly. In this process, we preserve the original OSM identifier and its associated geometries. We add a numbered suffix after the split to maintain unique line ids (e.g. way/3 becomes way/3-1 and way/3-2). The given electric parameters are mapped according to the semicolon splits. In some cases however, where the number of data points across columns is not equal (e.g. way/4 and way/5), we make the following assumption: we take the floor of the number of circuits divided by the number of entries in the voltage column. In the absence of better information, this may lead to an underestimation of the real number of circuits. If no information on cables nor circuits are available, we assume a single circuit, provided that a voltage level is given (e.g. way/6). Finally, we

line id	**cables**	**circuits**	**frequency** (Hz)	**type**	**voltage** (V)
way/1		2	50	cable	380 000
~~way~~relation/~~2~~1	3		50	cable	380 000
way/3	9	1;2	50	line	380 000; 220 000
way/4	9	3	50; 50	line	380 000; 220 000
way/5	8		50	line	110 000; 220 000
way/6			50	cable	300 000

Table 2. Illustrative example of AC lines and cables input data.

line id	**circuits**	**frequency (Hz)**	**type**	**voltage (V)**
way/1	2	50	cable	380 000
~~way~~relation/~~2~~1	1	50	cable	380 000
way/3-1	1	50	line	380 000
way/3-2	2	50	line	220 000
way/4-1	1	50	line	380 000
way/4-2	1	50	line	220 000
~~way/5-1~~	~~1~~	~~50~~	~~line~~	~~110 000~~
way/5-2	1	50	line	220 000
way/6	1	50	cable	300 000

Table 3. Illustrative example of AC lines and cables after cleaning. Changes highlighted in yellow.

remove all ways which represent bus bars and lines which are located fully inside of a substation outline (Figure **??**.b), as they are considered internal elements of the substation and provide no additional information for the purpose of static analyses.

DC links and converters

Due to their distinct electrical properties, we treat DC links differently from AC lines and cables. To avoid double counting, we remove all DC links from the original way queries. Instead, we query the OSM database for relations that contain DC links. As data on DC projects are widely available and because there are fewer of them,[?,?] we contribute to the OSM database by adding missing parameters such as the nominal rating and voltage level. This signifies the ease of data improvements with OSM for the benefit of all. In order for future DC projects to be traced by our workflow, the following tags are required: 'route' = 'power', 'frequency' = 0, and 'rating' in 'X MW' format. DC components need to be correctly linked in the OSM database as member (either 'cable' or 'line') of the parent relation, respectively.

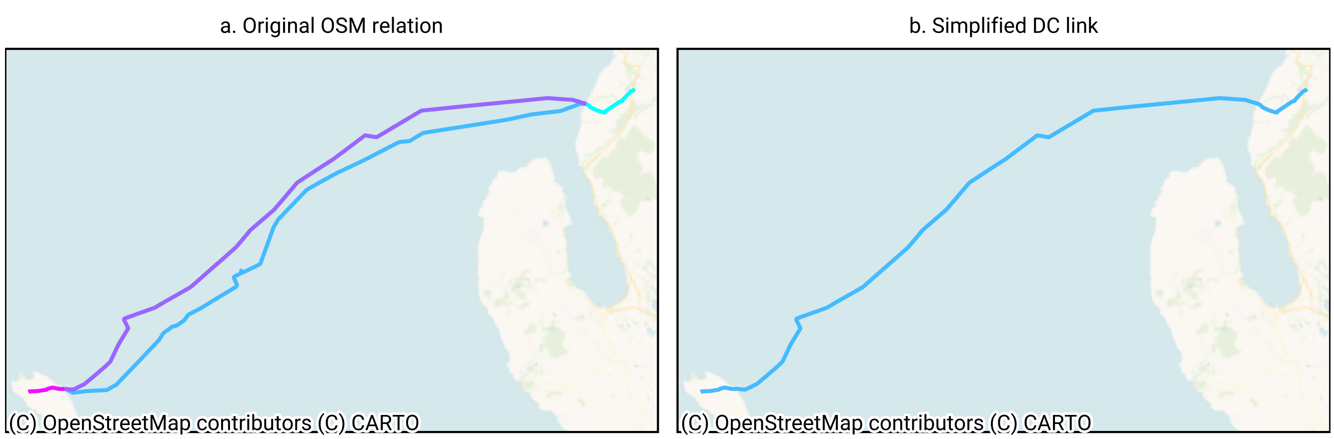

Figure 3. Example – Simplification of a DC link relation: Moyle interconnector (Scotland - Northern Ireland), OSM relation ID 6914309. *Different colors show the four segments, i.e. ways that compose the OSM relation.*

Note that some relations contain multiple DC link segments or components (e.g. converter stations or grounding), these are simplified into a single line with the sum of their nominal ratings. Figure **??** shows an example of how the Moyle interconnector from Northern Ireland to Scotland (Figure **??**.a) is simplified (Figure **??**.b). In this simplification, we preserve original end points of the DC link and the longest connected path. In PyPSA, converters are modelled as links connecting two buses. In analogy to how transformers are introduced to the network ex-post. i.e. connecting the terminals of the DC link, where the converter stations are also located on OSM and the closest AC bus in the transmission grid. As such, we guarantee that DC links are always topologically connected.

Step 3 — Building the ~~OSM~~ OSM network

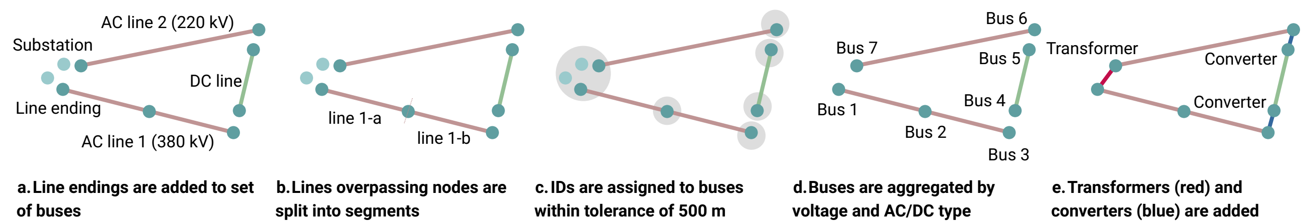

Figure 4. Illustration of building a topologically connected grid.

After having obtained a cleaned dataset, we need to ensure that the grid components are topologically and electrically connected. For this purpose, we propose a complete graph-based structure, i.e. buses/substations are connected by AC and DC lines, as well as converters and transformers. We introduce the following procedure, illustrated in Figure **??**.

First, we add the endpoints of both AC and DC lines to the set of buses (Figure **??**.a). We hereinafter refer to the buses created from endpoints as *virtual buses*. This step ensures that each line has two corresponding buses to which it is initially connected. Note that this may introduce potential duplicates of buses beyond those already present — which we will take care of later. Next, we take of long lines that are overpassing (multiple) substations. Here we assume that in reality, the substation is electrically connected to the overpassing line. To achieve this, we split the original line into the subsegments between the intersecting nodes and add a suffix to its original identifier (Figure **??**.b), to i) preserve the uniqueness of each line and ii) still allow for tracing back the line on OSM or OpenInfraMap.[?] We update the endpoints of the split lines, accordingly. Third, we cluster all buses within a radius of ~~5000 m. We do this for several reasons, i) to avoid duplicates of buses that represent the same substation in reality, ii) to improve the computational efficiency of the model and iii) to improve the topological connectedness of the obtained network. In an interative procedure, buses within the given radius are assigned the same ID (Figure ??.c). Fourth, we cluster all buses assigned to~~ 500 m: From each substation polygon provided by OSM and each virtual bus, a buffer of 500 m is created (see Figure **??**). Substations and virtual buses are assigned the same station ~~ID and AC/DC type. For each of the clusters, a bus is created~~identifier and clustered, if they overlap. Then we calculate an internal point based on the *Pole of Inaccessibility (PoI)*[?] which provides the geographic coordinates of the simplified substation. With this methodology, we can always find a polygon-internal point, even if the shape is non-convex. If the clustered shape contains one or multiple OSM substations, the largest substation determines the PoI of the simplified bus. Connected lines are remapped, accordingly (Figure **??**.d). Finally, we ensure that all given components are correctly electrically connected, i.e. AC buses of different voltage levels at the same substation are linked by transformers, DC buses which represent endpoints of DC lines are connected to the closest AC bus through converters (Figure **??**.e) of equal nominal rating, respectively. Figure **??** shows an example how the clustering algorithm is applied and how lines are connected.

The proposed methodology is an enhanced version of the data processing integrated in the PyPSA-Earth model[?] which has previously demonstrated the potential of using OSM data for global energy system modelling. Our proposed methodology improves the original implementation in efficiency, computational performance and enhancing the representation of the European high-voltage grid (see Technical Validation Section).

Step 4 — Creating a PyPSA-ready base network

In a final step, we create a network ready for modelling within PyPSA and PyPSA-Eur. The benefit of our our dataset is that it is provided in .csv format and easily readable. Further, we include all original and mapped technical parameters of the grid components. Hence, it may potentially be used outside our given use case, directly or with small adaptations.

Based on the voltage levels, we map each line to a standard line type library provided with PyPSA[?,?,?,?] with the closest voltage (e.g. 400 kV is mapped to a 380 kV line type). Using the standard grid model provided by 50Hertz,[?] we demonstrate in Figure **??** that this approach is effective for this particular region in the absence of more accurate data. Using the geometry line length and number of circuits, we calculate the electric parameters, such as impedance, reactance and apparent power S^{AC}_{nom} (Eq. **??**), as these are not contained in the original OSM input data. We point out, that while the mapped standard line type of a 380 kV and a 400 kV is the same, the calculated apparent power differs given the multiplication with their individual voltage

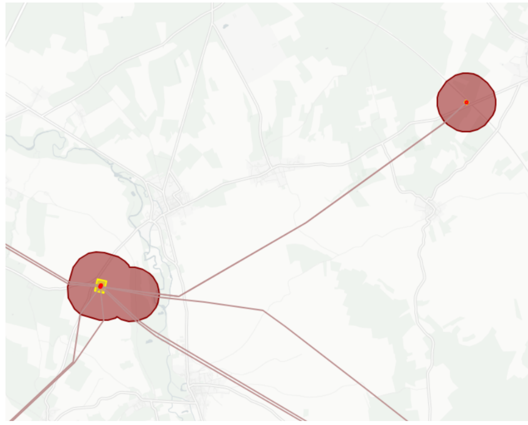

Figure 5. Example for clustering of buses. Taken from the interactive map linked on Zenodo. [?] *The darkred shape represents the union of the buffer created by virtual buses and an original OSM substation polygon (yellow). The bright red dot represents the internal point (PoI) of the union, this point sets the geographic coordinates of the obtained bus. Lines and cables are connected to the respective voltage level within the substation, transformers are added to connect buses of different voltage levels. In this example, no DC bus is connected to the substation, hence no converters are added.*

levels, respectively. We apply a factor of 0.7 to approximate the N-1 security margin (Eq. **??**).[?,?] Note that this factor can be individually set in the configuration file of PyPSA-Eur. We provide an overview of all resulting AC lines and cables in Table **??**.

$$S_{nom}^{AC} = n_{circuits} \cdot \sqrt{3} \cdot U_{nom}^{OSM} \cdot I_{nom}^{pandapower} \tag{1}$$

$$S_{n-1}^{AC} = 0.7 \cdot S_{nom}^{AC} \tag{2}$$

For DC links, we use the provided length and nominal rating, directly. We assume that all DC links can be operated in both directions. Lastly, after transformers and converters have been added to the network, we remove all unconnected or islanded components.

Data Records

The compiled representation of the European high-voltage grid (Figure **??**) is hosted online in .csv format and can be downloaded via the Zenodo repository.[?] The dataset includes the geographical scope of the ENTSO-E member states (without Cyprus, Iceland, Kosovo, and Turkey)~~.~~, i.e. Albania (AL), Austria (AT), Belgium (BE), Bosnia and Herzegovina (BA), Bulgaria (BG), Croatia (HR), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Kosovo (XK), Latvia (LV), Lithuania (LT), Luxembourg (LU), Moldova (MD), Montenegro (ME), Netherlands (NL), North Macedonia (MK), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Serbia (RS), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), Ukraine (UA), and the United Kingdom (GB).

We continuously update the dataset as the underlying OSM input data and the workflow is improved. As of the submission of this paper, the resulting network (Figure **??**) contains 5848 buses, 7320 AC lines and cables, 36 simplified/aggregated DC links (and converters at their endpoints, respectively), and 1059 AC transformers, comprising a total of 261 757 km in total route length. In the following, we describe the structure, parameters, and units of the grid components which stored comma-separated value files of the same name. The description refers to the version that serves as a foundation of this publication (i.e. version 0.6).[?]

Buses (buses.csv)

All AC and DC substations are represented as buses and stored in the 'buses.csv' file (0.9 MB). The file contains the following columns and properties:

- `bus_id` (string): Unique identifier of the bus. The name of a bus is derived in two ways: If a OSM relation or way was used to create the bus, the prefix starts with 'way/' or 'relation/', accordingly. As such, the original identifier is preserved. If the bus is a result of endpoints of connected lines or cables ('virtual buses'), without an underlying OSM, the prefix is the two-letter ISO3166-1 alpha-2 country code, numbered from North to South and West to East. The suffix represents the voltage level of the bus.

- `voltage` (integer): Nominal voltage level of the bus in kV as extracted from the OSM data or connected lines and cables (in the case of virtual buses).

- `dc` (boolean): Boolean flag indicating whether the bus type is DC (True/t) or AC (False/f).

- `symbol` (string): String that describes the nature of the bus. By design, all buses are substations, hence the symbol is 'Substation'.

- `under_construction` (boolean): Boolean flag indicating whether the bus is under construction (True/t) or not (False/f). This is needed to differentiate commissioned substations from planned transmission projects when activating extensions of the PyPSA-Eur model. By design, all buses included in this dataset are commissioned and hence not under construction.

- `tags` (string): Additional information on the bus, e.g. the prefix of the bus. This string can be used to access the underlying OSM way or relation, if available.

- `x` and `y` (float): Geographical coordinates of the bus in the WGS84 (EPSG:4326) coordinate system, calculated using the PoI approach.[?]

- `geometry` (shapely Point): Geographical point of the bus in the WGS84 (EPSG:4326) coordinate system. This property provides the 'x' and 'y' formatted as Point object of the open-source Python library 'shapely'.[?] It can be imported using `shapely.wkt.loads()` function.

AC lines and cables (lines.csv)

All AC lines and cables are stored in the 'lines.csv' file. Given the high resolution of the geographic linestrings, its file size is considerably large (19.7 MB) and makes up the majority of the dataset's content and size. The file contains the following columns and properties:

- `line_id` (string): Unique identifier of the AC line/cable. The name is directly derived from the underlying OSM way or relation, preserving the original identifier. The suffix includes the voltage level in kV. Merged lines include a 'merged_' prefix, followed by the OSM identifier of the longest contained line/cable as well as the number of additional lines/cables that were merged.

- `bus0` and `bus1` (string): Reference to the buses at the start ('bus0') and end ('bus1') of the line/cable, see 'buses.csv'.

- `voltage` (integer): Nominal voltage level of the line/cable in kV as extracted from the OSM data.

- `i_nom` (float): Nominal current of the line/cable in kA as mapped using using pandapower's standard line type library.[?]

- `circuits` (integer): Number of parallel circuits of the line/cable, as extracted from the OSM data.

- `s_nom` (float): Nominal apparent power capacity of the line/cable in MVA as calculated using Eq. **??** based on pandapower's standard line type library.[?] Note that this value represents the maximum technical capacity (100 %) taking into account the number of circuits.

- `r` (float): Line resistance in Ω as calculated using the length of the line/cable and pandapower's standard line type library.[?]

- `x` (float): Line reactance in Ω as calculated using the length of the line/cable and pandapower's standard line type library.[?]

- `b` (float): Line susceptance in S as calculated using pandapower's standard line type library.[?]

- `length` (float): The length of the line/cable in m as calculated using the linestring of the underlying OSM way or relation, transformed from the WGS84 (EPSG:4326) coordinate system to a metric distance projection, i.e. LAEA Europe (EPSG:3035).

- `underground` (boolean): Boolean flag indicating whether the element is underground (True/t) or overhead (False/f), hence an overhead line or a cable. This information is derived from the OSM data.

- `under_construction` (boolean): Boolean flag indicating whether the line/cable is under construction (True/t) or not (False/f). This is needed to differentiate commissioned transmission lines from planned transmission projects when activating extensions of the PyPSA-Eur model. By design, all lines included in this dataset are commissioned and hence not under construction.

- `type` (string): Type of the line as mapped using pandapower's standard line type library.[?]. This property is the foundation for calculating 'r', 'x', 'b', and 's_nom'.

- `tags` (string): Additional information on the line/cable, e.g. the contained OSM way or relation. For merged lines/cables, contained elements are separated by semicolons.

- `geometry` (shapely LineString): Geographical line of the line/cable in the WGS84 (EPSG:4326) coordinate system. This property contains geographically highly spatially resolved linestring of the OSM way or relation. The endpoints have been cleaned to exactly end in 'bus0' and 'bus1'. The property is provided as a shapely LineString object.[?] It can be imported using `shapely.wkt.loads()` function.

DC lines and cables (links.csv)

All DC lines and cables are stored in the 'lines.csv' file (0.4 MB). The file contains the following columns and properties:

- `link_id` (string): Unique identifier of the DC line/cable. The name is directly derived from the underlying OSM way or relation, preserving the original identifier. The suffix includes the voltage level in kV and a 'DC' identifier.

- `bus0` and `bus1` (string): Reference to the buses at the start ('bus0') and end ('bus1') of the line/cable, see 'buses.csv'.

- `voltage` (integer): Nominal voltage level of the line/cable in kV as extracted from the OSM data.

- `p_nom` (float): Nominal real power capacity of the line/cable in MW as provided by the OSM relation.

- `length` (float): The length of the line/cable in m as calculated using the linestring of the underlying OSM way or relation, transformed from the WGS84 (EPSG:4326) coordinate system to a metric distance projection, i.e. LAEA Europe (EPSG:3035).

- `underground` (boolean): Boolean flag indicating whether the element is underground (True/t) or overhead (False/f), hence an overhead line or a cable. This information is derived from the OSM data.

- `under_construction` (boolean): Boolean flag indicating whether the line/cable is under construction (True/t) or not (False/f). This is needed to differentiate commissioned transmission lines from planned transmission projects when activating extensions of the PyPSA-Eur model. By design, all lines included in this dataset are commissioned and hence not under construction.

- `tags` (string): Additional information on the line/cable, e.g. the contained OSM relation.

- `geometry` (shapely LineString): Geographical line of the line/cable in the WGS84 (EPSG:4326) coordinate system. This property contains geographically highly spatially resolved linestring of the OSM way or relation. The endpoints have been cleaned to exactly end in 'bus0' and 'bus1'. The property is provided as a shapely LineString object.[?] It can be imported using `shapely.wkt.loads()` function.

Transformers (transformers.csv)

All transformers are stored in the 'transformers.csv' file (0.1 MB). The file contains the following columns and properties:

- `transformer_id` (string): Unique identifier of the transformer. The prefix is determined by the substation where the transformer is located. The suffixes contain the voltage 'bus0' and 'bus1' in kV.'

- `bus0` and `bus1` (string): Reference to the buses at the start ('bus0') and end ('bus1') of the line/cable, see 'buses.csv'.
- `voltage_bus0` and `voltage_bus0` (integer): Voltage level at the 'bus0' and 'bus1' side of the transformer in kV, respectively.
- `s_nom` (integer): Rounded (ceiling) apparent power of the transformer in MV A. This is determined by the maximum throughput of the transformer, i.e. the maximum of the sum of connected lines/cables on either side.
- `geometry` (shapely LineString): Geometry of the transformer, represented by a linestring in (EPSG:4326) coordinate system, connecting two buses of different voltage levels at a substation. It can be imported using `shapely.wkt.loads()` function.

Converters (converters.csv)

All converters are stored in the 'converters.csv' file (0.01 MB). The file contains the following columns and properties:

- `converter_id` (string): Unique identifier of the converter. The suffix is determined by the substation where the converter is located. The suffixes contain the voltage 'bus0' and 'bus1' in kV.'
- `bus0` and `bus1` (string): Reference to the buses at the start ('bus0') and end ('bus1') of the line/cable, see 'buses.csv'.
- `voltage` : Maximum voltage level of the converter in kV as extracted from OSM data of the connected DC lines/cables.
- `p_nom` (integer): Nominal real power capacity of the converter in MW, determined by the sum of real power capacities of the connected DC lines/cables.
- `geometry` (shapely LineString): Geometry of the converter, represented by a linestring in (EPSG:4326) coordinate system, connecting an AC and DC bus at a substation. It can be imported using `shapely.wkt.loads()` function.

Interactive map (map.html)

The dataset is accompanied by an interactive map using the open-source packages geopandas[?] and folium. The map contains all components of the dataset, i.e. buses, lines, transformers, and converters, their geometries and technical parameters. Using any modern browser to open the map allows for visual exploration of the dataset. Different layers can be individually activated or deactivated — technical properties can be inspected by hovering or clicking on the components. As the map is self-contained and stores all information of the dataset, it can be used offline and is considerably large at 53.1 MB. We provide a screenshot of the map in Figure ??.

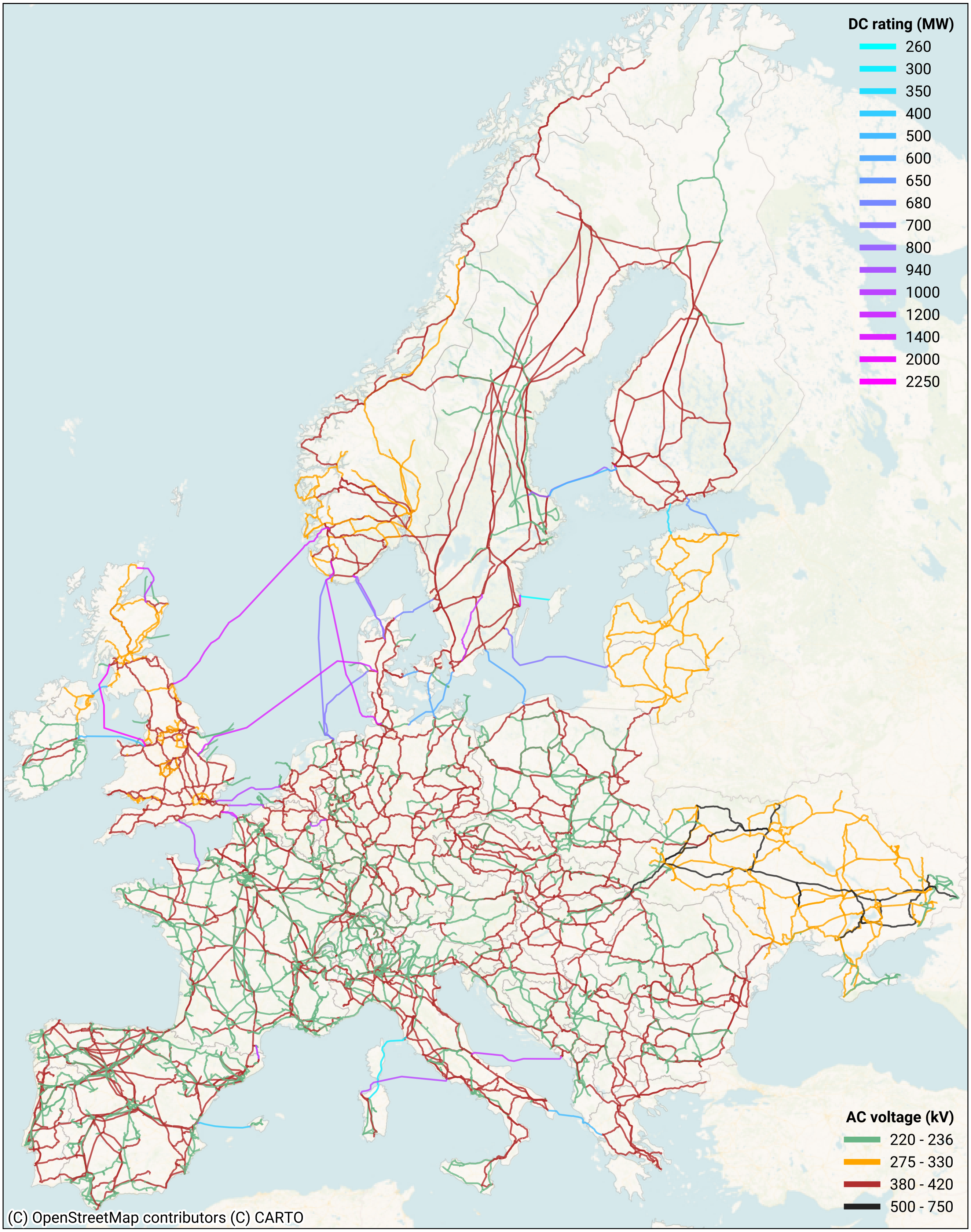

Figure 6. Map of the OSM-based European high-voltage grid. *This map was generated using the grid dataset provided with this publication.?*

Technical Validation

We perform two validation steps for assessing the quality of the dataset. First, we compare the dataset with official inventory statistics provided by ENTSO-E. Second, we compare the results of an representative PyPSA-Eur model instance based on the two high-voltage grid datasets: OSM (presented in **??**) and an extract from the online ENTSO-E map using GridKit tool (referred to as 'ENTSO-E map').[?] This network is currently being used by numerous PyPSA-Eur users, and is hence a good reference for comparison. In Figure **??**, we further provide a comparison between a geo-referenced, official dataset by 50Hertz[?] and the OSM-based grid of the region, respectively.

Comparison with ~~ENTSO-E~~ ENTSO-E statistics and map

Based on ENTSO-E's 2023 inventory of transmission,[?] we first compare the total route (a) and circuit lengths (b) of AC lines and cables on a per country level (Figure **??**.). Note that the inventory does not include all statistics for each country, i.e. route lengths are missing for Bosnia and Herzegovina, Switzerland, and Great Britain, while circuit lengths are missing for Montenegro and North Macedonia. While Ukraine and the Republic of Moldova have joined ENTSO-E on 1 January 2024 and 22 November 2023 as full and observing members, respectively, their inventory are not yet included in the dataset. For these two countries, we take reference data from third party sources.[?,?,?]

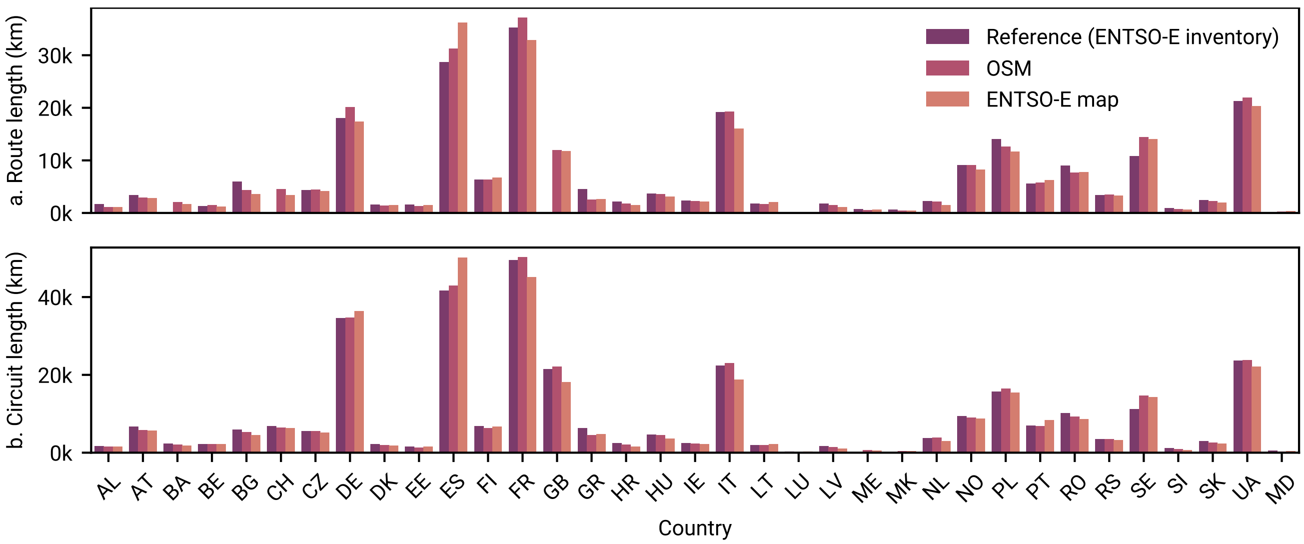

Figure 7. Comparison of total route and circuit lengths per country.

We find that our transmission grid based on OSM data is in agreement with the ENTSO-E inventory. Calculating the Pearson correlation coeffficient for both route and circuit lengths between the official statistics and the respective transmission grid representations, we see an overall improvement from the ENTSO-E map ($\rho_{routes} = 0.9497$ and $\rho_{circuits} = 0.9862$) to OSM ($\rho_{routes} = 0.9636$ and $\rho_{circuits} = 0.9980$) in the reproduction of the high-voltage grid (220 kV to 750 kV). One of the key reasons for these improvements is the much higher level of geographic detail of lines and cables in the OSM-based transmission grid compared to the stylised lines on ENTSO-E's interactive map. We observe larger discrepancies for Sweden, where both transmission grid representations seem to overestimate the total lengths of the inventory.

As another validation step, we compare the total line volume on NUTS1 region level (Figure **??**.a). Here we see strong similarities between the OSM-based and the extracted transmission grid of the ENTSO-E map, with few outliers ($\rho_{MVAkm} = 0.9484$). While a higher geospatial resolution of lines of the OSM-based transmission grid may contribute to the increase in line volume on average, we calculate S^{AC}_{nom} using the more differentiated voltage levels given in the OSM data (see Table **??**) as opposed to the clustered voltage levels given in the ENTSO-E map, i.e. 220 kV, 300 to 330 kV, 380 to 400 kV, 500 kV, and 750 kV. This may lead to a more accurate representation of the line volume in the OSM-based transmission grid.

To assess the transmission capacity across regions, we compare the capacity (Figure **??**.b) and number of line crossings (Figure **??**.c) per NUTS1 border (Figure **??**.b). While the two transmission grids strongly correlate, we observe notable differences at individual borders ($\rho_{MVA} = 0.8491$), the same is true for the absolute number of line crossings ($\rho_{crossings} = 0.8573$). Due to different quality in geospatial information contained in both transmission grid representations, buses in one may be offset (or not even exist) in the other. Stronger outliers can primarily be traced back to buses close to NUTS1 borders (Figure **??**.b). Notable outliers are located in Spain (light green), in Ukraine (pink), and southwestern parts of Germany (ocher). The reasons for discrepancies can be manifold, e.g. due to differences in exact locations of boundary nodes, missing, outdated or

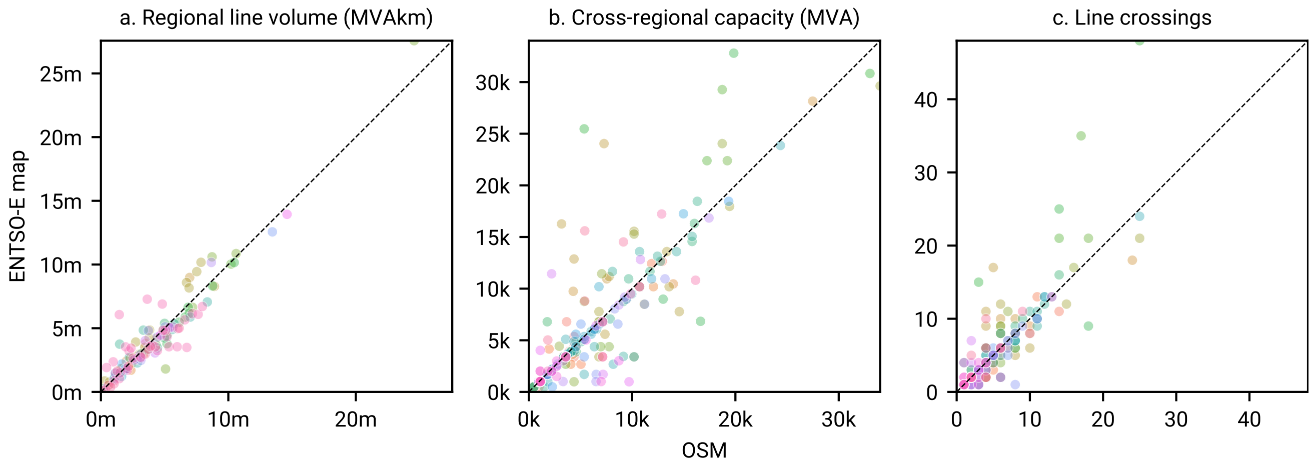

Figure 8. Comparison of line volume per NUTS1 region – Colors represent individual countries. *Line volume is the product of the nominal capacity and the length, summed over all lines within the region.*

wrong data. In the case of Spain, the main reason for the large discrepancy lies in the representation of the high-voltage grid in and around the Madrid area, where the ENTSO-E map is stylised for clarity. A comparison with an official map provided by the National Geographic Institute of Spain[?] confirms the OSM topology to be more accurate.

Comparison of model results

In order to assess the impact of the new transmission grid representation, we compare the results of a representative PyPSA-Eur model run based on the OSM dataset to a run based on the ENTSO-E map which is currently being used in PyPSA-Eur.[?] Note that the results shown in this publication are based on version ~~0.3~~ 0.6 of the released prebuilt high-voltage grid representation on Zenodo (https://doi.org/10.5281/zenodo.14144752).[?] We use the same model setup and input data in both model runs, except for the grid representation. We focus on the electricity sector, taking techno-economic assumptions projected for the year ~~2030.~~ 2030 based on version 0.9.2 of the PyPSA technology dataset. [?] We allow for capacity expansion in renewable energy as well as gas-fired generation capacities. To narrow down the effect of the transmission grid, we do not allow for grid expansion and disable dynamic line rating. We set the carbon price to 100 € per tonne of CO_2 emitted.

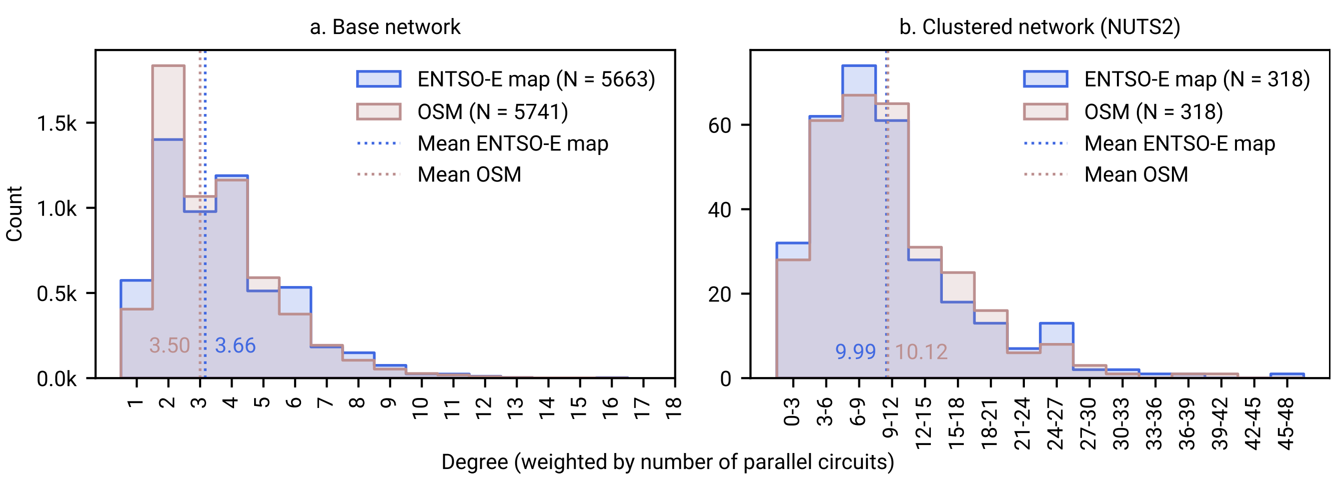

Figure 9. Comparison of the weighted degree distribution in both transmission grid representations before and after clustering (NUTS2). *Ukraine at geoBoundaries[?] administration level 1, Moldova in full bus resolution. A comparison at NUTS3 resolution is provided in Figure* **??**.

As the number and exact locations of buses differ, we cluster the networks to make them comparable (N = 318 regions/buses). In energy system modelling, clustering is often motivated by the spatial reduction of the optimisation problem. While oftentimes clustering algorithms based on grid topology or resource class are used,[?] we are interested in the regional differences of the two grid representations. As such, we map the buses of both grids to clusters based on administrative boundaries, i.e. NUTS2. For non-NUTS countries such as Ukraine, we use the administration level 1 (geoBoundaries[?]) and for Moldova we keep the full high-voltage substation resolution, i.e. 8 nodes. This yields 318 regions/buses for each of the clustered high-voltage grids, respectively. Note that the clustering process in PyPSA-Eur involves a transformation of all transmission lines and cables to the default voltage level of 380 kV. We then run the model at hourly resolution of the year 2030, yielding 8760 time steps.

Figure **??** compares the weighted degree distribution for the two network topologies. We weight the degree by the number of parallel circuits (Eq. **??**) to account for potential different representations of lines and links connecting the same two buses (e.g., single lines with multiple number of circuits or multiple lines with single circuits). If $G = (V, E)$ is a weighted graph with vertex set V (buses) and edge set E (lines, links, converters, and transformers), and each edge $e \in E$ has a weight $w(e)$, then the weighted degree of a vertex $v \in V$ is given by:

$$d_w(v) = \sum_{e \in \text{IncidentEdges}(v)} w(e) \tag{3}$$

where $\text{IncidentEdges}(v)$ is the set of edges incident to v. We find that the two base networks have a similar weighted degree distribution (Pearson correlation coefficient $\rho_{degree,base} = 0.8518$). Notably, the OSM-based transmission grid demonstrates a higher number of buses with degree 2. Clustering the two networks before running the optimisation problem will increase the Pearson correlation coefficient to $\rho_{clustered,base} = 0.8769$ (using unbinned data), $\rho_{clustered,base} = 0.9937$ (using binned data) — indicating that at NUTS2 resolution, the two networks are very similar in terms of connectivity~~and adequately represent the real grid~~.

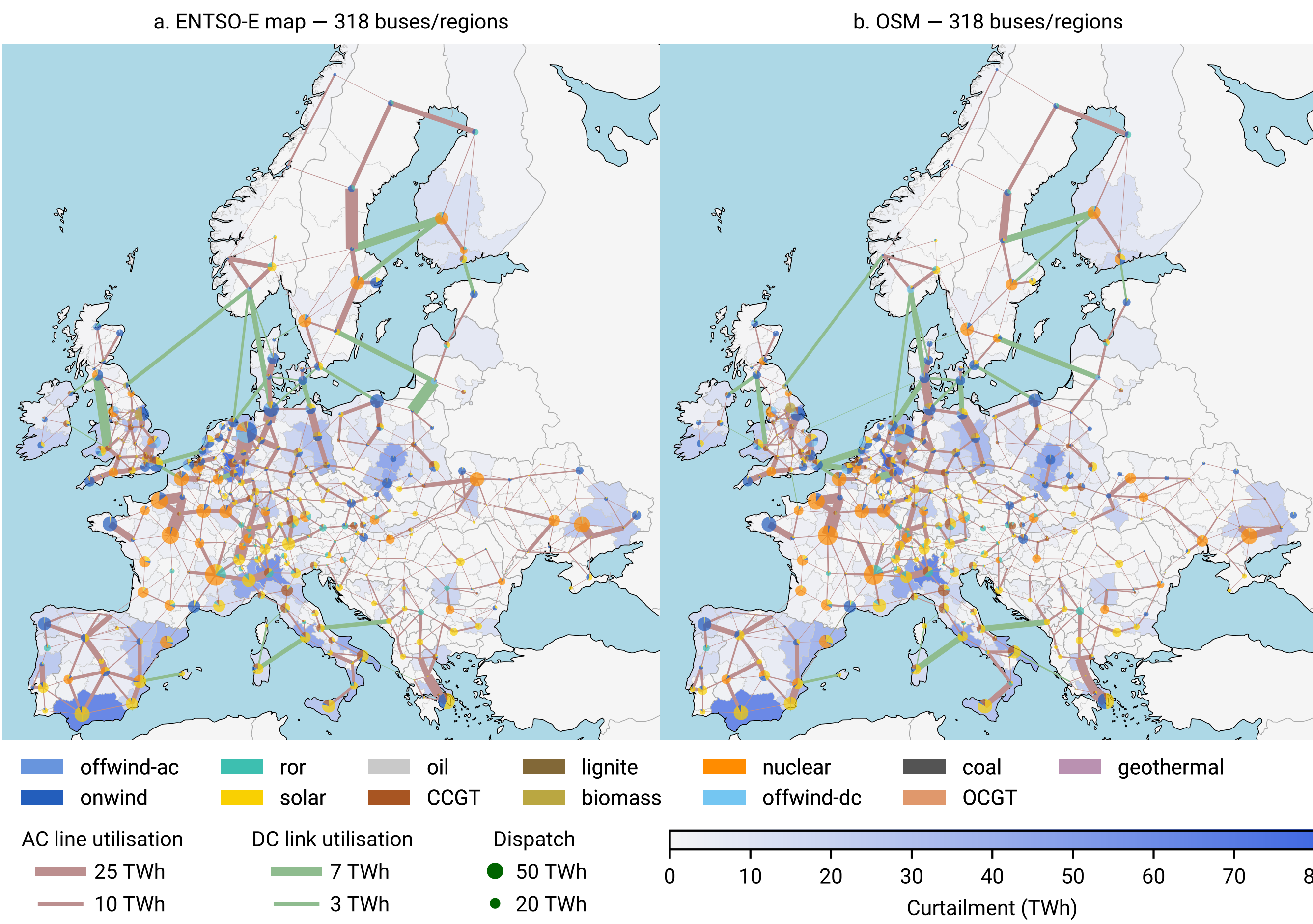

Figure 10. Regional dispatch, line utilisation and curtailment. *A map comparing nominal ratings of the two clustered grids is provided in the Figure* **??**.

We solve the two optimisation problems on a high-performance cluster (AMD EPYC 7543 32-Core processor) using up to 130 GB of memory. Each problem takes up to 274 iterations to converge, translating into more than 18 hours. Running the model for the two transmission grid representations, we find that regional results align closely, including the dispatch of generation assets, utilisation of lines and curtailment (Figure ??). This is also true for the aggregated picture (Table ??). Total system costs drop from 312.94 bn. € in the ENTSO-E map based run to 311.7 bn. € in the OSM-based optimisation, corresponding to mere 0.40 % in difference. The higher weighted degree for both the base and clustered OSM-based high-voltage grid (Figure ??) indicate a higher topological connectivity, potentially translating into higher degrees of freedom in the optimisation problem compared to the ENTSO-E map based run. This is confirmed when we look into i) the line and link utilisation and ii) compare the investments. Since aggregate statistics over a continental area can be deceiving (smooth out errors), we show the differences in regional generation, line and link utilisation as well as curtailment in Figure ??. Here, we can clearly see that the high-voltage grid in OSM is higher utilised than its ENTSO-E map based counterpart. We can also observe that the ENTSO-E map based model compensates by investing more into generation (especially decentral, semi-circles in the bottom half) and storage capacities, i.e. +4.9 GW in solar photovoltaics, +4.8 GW in onshore wind, +1.1 GW in offshore wind (AC), and +2.4 GW in battery storage. In the OSM-based model run, we see a slightly stronger build-out of DC connected offshore wind (+2.7 GW). We also provide an overview of average electricity prices, CAPEX and OPEX at nodal level in Figure ??.

	System costs (bn. €/a)	**CAPEX** (bn. €/a)	**OPEX** (bn. €)/a	**Curtailment** (TW h/a)	**Generation** (TW h/a)
ENTSO-E map	312.94	274.46	38.48	2177.91	3120.0
OSM	311.7	273.47	38.24	2175.57	3110.03
Delta (%)	-0.4	-0.36	-0.64	-0.11	-0.32

Table 4. Comparison of key result metrics between ENTSO-E map and OSM-based transmission grid.

Bottlenecks in both model runs are located in the same regions, contributing to an annual curtailment in the range of 2176 TW h to 2178 TW h. More prominent differences in line utilisation are visible in Norway and Poland from North to South, in the western region of Ukraine, southern and central Spain around the Madrid area, as well as southern Italy.

Overall, the results of the two model runs are very similar, indicating that i) both grids seem to adequately represent reality and ii) the OSM-based transmission grid is a suitable replacement for the ENTSO-E map based grid. The higher utilisation of the OSM-based transmission grid is in line with the higher topological connectivity of the network. The differences in the investment decisions are marginal and can be attributed to the differences in grid topology.

We have shown that the dataset is in good agreement with official statistics and the ENTSO-E map, and the results of a representative PyPSA-Eur model instance based on the two high-voltage grid datasets are very similar. Its core strengths lie in the high level of geographic detail and the continuous updates to the OSM database in combination with a strong PyPSA-Eur user base. The workflow is completely transparent and the data is provided openly. While we cannot guarantee the correctness of the data, as only TSOs have access to the real grid data, we believe that the dataset provides the best publicly available representation of the European high-voltage grid.

Δ OSM minus ENTSO-E map — 318 buses/regions

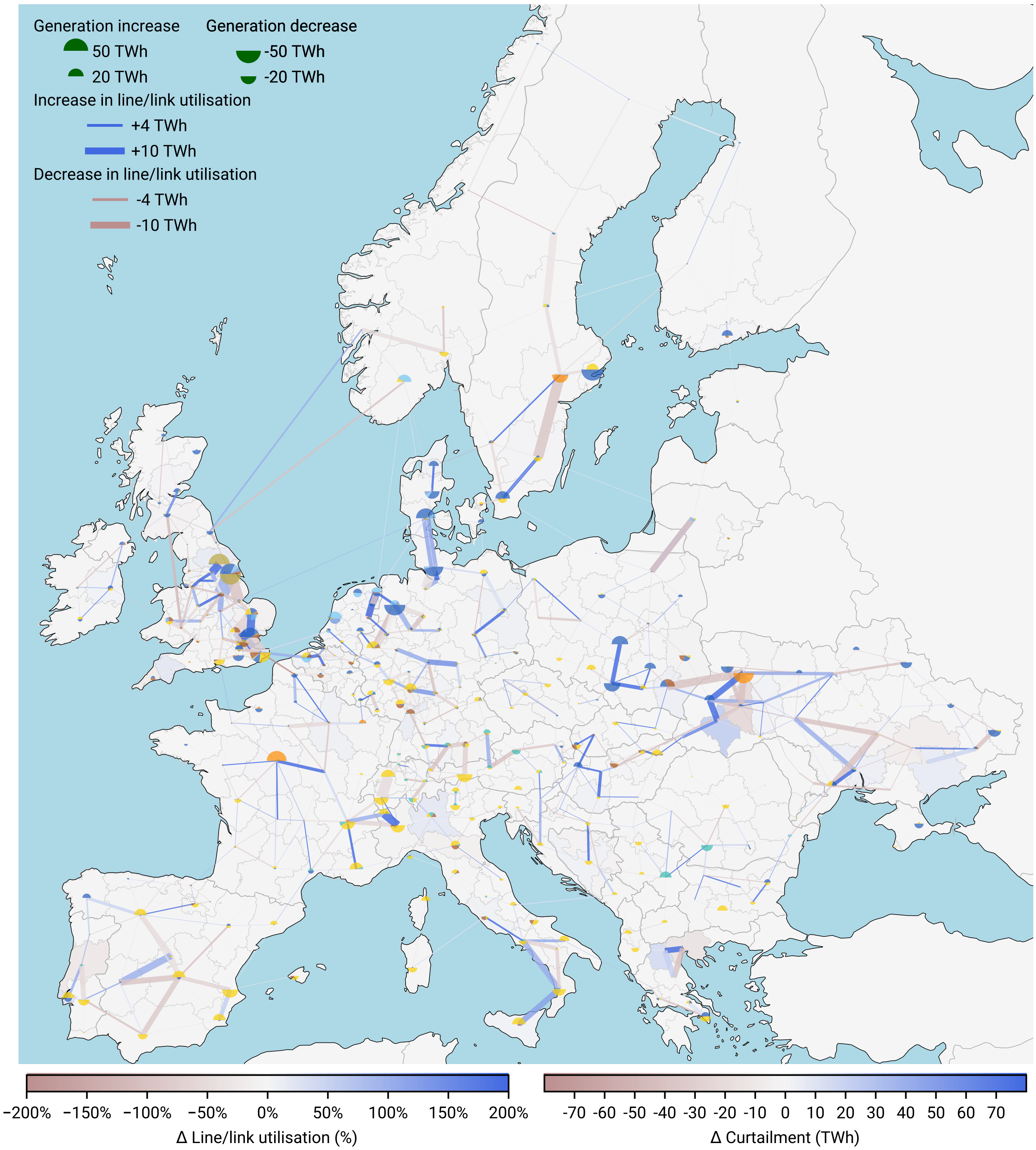

Figure 11. Regional dispatch, line utilisation and curtailment. *Blue indicates an increase in curtailment or line utilisation from the ENTSO-E map to the OSM-based transmission grid, while red indicates a decrease. For full transparency, note that this map shows an outer join of all transmission grid elements, including lines and links that are not present in the other network.*

Usage Notes

The published dataset is provided under the Open Data Commons Open Database License (ODbL) 1.0 licence. Geoinformation is encoded in the WGS84 (EPSG:4326) coordinate system. Although the dataset and workflow are provided as part of PyPSA-Eur, they are also suitable for a wide range of other applications, including network analyses, power flow calculations, as well as an input for other energy energy system models and frameworks. Note that further validation and testing is needed for purposes outside the original scope of this work.

- In order to reproduce the network with the latest OSM data, the configuration file 'config.yaml': needs to be set to `base_network = 'osm−prebuilt'` and the command `snakemake base_network −call` needs to be executed.
- To rebuild the network from scratch, this setting can be changed to `base_network = 'osm−raw'`, followed by the command `snakemake prepare_osm_network_release −call`.
- Per default, buses within the perimeter of a 5000 m radius are merged together. This value can be changed in the script, however this may change the topological connectedness of the obtained network.
- Networks can also be built for specific countries, regions or a subset of the countries within PyPSA-Eur by setting list of `countries` the configuration file.

To abide to the fair use policy of the OSM Overpass turbo API, we kindly encourage users to download the prebuilt network topology from the Zenodo repository and only rebuild the network, if necessary. We would further like to encourage readers to actively contribute to the OSM database.

Code availability

The code to replicate the entire workflow and dataset is provided as part of PyPSA-Eur and released as free software under the MIT licence. Different licences and terms of use may apply to the underlying input data.

- PyPSA-Eur? on GitHub:
  https://github.com/pypsa/pypsa-eur
- Version ~~0.3~~ 0.6 of the prebuilt network? based on OSM data can be retrieved via the Zenodo repository. This link will also point to future updates:
  https://~~zenodo~~doi.org/~~records~~10.5281/~~13358976~~zenodo.14144752
- An interactive map is bundled with the dataset on Zenodo (see Figure **??**). It can also be directly accessed via the PyPSA-Eur documentation under:
  INSERT LINK WHEN READY

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Author contributions statement

B.X. – Conceptualisation, Data curation, Methodology, Software/Programming, Model building and validation, Visualisation, Writing – original draft, review and editing. D.F. – Conceptualisation, Software/Programming, Writing – review and editing. F.N. – Conceptualisation, Discussion, Writing – review and editing. I.R. – Discussion, Writing – review and editing. T.B. – Supervision, Writing – review and editing.

Competing interests

The authors declare no competing interests.

Figures & Tables

Grid element	Overpass turbo query
AC power lines and cables	way[‘power’=‘line ’] ~~and~~ , way[‘power’=‘cable ’] and relation [" route "="power"][‘ frequency ’!=‘0’]
DC links	relation [‘ route ’=‘power ’][‘ frequency ’=‘0’]
substations	way[‘power’=‘ substation ’] and relation [‘power’=‘ substation ’]

Table 5. Overpass turbo queries used to extract the high-voltage grid elements from OSM.

Project	Regional scope	Tools/data	Last update	Geo-referenced	Data published
50Hertz static grid model[?]	Germany (50Hertz control area)	based on asset inventory	April 2022 (updated once a year)	Yes	Yes
ELMOD[?]	Europe	ENTSO-E interactive map[?] plus manual changes	January 2014 (data not published)	Yes	No
ELMOD-DE[?]	Germany	VDE, TSO maps, and OSM	March 2016 (single release)	Yes	Yes (not reproducible)
Hutcheon & Bialek[?]	Europe (UCTE plus Balkan region)	PowerWorld model	June 2013 (updated once)	No	Yes (not reproducible)
JAO static grid model[?]	CORE capacity calculation region	based on CORE TSO asset inventory	April 2024 (updated frequently)	No	Yes
PyPSA-Eur[?]	Europe	ENTSO-E interactive map[?] using GridKit[?] plus manual changes	January 2022 (updated once)	Yes	Yes (reproduction complex)
osmTGmod[?]	Germany	OSM using Osmosis (SQL and Java)[?]	November 2017 (single release)	Yes	Yes (reproduction complex)
SciGrid (Power)[?]	Europe, Germany	OSM using GridKit[?]	November 2015 (updated once)	Yes	Yes (reproduction complex)
This publication	Europe	OSM using Overpass turbo API and Python	~~August~~ November 2024 (updated frequently)	Yes	Yes[?] (reproducible)

Table 6. Notable projects and datasets modelling the high-voltage grid in Europe (alphabetical order). *Note that the specific regional scope referring to ‘Europe’ may vary across the listed projects. A comparison of our dataset with the 50Hertz static grid model is shown in Figure* **??**.

OSM relation identifier	**DC project name** (sorted alphabetically)	**From**	**To**	**Voltage** (kV)	**Rating** (MW)	**Calc. length** (km)

relation/157755

Western HVDC Link GB-SCT GB-WLS 600 2250 401

Table 7. List of DC projects in the OSM-based transmission grid. *Note that OSM relation identifiers are unique and persistent as long as the object is not deleted. Projects can be directly accessed via the OSM website by clicking on their respective relation identifier in the table.*

U_{nom}^{OSM} (kV)	Line type	$I_{nom}^{pandapower}$ (A)	$n_{circuits}$	S_{nom}^{AC} (MV A)	Total route length (km)
220	Al/St 240/40 2-bundle 220.0	1.290	1	492	52897
220	Al/St 240/40 2-bundle 220.0	1.290	2	983	22719
220	Al/St 240/40 2-bundle 220.0	1.290	3	1475	524
220	Al/St 240/40 2-bundle 220.0	1.290	4	1966	37
225	Al/St 240/40 2-bundle 220.0	1.290	1	503	19355
225	Al/St 240/40 2-bundle 220.0	1.290	2	1005	4465
236	Al/St 240/40 2-bundle 220.0	1.290	1	527	19
275	Al/St 240/40 3-bundle 300.0	1.935	1	922	1097
275	Al/St 240/40 3-bundle 300.0	1.935	2	1843	2845
300	Al/St 240/40 3-bundle 300.0	1.935	1	1005	4127
300	Al/St 240/40 3-bundle 300.0	1.935	2	2011	20
330	Al/St 240/40 3-bundle 300.0	1.935	1	1106	17335
330	Al/St 240/40 3-bundle 300.0	1.935	2	2212	1115
380	Al/St 240/40 4-bundle 380.0	2.580	1	1698	13971
380	Al/St 240/40 4-bundle 380.0	2.580	2	3396	13989
380	Al/St 240/40 4-bundle 380.0	2.580	3	5094	362
380	Al/St 240/40 4-bundle 380.0	2.580	4	6792	259
400	Al/St 240/40 4-bundle 380.0	2.580	1	1787	56750
400	Al/St 240/40 4-bundle 380.0	2.580	2	3575	30977
400	Al/St 240/40 4-bundle 380.0	2.580	4	7150	84
412	Al/St 240/40 4-bundle 380.0	2.580	1	1841	32
420	Al/St 240/40 4-bundle 380.0	2.580	1	1877	4839
420	Al/St 240/40 4-bundle 380.0	2.580	3	5631	11
500	Al/St 240/40 4-bundle 380.0	2.580	1	2234	248
750	Al/St 560/50 4-bundle 750.0	4.160	1	5404	4148

Table 8. Nominal capacities in the OSM base network AC lines and cables to pandapower standard type library.

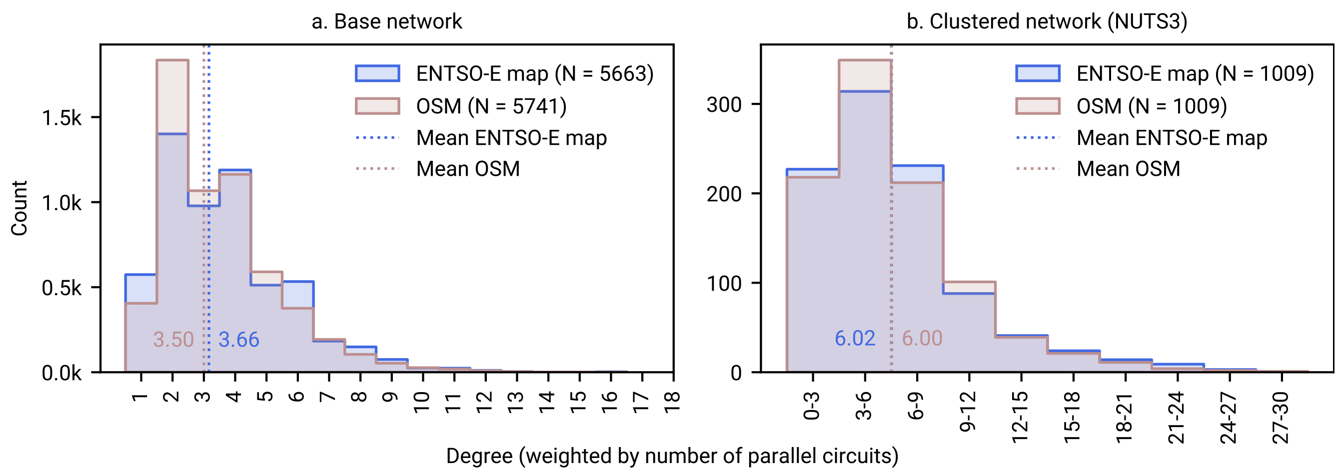

Figure 12. Comparison of the weighted degree distribution in both networks before and after clustering (NUTS3). *Ukraine at geoBoundaries*[?] *administration level 1, Moldova in full bus resolution.*

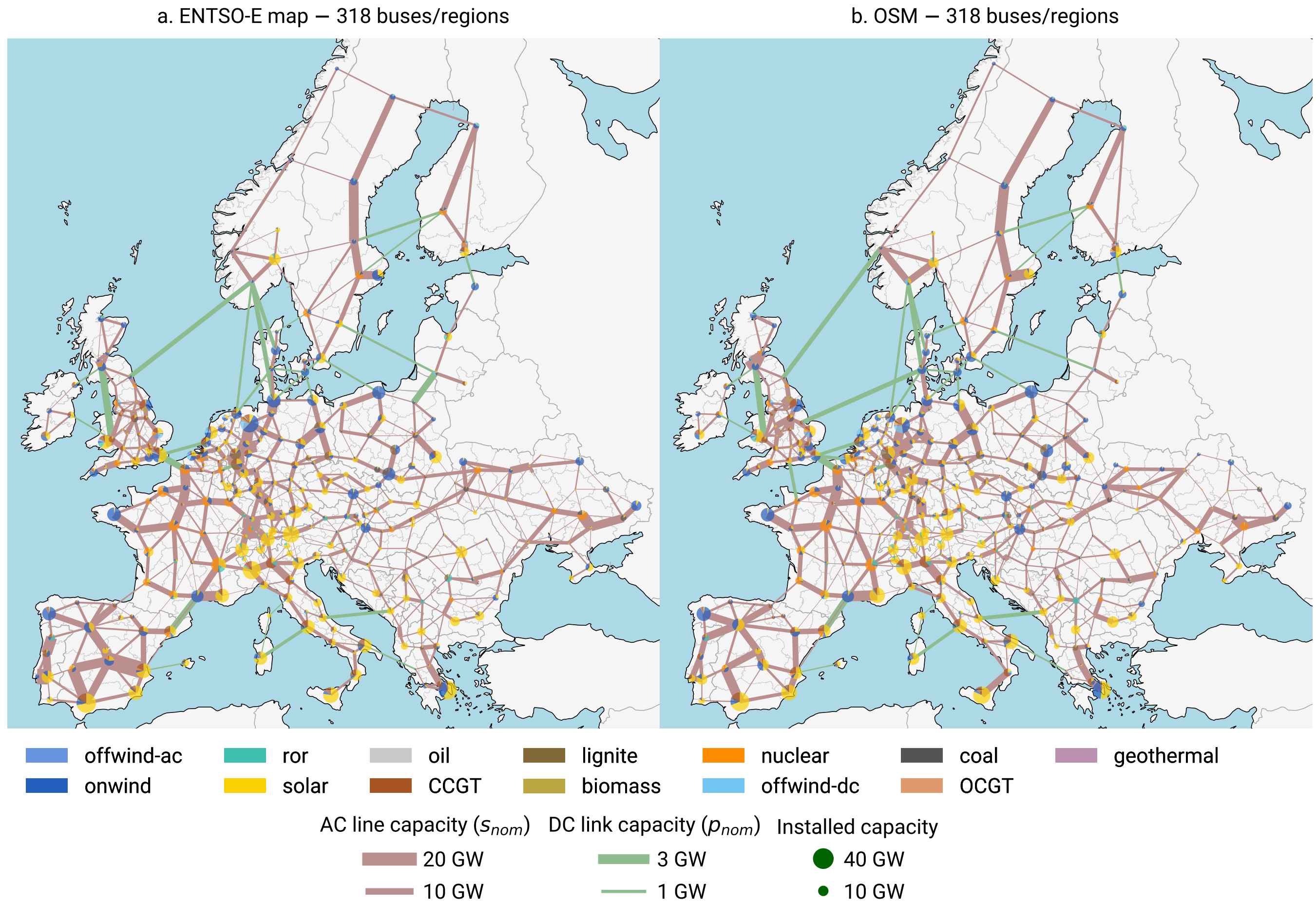

Figure 13. Clustered AC line capacities, DC link nominal ratings, and optimal generation capacities.

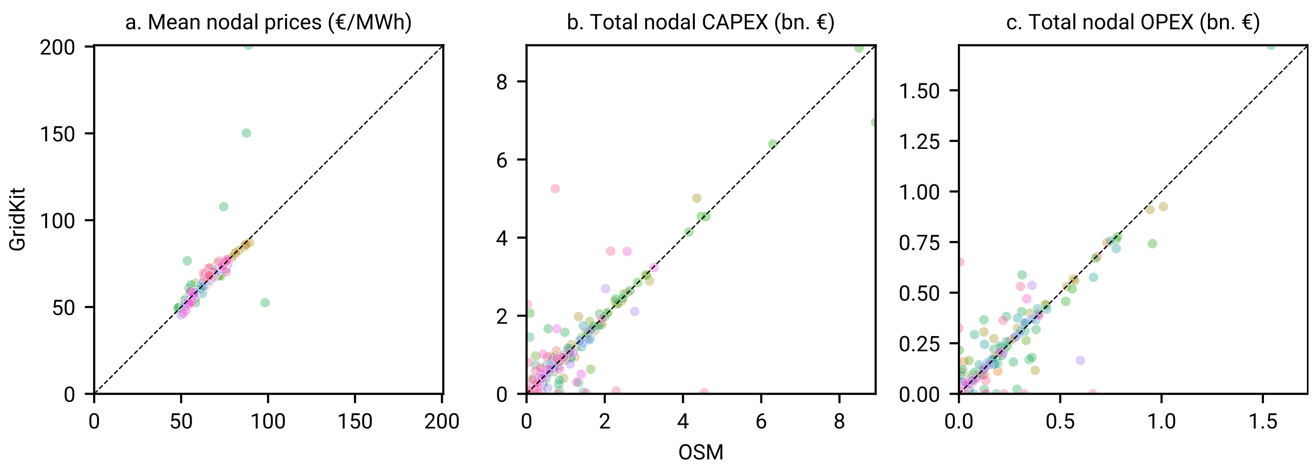

Figure 14. Comparison of nodal prices, capital expenditures (CAPEX) and operational expenditures (OPEX). *Outliers nodal prices (a): Great-Britain (green). Outliers nodal CAPEX (b): Ukraine (pink).*

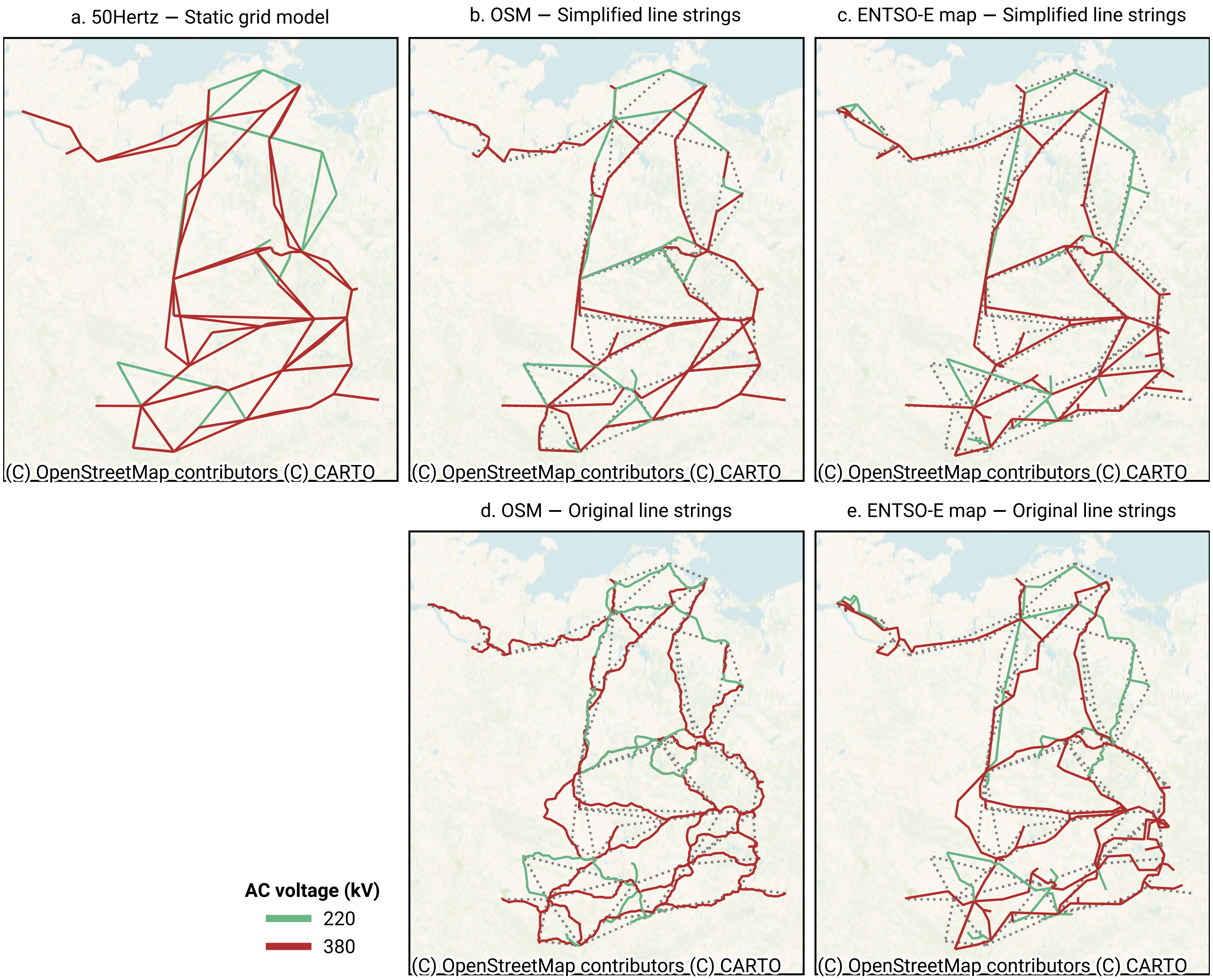

Figure 15. Comparison of OSM and ENTSO-E map-based transmission grid with reference 50Hertz static grid model.[?] *Dashed grey lines underneath show the 50Hertz static grid model for comparative purposes. Note that the geospatial data is provided in simplified, point-to-point form, only. Many of the dashed grey lines are also included in the OSM or ENTSO-E map-based grid representations, however, intermediary buses exists along the line. As such, in their simplification they are not simplified to the level of the 50Hertz static grid model.*

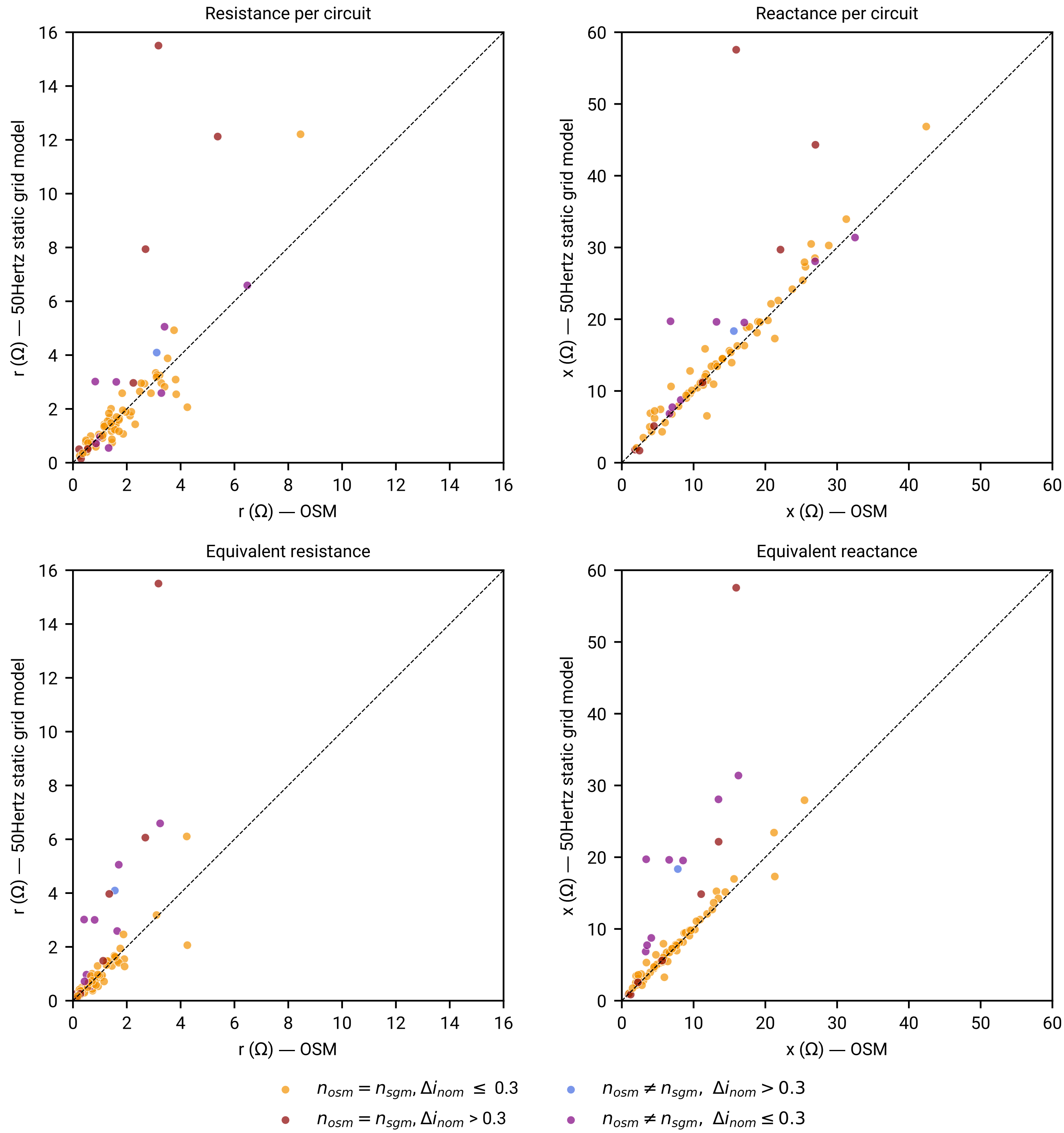

Figure 16. Comparison of AC line/cable resistance and reactance between the OSM-based transmission grid and reference 50Hertz static grid model.? *n_{osm} and n_{sgm} refer to the number of parallel circuits for a distinct line in each network, while $\Delta i_{nom} = \frac{|i_{nom,osm} - i_{nom,sgm}|}{i_{nom,sgm}}$ refers to the relative change in underlying nominal current.*

Figure **??** was generated by mapping AC lines and cables of the OSM-based transmission grid to the 50Hertz static grid model (SGM) using OSM tags and SGM names (right join). Note that this data explains 4475 km of 5126 km in route length, as not all lines could mapped. For 79 % of the data, using pandapower's standard line types? for calculating the resistance and reactance comes close to official data in the SGM (orange). Purple data points a discrepance primarily due to unequal number of parallel circuits in both datasets (SGM data larger by factor 2). Red and blue data points indicate that underlying line types are entirely different. This is the case for some lines where SGM e.g. has a newer 380 kV (allowing higher higher currents) or weaker 220 kV line type.

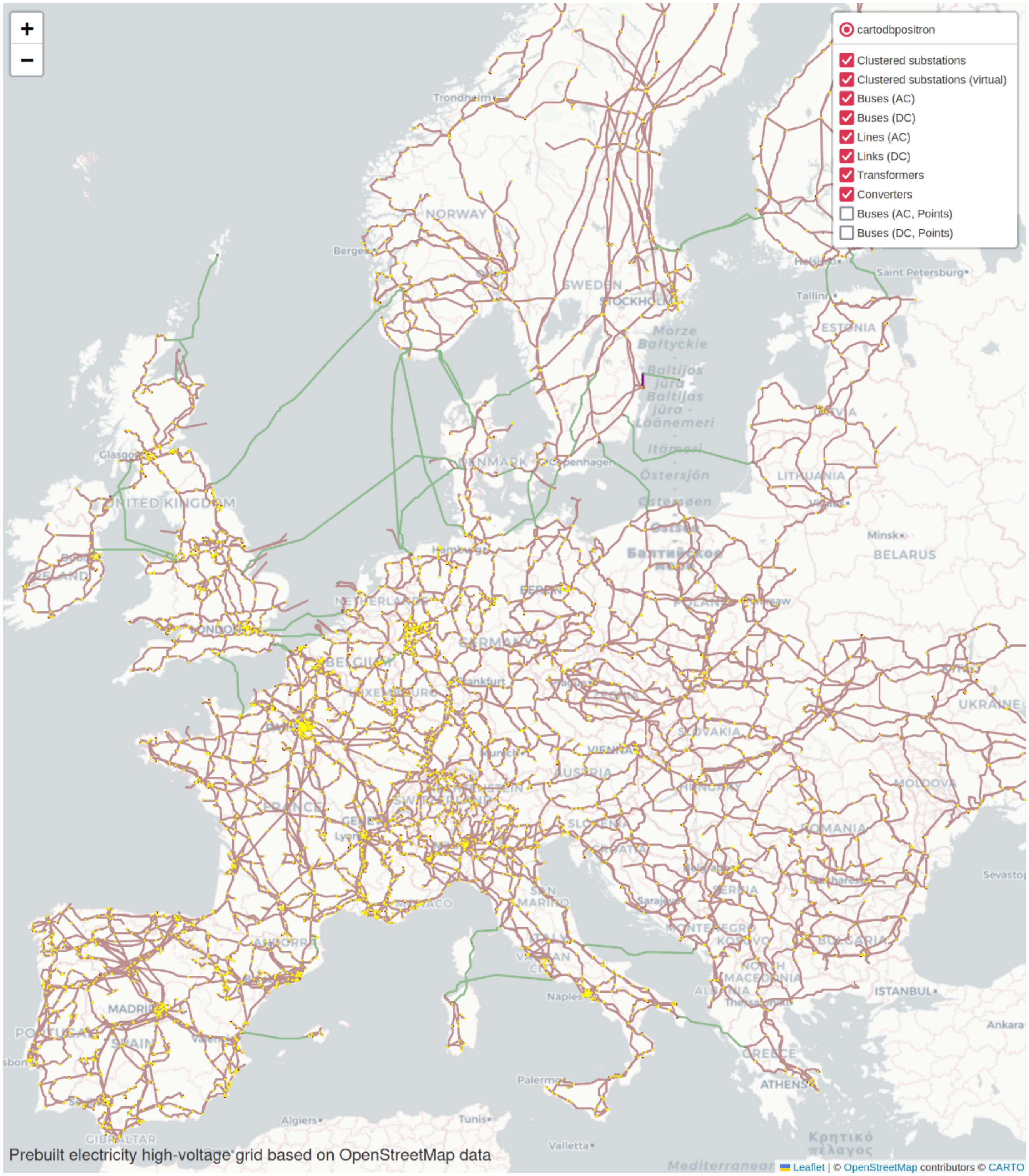

Figure 17. Screenshot of the interactive map visualising the OSM-based transmission grid. The map is included in the dataset released on Zenodo (map.html).[?]