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***Abstract*—A numerical model of a power system can be used to get accurate insights into the impact of policies and investment decisions regarding the transformation of the energy system, while also helping in identifying bottlenecks in implementing decisions. Spatial aggregation, especially for generation and load, must be carefully approached to obtain such a valid model of a power system. The two main contributions of this paper are introducing a valid model of the Dutch high-voltage power system based on open data and open-source software, and proposing a method for spatially aggregating generation and load capacities to high-voltage nodes of the power system. The representative model will enable interdisciplinary research on policy-making and investment decisions specific to the Netherlands.**

***Index Terms*—open data, open-source, power system model, spatial aggregation, renewable energy integration**

I. INTRODUCTION

Decarbonisation and electrification of energy in various energy end-use sectors will directly impact the power grid as both the final and peak demand for electricity will increase. This can lead, among others, to an increase in curtailment events, challenging ramping situations, periods of oversupply as well as shortage of electricity, and an increase in grid congestion [1]. To better plan for such a future, a model-based assessment is needed. One method applicable for both analysing the effects of, and providing insights in, energy demand transformation, as well as studying potential pathways towards climate-neutral energy systems, is the use of energy system models and modelling frameworks [2].

Authors in [3], [4] plead for the accessibility of energy system model input data and source code, in order to enable replication of research results. Besides reproducibility, authors in [5] argue that open data and open models avoid redundant work, thereby reducing the threshold for performing quantitative energy research. Furthermore, the importance of the open data and open-source software for this paper is underpinned by the aim to enable interdisciplinary research on policy making and investment decisions specific to the Netherlands.

Several energy system models specific to the Netherlands are discussed in literature. The OPERA model is an example of such a model. It is used to formulate strategic energy policy advice for the Dutch government [6], by conducting studies on the implications of low-carbon energy technologies, energy sector integration and energy system costs for climate-neutral energy system scenarios [7]. Another energy system model specific to the Netherlands is a proprietary model developed by Dutch TSO's TenneT and Gasunie to evaluate hydrogen, gas, and power system evolution in the Netherlands [8]. The model was replicated by authors in [9] to study the flexibility provided by energy sector integration in the future energy system. An example of an energy system model specific to Europe is PyPSA-Eur [10]. The PyPSA-Eur model includes a European power system model and is mainly used in studies on generation and transmission expansion planning.

The drawbacks shared by these energy system models is twofold: (1) the lack of detail in the underlying power system model and (2) the lack of transparency in the overall energy system model. The former relates to the spatial aggregation of generation and load capacities, and the latter relates to the use of commercial software and inaccessible data in energy system models. Authors in [2] have studied the effect of spatial aggregation in the power system and conclude that the spatial detail is of prime importance for renewable sources, as their generation potential highly depends on their location. Authors in [11], [12] have shown the importance of spatial aggregation on costs estimation and the level of curtailment.

In this paper, the focus lies on introducing a valid model of the Dutch high-voltage power system based on open data and open-source software, and proposing a method for spatially aggregating generation and load capacities. To do so, the open data sources used for this paper are discussed in Section II, along with the methods used for creating the model. Section III describes the validation and limitations of the model. Finally, Section IV concludes the contributions of this paper.

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II. MODEL AND METHOD

This section will focus on the open source modelling framework used, the data collection from open data sources, and the spatial aggregation for generation and load capacity mapping.

A. *Open-Source Power System Modelling Framework*

Open-source models and frameworks applicable to energy system modelling and, more specifically, to power system modelling are listed in [13]. The listed open-source power system modelling frameworks based on the Python and Matlab programming languages are GridCal, pandapower, PyPSA, PYPOWER, and MATPOWER. In contrast to other open-source power system modelling frameworks (e.g., GridCal, PyPSA, PYPOWER, MATPOWER), pandapower claims that all pandapower element behaviour is tested against commercial tools, such as DIgSILENT PowerFactory or PSS Sincal [14]. Therefore, the pandapower package for Python was used at first for creating the desired power system model. The model will be made available for both the pandapower and MATPOWER community.

B. *Power Grid Model Type*

Authors in [15] classify the technical and physical behaviour of a power grid in four different types of grid models, ranging from an unconstrained electrical grid to a fully constrained AC electrical grid. The simplest model described in [15] is the single-node model, representing an unconstrained electrical grid with all power system components aggregated into one virtual point, or node. The second type described in [15] is the transshipment model consisting of multiple nodes that are able to mutually exchange power, solely constrained by net transfer capacity. The third and fourth type of grid model described in [15] are the DC and AC power flow models, respectively. The DC power flow model comprises several nodes and power lines, which are constrained by the resistance and maximal capacity of the power lines. The AC power flow model comprises the DC model with added constraints; e.g., reactance, capacitance and inductance. To accurately analyse the effects of, and provide insights in, nationwide energy demand transformation, there is need for a high level of spatial and technical detail in the desired power system model. Therefore, the DC and AC power flow grid model types are utilised as bases in this paper.

C. *Classification of Power System Model*

The prevalent usage and categorisation of energy system models in the UK is presented in [16]. The authors propose a classification schema based on review papers on energy system models [17], utilised computer tools for energy system modelling [18], and classification methodology for energy system models [19]. The aim of the proposed classification schema is to make the future literature on energy system modelling more transparent [16], and to facilitate the selection of a suitable energy system model for future research [19]. The classification of the model developed in this paper is listed in Table I.

TABLE I
CLASSIFICATION OF THE DESIRED POWER SYSTEM MODEL

1. Purpose of the model	**In general** Exploring scenarios **More specific** Demand-supply and impact analysis
2. Structure of the model	Less degree of endogenisation Less detail in non-energy sectors More detail in energy end-users and supply technologies
3. Geographical coverage	National
4. Sectoral coverage	Power sector
5. Time horizon	Long term
6. Time step	Hourly
7. Renewable technology	Solar PV Wind
8. Demand characteristics	Households demand Buildings demand Transport demand Agriculture demand Industry demand
9. Cost inclusion	Fuel and CO_2 prices
10. Analytical approach	Bottom-up
11. Underlying methodology	Operation and cost optimisation
12. Mathematical approach	Linear and nonlinear programming
13. Data requirements	Quantitative and aggregated

D. *Open Data Collection*

TenneT maintains a map comprising open data on all high-voltage stations, high-voltage transformers, and high-voltage lines in the Netherlands [20]. The data of significance for this paper are: geodata, voltage level, object ID, connection ID's, and shape length. Geodata is used for visualising the grid assets and results. The voltage level is used to group all assets, and to map generation and load capacity. The object ID and connection ID's are used for defining the name of each bus and subsequently defining the connection points of all lines to the correct buses. The shape length is used to define the length of lines between buses. The Dutch high-voltage power grid obtained from the ArcGIS data is shown in Figure 1.

High-voltage stations are modelled as buses in the pandapower package. The buses are the nodes of the model that all other elements can connect to. Each bus is assigned a name, voltage level, and geodata corresponding to the asset data obtained from the ArcGIS data. Missing geodata is manually added to the buses, by locating the stations via Google Maps. The name, voltage level, and total number of high-voltage stations are verified with grid diagrams [21], [22]. The maximum and minimum bus voltages in p.u. are set to 1.05 and 0.95, respectively.

High-voltage lines connect two high-voltage stations at the same voltage level. The connecting buses, voltage levels and line lengths are obtained from the ArcGIS data. For the 220 kV and 380 kV lines, the lengths are verified with and the parameters (e.g., resistance, reactance, and maximum current) are obtained from [23]. For the 110 kV and 150 kV lines, it is assumed that the length obtained from the ArcGIS data is accurate. The parameters of the 110 kV and 150 kV lines are based on standard line types provided by the pandapower package. The selected line types are lower voltage versions of the most comparable line types for 220 kV and 380 kV.

Fig. 1. Dutch high-voltage power grid in 2021 as modelled in pandapower. Prints use map data from Mapbox and OpenStreetMap and their data sources. Black, blue, green, and red lines represent the 110 kV, 150 kV, 220 kV, and 380 kV level, respectively.

All European interconnection lines are modelled as high-voltage lines originating from one of the buses near the Dutch border and ending at one of the external grid nodes, which are modelled as buses on the locations where the interconnection lines cross the border. To each external grid node a generator is mapped. The generator can act as a source or sink of electricity. The limits of each generator are set to the maximum transport capacity of the corresponding interconnection line. The external grid connections are obtained from the ArcGIS data. The name and location of the bus connecting the external grid to the Dutch grid is verified with the grid diagrams [21], [22]. The capacity of interconnection lines to other countries was acquired from the TenneT website.

Transformer stations connect two high-voltage stations at different voltage levels. The location of the transformers and the connecting high- and low-voltage buses are obtained from the ArcGIS data and are verified with the grid diagrams [21], [22]. The capacity and other parameters of each transformer are obtained from [24], [25]. The short circuit voltages and losses are modelled as standard transformer type values in pandapower.

An Optimal Power Flow (OPF) determines the optimal operating levels of generating units to meet the electricity demand in the power system. The objective of an OPF is to minimise the operating cost. For running an OPF, the merit order of the generation capacity needs to be determined. The merit order is based on the marginal cost (e.g., fuel cost and CO_2 emission cost) for running the power plant. The fuel cost per plant type is determined by a combination of the fuel efficiency of the generator [26], the CO_2 Emission Factor (EF) of that specific fuel type [27], the CO_2 Emissions Trading System (ETS) price, and the fuel price. The CO_2 ETS, natural gas, and coal prices can be found on financial data platforms, such as Market Insider and Yahoo! Finance. The fuel cost for biomass and waste plants are assumed zero, as both fuels are heavily subsidised. The fuel cost for plants running on Blast Furnace Gasses (BFG) are assumed zero, as BFG is a waste product from industry. The marginal cost for these fuel types (i.e., biomass, waste, and BFG) is based solely on their CO_2 emissions. The marginal cost for a nuclear power plant is based on values given in the Energy Transition Model (https://energytransitionmodel.com/). The marginal cost for the renewable power plants are zero.

TABLE II
OVERVIEW OF THE DUTCH HIGH–VOLTAGE NETWORK

Model resolution	Detailed	Aggregated
Buses		
No. of 110 kV buses	106	–
No. of 150 kV buses	194	–
No. of 220 kV buses	17	10
No. of 380 kV buses	37	25
No. of external grid buses	10	10
Lines		
No. of lines	724	92
Length of lines [km]	10,365	3,039
Transformers		
No. of transformers	33	3

E. *Model Aggregation*

A detailed high-voltage power system model was created, using the collected open data. The necessary level of detail in a power system model relates to the type of study for which it will be utilised. Fine spatial detail becomes more important when analysing renewable energy systems, while coarse spatial detail keeps models solvable within reasonable time [2]. Therefore, an aggregated version of the Dutch high-voltage power system model is created, giving researchers the ability to select the level detail needed for their study. The 220 kV and 380 kV high-voltage transmission grid forms the backbone of the Dutch power grid and is responsible for transporting the bulk of the power [28]. Therefore, only the grid components in the 220 kV and 380 kV network are considered for the aggregated version. The number of 220 kV and 380 kV buses is reduced by assessing the distance between the buses and the number of connected producers and consumers. The 220 kV buses that are located within 15 km from each other are aggregated. The 380 kV buses that are located within 5 km from each other are aggregated. Buses with less than three external connections are removed and loads are moved to the closest remaining bus. An overview of the detailed, and aggregated Dutch high-voltage network is given in Table II.

F. *Spatial Mapping of Generation and Load Capacities*

One of the major limitations of the available open data evolves around load and generation mapping. Apart from the locations of large nonrenewable power plants and large off-shore and onshore wind farms, the spatial electricity generation throughout the rest of the Netherlands is hard to determine.

Additionally, the bus connecting the power plants to the high-voltage power grid is often not explicitly mentioned. Therefore, assumptions must be made for the mapping of generators to the network model. The same holds true for load mapping. Even though the spatial electricity demand is better established in databases like the Klimaatmonitor (https://klimaatmonitor.databank.nl/) or StatLine (https://opendata.cbs.nl/statline/), assumptions must be made for mapping the municipal demand to the buses of the high-voltage network modelled here.

For modelling simplicity, only nonrenewable power plants with a generation capacity of more than 25 MW and renewable power plants with a generation capacity of more than 50 MW are mapped onto separate nodes. The locations for mapping the power plants are determined by checking the closest connecting node to the high-voltage power grid. Most of the locations of nonrenewable power plants are included in [29]. The missing locations are obtained from the web pages of the power plants owners and operators. The locations of the renewable power plants are retrieved from the web pages of Bosch & van Rijn and Windenergie Nieuws. The locations are overlayed on the ArcGIS map to find the closest connecting node for each power plant. The remaining renewable generation capacity is aggregated per province and mapped onto the most interconnected node in that province. As the 110 kV and 150 kV high-voltage lines are responsible for distributing electricity within provinces and municipalities, the detailed power system model is used to determine the most interconnected node in each region.

The mapping and aggregation of the loads are performed per electricity end-use sector. Five main electricity end-use sectors are selected based on distinct characteristics, such as consumption profiles, load capacities, and spatial distribution of load capacities. The five identified end-use sectors are: (1) households sector, (2) buildings sector, (3) transport sector, (4) agriculture sector, and (5) industry sector. The load of the households sector is divided in two: the load of the four largest cities (i.e., Amsterdam, Rotterdam, The Hague, and Utrecht) and the remaining load. The load of the households sector in the four largest cities are mapped on the closest connecting node to the grid. All remaining load of the households sector is aggregated per province and mapped onto the most interconnected node in that province. The load of the buildings, transport, and agriculture sector are aggregated and mapped similar to the remaining load of the households sector. As the load of the industrial sector is generally more clustered in rural locations, other nodes are used for mapping the load. The total annual load of all middle- and large-consumers of electricity over all municipalities in the Netherlands [30] is used to determine the closest node connecting the largest electricity-consuming municipalities via the local distribution grid to the high-voltage grid. The node is determined by first grouping the municipalities per province, and then selecting the largest electricity-consuming municipalities per province.

A summary of the aggregated generation and load is given in Table III. The mapping of the aggregated generation and load is visualised in Figure 2.

TABLE III
OVERVIEW OF AGGREGATED GENERATION AND LOAD

Model resolution	Aggregated
Generation	
No. of nonrenewable generators	78
No. of renewable generators	43
No. of buses mapped with a generator	27
Load	
No. of loads	132
No. of buses mapped with a load	28

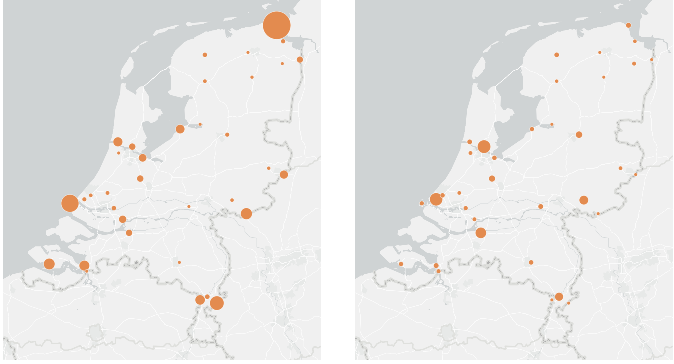

(a) Generation capacity
(b) Load capacity

Fig. 2. Spatial generation and load capacity mapped per node. The larger the circle the larger the total yearly demand. Basemap obtained from Esri.

The method described for spatial mapping of the generation and load capacity can be universally applied if the following data is available: (1) location and capacity of large centralised power plants, (2) spatial annual load data of the country divided per end-use sector, and (3) map of the underlying local distribution grids.

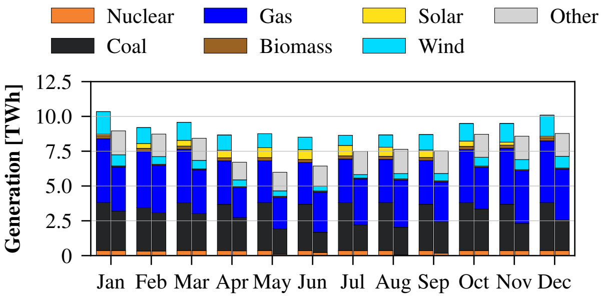
III. RESULTS AND DISCUSSION

Every modelling approach differs from reality as a result of aggregation, past trends and other assumptions. They provide a good approximation of the power system at best. However, they are crucial for analysing policy and technology decisions, and their effects on the power system. Therefore, the level of accuracy of the model's output must be established by verifying and validating the power system model. The preferred validation method for a simulation model based on a non-observable system—a system where no data is available on the system operations—is face validation [31]. This entails that an expert on the system evaluates the model by examining the modelling principles. If face validation is not an option and other models on the system are not available, it is unlikely that a high degree of confidence in the model's behaviour can be achieved. As no open data on operational conditions (e.g., voltages, and active and reactive power injections) can be found, the model is validated following three verification and validation steps presented in [31]. In this paper, the detailed, and aggregated model of the Dutch high-voltage power system are validated. The third step of validation is only performed for the aggregated model.

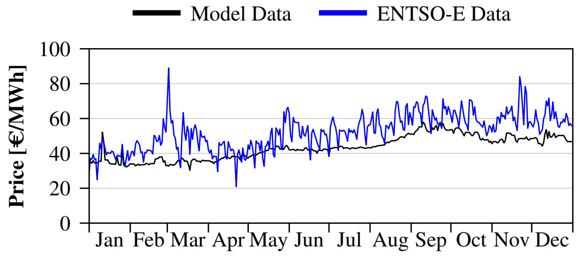
The first step is conceptual model validation, defined as ensuring that the underlying assumptions and theories for the conceptual model are accurate, and the problem is properly depicted for the intended use of the model. The underlying assumptions and theories for the conceptual model are compared to [8]. The modelling approach and assumptions taken are: (1) create hourly values for demand and supply, based on historical weather data, (2) import/export of power is the models last option for balancing the electricity system, (3) regionalisation of the national supply and demand data for localising bottlenecks in the grid, (4) create a model based on a linear programming algorithm that calculates the optimised network flow pattern, and (5) each line is assumed to have a (bidirectional) transport capacity expressed as a maximum possible energy flow in MW. All underlying assumptions and the modelling approach used in developing both models are similar to the assumptions and approach used by TenneT. Hence, it is concluded that the models are conceptually valid.

The second step is computerised model verification, defined as assuring that the conceptual model is correctly programmed and implemented. Several modelling entities are tracked, per time step, from input to output for the correct mathematical relationships, among which: (1) the mapping of demand per node, (2) the maximum available generation capacity for solar and wind energy sources, (3) the merit order, and (4) the model operates within its constraints. All modelling entities tracked in this research showed no abnormalities. Hence, it is concluded that the programming and implementation of the models are correct.

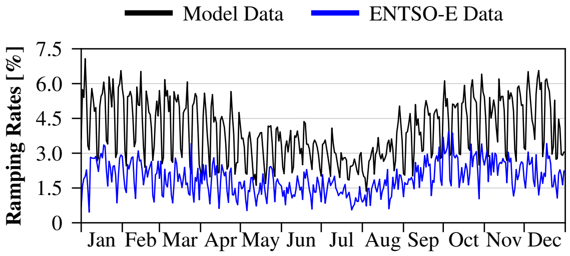
Finally, operational validation is performed, defined as determining if the accuracy of the model's output behaviour is sufficient for the intended purpose of the model. The operational generation capacity, historical solar and wind profiles, and historical fuel prices are obtained for the year 2018. This is used as input data for the aggregated power system model described above. An hourly DC OPF is executed for the year 2018 and, among others, the following performance indicators are depicted per time step: (1) hourly generation per generator type, (2) hourly electricity market clearing price, (3) hourly ramping rates per generator type, and (4) hourly high-voltage line and transformer loading percentages. Figure 3 depicts the performance indicators used for operational validation of the system. All graphs are compared to common knowledge and expectations for the Dutch power system, the graphs depicted in [32], and data obtained from the ENTSO-E Transparency Platform (https://transparency.entsoe.eu/). It can be observed that the general trends in model data are visible in the ENTSO-E 2018 historical data. Mismatches are predominantly a result of the exclusion of electricity import and export in the ENTSO-E data (Figure 3a), the absence of electricity market bidding strategies (Figure 3b and 3c), and the absence of actual line loading data (Figure 3d). It can be concluded that the degree of confidence for the intended use of the model is sufficient for it to be used as a representative model for interdisciplinary research on policy-making specific to the Netherlands.



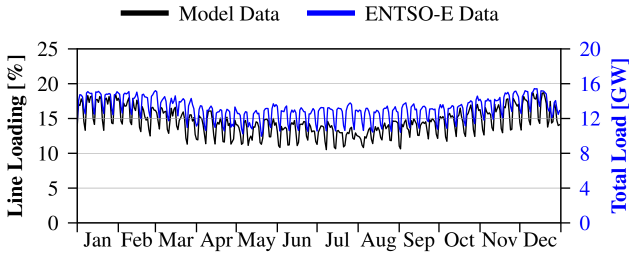
(a) Monthly total generation per plant type in 2018. Model and ENTSO-E data are depicted per month by the left and right bar, respectively.



(b) Daily averaged electricity market clearing price in 2018.



(c) Daily averaged ramping rates for gas-fired power plants in 2018.



(d) Daily averaged high-voltage line loading and daily averaged total load capacity in 2018.

Fig. 3. Examples of performance indicators used for validating the power system model.

Although a good representative model, all models, including this one, suffer from limitations. For the developed models, these are twofold: (1) lower degree of confidence in the models output due to the unavailability of open data sets, and (2) not all technical parameters are included in the model due to either the unavailability of open data or inability of the software used (e.g., dynamic line loading and minimum up- and down-time of generators).

IV. CONCLUSION

One of the contributions of this paper is to create a representative model of the Dutch high-voltage power system based on open data. The idea behind using open data is to give other researchers the possibility to utilise this model for interdisciplinary research on policy-making and investment decisions specific to the Netherlands. However, the downside of creating a model based only on open data is that not all the necessary data will be available. The unavailability of data led to several assumptions. The validation methods used in this paper result in a sufficiently accurate model for future research. The other contribution of this paper is a common methodological approach for spatial mapping of generation and load capacity.

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