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Definition and Implementation of a Standardized Electricity Grid Model

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Executive Summary

The increasing presence of distributed generators (DGs) is altering the grid structure, making it increasingly challenging to manage. In the context of the evolving grid, the role of the distribution system (DS) is becoming more significant. The utilization of the flexibility provided by the DS in power system management is of paramount importance. Therefore, enhancing interoperability among institutions, e.g., transmission system operators (TSOs) and distribution system operators (DSOs) is crucial for effective power system management. However, this interoperability is often hindered by stakeholders' data privacy concerns, especially for customers. Grid operators, for instance, are reluctant to share power system models containing sensitive data with other partners. This reluctance poses a significant challenge for collaborative efforts aimed at improving the efficiency and reliability of the power system. To address this issue, the creation of power system models that can accurately represent the real-world grid using open-source data is gaining considerable importance. These models can facilitate collaboration while maintaining data privacy. In this context, work package 4.3 from the DigIplat project involves the modeling of the power system from low voltage (LV) to medium voltage (MV) and high voltage (HV) levels. Specifically, the Bergwald region is considered for LV, Karlsruhe for MV, and the DACH region (Germany, Austria, Switzerland) for HV. The development of these models involves leveraging open-source data to ensure that they accurately reflect real-world conditions as possible. Models of varying complexity levels are developed to meet the different analytical needs and computational capacities. Consequently, the models created can be utilized by different project partners for various purposes, thus circumventing data privacy concerns. These models serve as vital tools for analyzing and managing the grid, enabling project partners to simulate different scenarios and develop robust solutions. Additionally, these models are converted into different formats according to the specific needs of the project partners. By providing these models in multiple formats, the work package facilitates their usage across different platforms and by various stakeholders, thereby enhancing the overall efficiency and effectiveness of the project. By creating comprehensive models and sharing them with project partners, this work package contributes significantly to the development of market-based approaches and supports the enhancement of methods that will increase interoperability within the network.

Kurzfassung

Die zunehmende Präsenz von dezentralen Erzeugern (DGs) verändert die Struktur des Netzes und macht es zunehmend herausfordernder zu verwalten. Im Kontext des sich entwickelnden Netzes wird die Rolle des Verteilungsnetzes (DS) immer bedeutsamer. Die Nutzung der vom DS bereitgestellten Flexibilität im Energiemanagement ist von größter Bedeutung. Daher ist die Verbesserung der Interoperabilität zwischen Institutionen, z.B. Übertragungsnetzbetreiber (ÜNB) und Verteilnetzbetreiber (VNB) entscheidend für ein effektives Energiemanagement. Diese Interoperabilität wird jedoch oft durch Datenschutzbedenken der Stakeholder insbesondere der Endkunden behindert. Netzbetreiber zum Beispiel zögern, Energiesystemmodelle mit sensiblen Daten mit anderen Partnern zu teilen. Diese Zurückhaltung stellt eine bedeutende Herausforderung für gemeinsame Bemühungen zur Verbesserung der Effizienz und Zuverlässigkeit des Energiesystems dar. Um dieses Problem anzugehen, gewinnt die Erstellung von Energiesystemmodellen, die die reale Netzsituation genau widerspiegeln, unter Verwendung von Open-Source-Daten erheblich an Bedeutung. Diese Modelle können die Zusammenarbeit erleichtern, während der Datenschutz gewahrt bleibt. In diesem Zusammenhang umfasst Arbeitspaket 4.3 im DigIplat Projekt die Modellierung des Energiesystems vom Niederspannungs- (NS) über das Mittelspannungs- (MS) bis hin zum Hoch- und Höchstspannungsbereich (HS/HöS). Speziell wird die Region Bergwald für die NS, Karlsruhe für HS und die DACH-Region (Deutschland, Österreich, Schweiz) für HöS berücksichtigt. Die Entwicklung dieser Modelle umfasst die Nutzung von Open-Source-Daten, um sicherzustellen, dass sie die realen Bedingungen so gut wie möglich nachgebildet werden. Modelle unterschiedlicher Komplexitätsstufen werden entwickelt, um unterschiedlichen analytischen Anforderungen und Rechenkapazitäten gerecht zu werden. Folglich können die erstellten Modelle von verschiedenen Projektpartnern für verschiedene Zwecke genutzt werden, wodurch Datenschutzbedenken umgangen werden. Diese Modelle dienen als wichtige Werkzeuge zur Analyse und Verwaltung des Netzes, die es den Projektpartnern ermöglichen, verschiedene Szenarien zu simulieren und robuste Lösungen zu entwickeln. Zusätzlich werden diese Modelle je nach den spezifischen Anforderungen der Projektpartner in verschiedene Formate konvertiert. Die Bereitstellung dieser Modelle in mehreren Formaten erleichtert ihre Nutzung über verschiedene Plattformen hinweg und erhöht die Gesamteffizienz und Effektivität des Projekts. Durch die Erstellung umfassender Modelle und deren Bereitstellung für die Projektpartner trägt dieses Arbeitspaket erheblich zur Entwicklung neuer marktbasierter Untersuchungen bei und unterstützt die Entwicklung neuer Methoden, die die Interoperabilität im Netz insbesondere zwischen den ÜNB und VNB erhöhen.

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List of abbreviations

CIM	*Common Information Model*
DGs	*Distributed Generators*
DA/RE	*Datenaustausch/Redispatch*
DigIplat	*Digital Solutions for Interoperability of Flexibility Platforms*
DS	*Distribution System*
DSO	*Distribution System Operator*
ENTSO-E	*European Network of Transmission System Operators for Electricity*
EVs	*Electric Vehicles*
GIS	*Geographic Information System*
HV	*High Voltage*
LV	*Low Voltage*
MV	*Medium Voltage*
OPF	*Optimal Power Flow*
OSM	*OpenStreetMap*
PVs	*Photovoltaics*
RNMs	*Reference Network Models*
TS	*Transmission System*
TSP	*Traveling Salesman Problem*
TSO	*Transmission System Operator*

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1 Introduction

The power grid has undergone substantial changes with the widespread adoption of distributed generators (DGs). However, effectively managing the grid has become progressively more difficult due to uncertainties related to DGs and the emergence of bi-directional power flows [1]. Numerous research endeavors aim to facilitate the safe integration of DGs into the power system while enhancing its operational efficiency [2, 3]. Yet, the escalating uncertainties and complexities of the grid pose challenges in maintaining a harmonious balance between electricity production and consumption. Consequently, there's a growing imperative for flexibility measures to ensure optimal grid performance.

To address these challenges and mitigate energy bottlenecks in the electricity market, resolving AC optimal power flow (AC-OPF) and making informed dispatch decisions are crucial [4]. The utilization of AC-OPF and dispatch mechanisms presents significant potential for economic benefits. For instance, only a 5% increase in market efficiency through AC-OPF implementation in the United States could yield annual savings of up to $6 billion [5]. With anticipated uncertainties on the horizon, leveraging effective AC-OPF and dispatch mechanisms stands poised to unlock even greater economic advantages.

Traditionally, the resolution of AC-OPF has been the sole responsibility of system operators. However, in today's evolving electricity grid landscape, collaboration among various stakeholders such as transmission system operators (TSOs), distribution system operators (DSOs), DG companies, and aggregators has become imperative. A notable example is Germany's Redispatch 2.0 initiative, where all conventional plants and DGs with a capacity of 100 kW or more, along with DSOs, are mandated to participate in redispatch activities [6]. Moreover, in the forthcoming Redispatch 3.0 framework, private consumers will have the opportunity to engage in the market through aggregators. Consequently, the execution of AC-OPF and redispatch operations necessitates the involvement of diverse stakeholders, moving beyond the previous paradigm of exclusive system operator involvement.

This shift underscores the heightened importance of collaboration among institutions. Accordingly, various entities, including universities, TSOs, DSOs, and consulting firms, are collaborating on research and development initiatives like DigIplat. These endeavors aim to devise and implement effective cooperation mechanisms for making flexibility decisions in the grid.

Ensuring data privacy stands out as a pivotal concern complicating collaboration among industry partners. Take, for instance, a project aiming to establish a shared platform for the redispatch mechanism: a TSO finds itself in the position of needing to divulge sensitive data like grid topology and voltage and current measurements to collaborators engaged in market research. Thus, a mechanism that safeguards data privacy between the owner of the model and other involved parties becomes imperative.

Undoubtedly, data privacy apprehensions among stakeholders pose substantial obstacles to interoperability, impeding the efficient functioning of the power system [7]. A case in point is Germany, where the costs linked to redispatch due to network congestion reached 2.689 billion euros in 2022 [8]. These expenses could be markedly reduced by integrating DGs situated within Distribution Systems (DS) into dispatch and redispatch decisions. However, given the complex TSO-DSO landscape in Germany, featuring four TSOs (50Hertz, Amprion, TenneT, TransnetBW) and over 800 DSOs [9], the development of robust methodologies to address data privacy concerns becomes very important.

Various research efforts are underway to use flexibility offered by DGs at the TSO level while also prioritizing data privacy considerations. One such initiative is DA/RE, an IT platform designed to leverage DGs in managing network congestion within the framework of Redispatch 2.0 in Germany [10]. However, to address the privacy concerns of DSOs, this platform adopts measures to prevent the transmission of sensitive DSO data by employing "light models" of the DS [11]. Furthermore, the platform utilizes a linearized version of the distribution system, foregoing the complete grid model, thereby introducing a trade-off between calculation accuracy and data privacy considerations.

Another strategy in this direction is the active-reactive power (PQ) chart approach [12]. This strategy involves consolidating the flexibility capabilities of DSs at the interface between TSOs and DSOs, utilizing them to bolster the secure operation of the Transmission System (TS) [13]. By implementing this approach, the TSO can activate optimal flexibility and convey updated set points to the DSO [14]. The objective is to manage the system while staying within the constraints of both the TS and DS, facilitated by iterative communication between the TSO and DSO [15].

In light of these insights, it's evident that data privacy concerns among stakeholders in the energy sector have encouraged researchers to explore diverse studies and develop various methodologies. These approaches typically aim to either prevent the sharing of power grid models or minimize the dissemination of shared data. This underscores the significance of constructing generic models derived from open-source data.

Creating generic models that accurately represent real-world networks using open-source data can greatly enhance the efficacy of developed algorithms and methodologies in research projects. Moreover, since project partners and industry stakeholders operate within different domains and utilize network models in varying formats for their work, it's crucial that these created models are easily convertible to different formats and readily shared with diverse partners.

The aim of work package 4.3 and the corresponding deliverable is to create standardized power grid model and provide it to project partners in different formats so that project partners can use it effectively. The rest of the deliverable is organized as follows: Section 2 introduces the project requirements. In Section 3, the process of generating the distribution system model is described. Following this, Section 4 outlines the generation of the transmission system model. Section 5 illustrates the model conversion process, and Section 6 concludes the deliverable.

2 Project Requirements

The development of accurate power system models is crucial for the success of research projects involving multiple partners from diverse domains. While sharing realistic models is often hindered by data privacy concerns, it is essential to create models that faithfully represent real-world network conditions. Within the project, the Karlsruhe Institute of Technology (KIT) undertakes the task of producing comprehensive power system models that encompass both Distribution and Transmission System components. These models cover a wide range of voltage levels, including Low Voltage (LV), Medium Voltage (MV) Distribution System, and High Voltage (HV) Transmission System.

The models generated by KIT serve as foundational assets that can be utilized by other project partners across various work packages. These partners benefit from the use of realistic models to enhance the efficiency and effectiveness of their methodologies and research activities. Figure 1 illustrates the integration of KIT's power system models into different work packages by other partners.

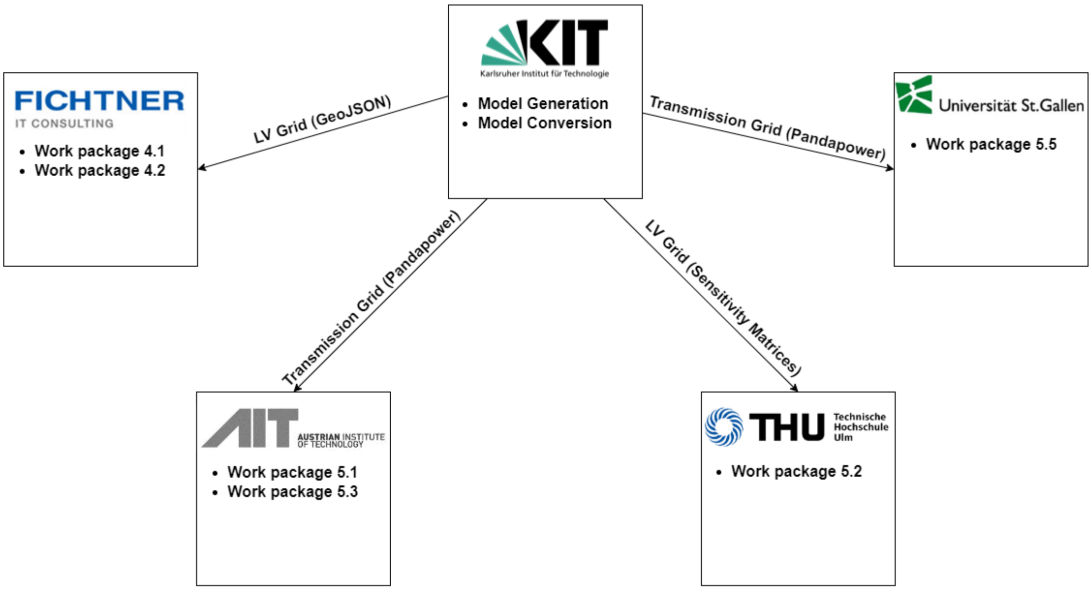

Figure 1 The integration of KIT's power system models into different work packages by other partners

Indeed, the power grid models developed within this work package serve as foundational resources for various purposes across different project partners. To ensure seamless collaboration and effective utilization of these models, it is crucial to convert them into appropriate data formats based on the specific requirements and preferences of each partner. In subsequent sections of this work package, detailed procedures for converting the models into GeoJSON format will be provided. Additionally, the utilization of sensitivity matrices for model representation will be elaborated upon in Work Package 5.2. Furthermore, the conversion of models to the Pandapower format will be facilitated using Pandapower's dedicated converter tool.

By undertaking these conversion processes, the project ensures seamless integration and utilization of the power grid models across different domains and applications. This interoperability enhances collaboration and enables partners to leverage the models effectively for their respective research and development endeavors.

3 Generation of Distribution System

Within the project, one focus is on examining how the flexibility derived from DGs within the DS will impact network management. With the increasing prominence of DGs, particularly in the LV grid, the importance of this grid is expected to grow substantially in the near future. This work package is specifically aimed at modeling the LV grid within the DS. It's important to note that in Germany, the Distribution System encompasses not only the 20 kV medium voltage level but also includes the 110 kV high voltage level. As part of this work package, the 110 kV network in Karlsruhe, selected as the sample region for examination within the project, will be modeled. However, it's crucial to clarify that this model is intended solely to facilitate the proper coupling of the LV distribution system with the HV transmission system.

3.1 Residential Low-Voltage Distribution Grid Models

The rapid evolution of technology is driving profound changes in traditional consumer behavior, leading to a shifting consumer landscape resulting in a transformation towards prosumers. As electric vehicles (EVs), heat pumps, batteries, and Photovoltaics (PVs) become increasingly prevalent, they are being connected to the grid at an accelerating pace. This trend amplifies the complexity of the low voltage (LV) grid and underscores its growing significance in the energy ecosystem.

The integration of these elements into the LV grid places considerable strain on its capacity, necessitating comprehensive studies for their seamless integration. These studies are vital for ensuring the efficient and rapid assimilation of EVs, heat pumps, batteries, and PVs into the LV grid. By addressing the challenges associated with this integration, such as grid capacity limitations and increased complexity, stakeholders can pave the way for a more sustainable and resilient energy infrastructure.

In recent years, there has been a notable increase in studies focusing on LV grids within the academic literature [16]. However, it's worth noting that detailed examination of these areas is still in its early stages, and even system operators often lack comprehensive network models of the LV grid. This lack of detailed information poses challenges for research in this area. Moreover, a significant obstacle arises from the reluctance of system operators to share their models with external partners due to concerns surrounding data privacy. Unlike the power transmission system, data pertaining to DS is typically not freely accessible or is only partially available with restrictions.

To circumvent these challenges, there is a growing trend towards power system modeling efforts utilizing open-source data. This approach enables researchers to conduct the necessary scientific studies and develop research projects despite the limitations imposed by data availability. In this context, Geographic Information System (GIS) based data-driven model generation approaches are frequently employed by researchers to overcome data constraints and advance understanding in this domain.

The process outlined in [17] for creating Reference Network Models (RNMs) represents a seminal contribution to the field of automated power grid modeling. This innovative approach leverages various datasets, including information on customer locations and demand, the capacity and locations of DG and transmission substations, as well as economic and technical parameters. With these inputs, European-style power grid models are generated seamlessly, spanning from the High Voltage (HV) level down to individual LV customers. Central to this methodology is a heuristic branch-exchange technique, employed to minimize grid costs while adhering to a predefined catalog of standard equipment. This systematic approach allows for the efficient creation of grid models that accurately reflect real-world conditions and optimize grid performance.

Building upon this foundation, [18] presents a further advancement in the field, focusing on the development of an online tool for automated model generation. This tool harnesses OpenStreetMap (OSM) data, along with area parameters such as consumer density, power factor, and MV/LV transformer locations, in addition to DSO indicators. By integrating these datasets and indicators, the online tool streamlines the process of generating grid models, enhancing accessibility and efficiency in power grid modeling endeavors.

In [19], a methodology is outlined for expanding an existing distribution grid by utilizing street-layout data and a graph representation derived from it. The objective is to extend the scope of OpenStreetMap (OSM) and graph-based research to encompass regions beyond its current coverage. This approach offers a promising avenue for enhancing grid modeling efforts in diverse geographical contexts. On a related note, [20] presents a method for generating grid datasets specifically tailored for benchmarking purposes. However, it focuses solely on the few secondary substations available within the OSM dataset.

In [21], attention is directed towards the German power grid, where a methodology leveraging OSM data and the known total number of LV networks in Germany is employed. This approach results in the generation of a substantial dataset comprising 500,000 LV distribution grid topologies. These generated topologies undergo validation against real grid data, including parameters such as the number of nodes and edges per LV grid, as well as total line length. Concurrently, other methodologies within the same research domain concentrate on generating models for higher voltage levels. For instance, [22] focuses on transmission grid models, while [23] pertains to MV grid models, diverging from the LV level.

Meanwhile, the method described in [24] has been adapted to regional distribution grid structures similar to those observed in Germany. It draws upon nine distinct data sources to classify buildings for load estimation purposes and to facilitate the generation of both MV and LV grid topologies. These multifaceted approaches collectively contribute to advancing understanding and modeling capabilities across various voltage levels within the power grid infrastructure.

In [25], an innovative approach is introduced specifically tailored to the creation of complex U.S.-style power grids, characterized by their typical single-phase connections and the presence of voltage regulators on the LV level. Unlike previous methods that rely on the direct input of customer location and demand data, [25] outlines a method for estimating this demand using land use data sourced typically from commercial vendors, along with a library of reference buildings. This approach is particularly significant given the complex nature of U.S.-style distribution grids, which often exhibit unique characteristics and configurations. Optimal secondary substation locations are determined alongside the development of a loss-optimized grid in [26]. Notably, the emphasis of this approach lies in the planning of new grid configurations rather than the depiction of existing real-world LV networks.

Despite the array of approaches discussed, several key areas in research within this domain remain open for exploration. Many existing methodologies in the literature rely on proprietary data or highly specific knowledge, limiting their broader applicability. Additionally, to our knowledge, there has been a lack of comparison between models generated using different available data sources. To address these gaps, we introduce a method that necessitates minimal data input. Furthermore, we conduct a comparative analysis of the models generated under various input data scenarios.

3.1.1 Methodology

We introduce a novel open data-driven grid generation method to generate residential LV grids, requiring minimal data requirements in [27, 28]. The methodology begins by generating load data for buildings within a specified area. Subsequently, both the 20 kV Grid and LV Grid are generated. Finally, utilizing these grid structures, a PowerFactory model is generated [29]. The load estimation process relies on a combination of open and proprietary data sources to estimate the load for each building, a crucial input for the subsequent two-stage grid layout optimization. In the first stage, the methodology focuses on generating the 20 kV grid topology, incorporating 20/0.4 kV substations. This is achieved through a k-means clustering approach for determining substation placements, coupled with a traveling salesman problem (TSP) optimization to establish the optimal routing of lines between these substations. Following the establishment of the 20 kV grid, the second stage of optimization focuses on generating the underlying 400 V grid. This is achieved by solving a variant of the minimum cost flow linear optimization problem. These optimization stages collectively contribute to the creation of a comprehensive and efficient grid layout, accommodating the diverse energy demands of residential areas. The model generation process is shown in Figure 2.

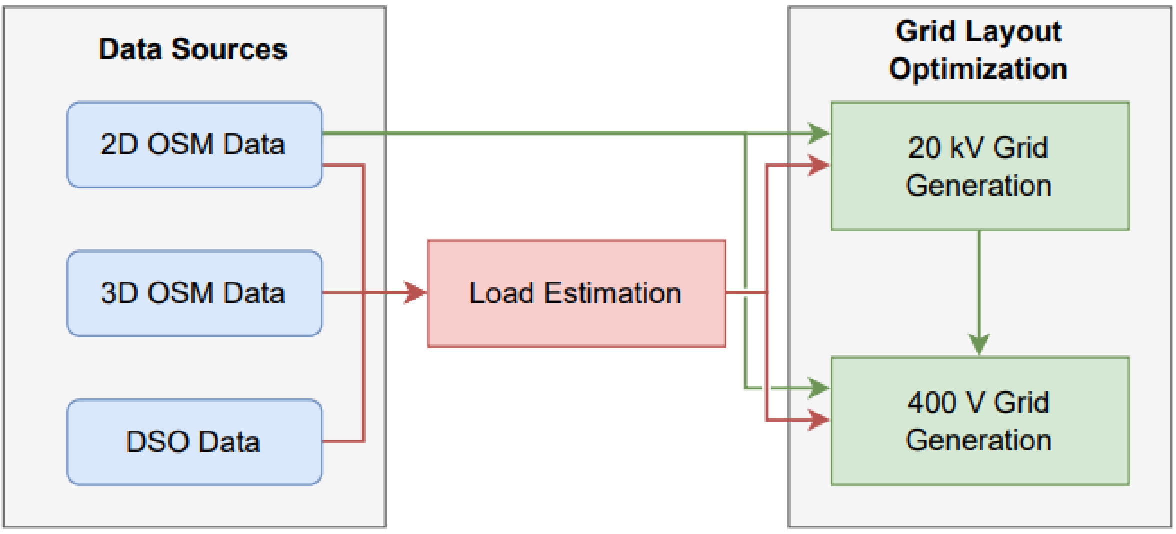

Figure 2 Model generation process

As an initial step, we leverage OSM data and 3D OSM Buildings data, along with information on the number and location of electricity meters provided by a local DSO, to generate load data for buildings. To estimate the load of a residential building, we utilize a standard household profile, denoted as H0 [30]. However, to apply this profile, we require the yearly energy consumption of each building. Thus, we first estimate the yearly energy consumption based on factors such as building height and floor area. Subsequently, we finalize the load estimation process by incorporating the electricity meter data provided by DSOs for individual buildings (Further details see [27]).

After obtaining building data, the automatic generation of the 20 kV distribution grid commences, leveraging both map data and building data. Initially, the number of 20/0.4 kV substations is determined based on the peak power demand of the buildings. Subsequently, the locations for these substations are identified using a k-means clustering algorithm. Following this, a graph representation of the street layout is constructed, encompassing the closest HV/MV substation and the designated area for grid generation. The calculated substation positions are then incorporated as nodes within this graph structure. To establish the network topology, an optimization approach is employed, framing the problem as TSP [31]. The HV/MV substation serves as both the starting and ending point, with the 20 kV substations designated as the intermediate destinations. The distances between these points are determined by the shortest paths on the corresponding graph, weighted with the actual geographical length of each road. This systematic approach yields the generation of the 20 kV distribution grid (Further details see [27]).

To generate LV grid, we utilize street layouts sourced from OSM as potential cable routes. These layouts are transformed into a graph representation via a Python application, with additional incorporation of residential building data extracted from OSM. Subsequently, to derive the grid topology, a variation of the minimum cost flow optimization problem is employed. This optimization process adjusts the graph to conform to the electrical LV grid topology standards. Notably, this optimization is conducted while adhering to specified locations of 20 kV substations. Formulating this optimization problem involves expressing it as a mixed integer linear program (MILP) with binary decision variables. Following the resolution of the optimization problem, the LV grid is generated accordingly. Finally, the resulting grid data structure is transformed into a DIgSILENT PowerFactory model, facilitating its integration and further analysis within the PowerFactory environment (Further details see [27]).

3.1.2 Low Voltage Distribution Grid Model of Bergwald

One of the main objectives of this deliverable within the project is to generate a comprehensive LV grid model. To achieve this goal, the Bergwald region in Karlsruhe, Germany is selected as the target area. The rationale behind selecting this region for automatic network generation is to ensure the availability of requisite information for validating the resulting network model. Following the application of the model generation methodology outlined in the previous section, we successfully obtain the Bergwald grid model, as illustrated in Figure 3.

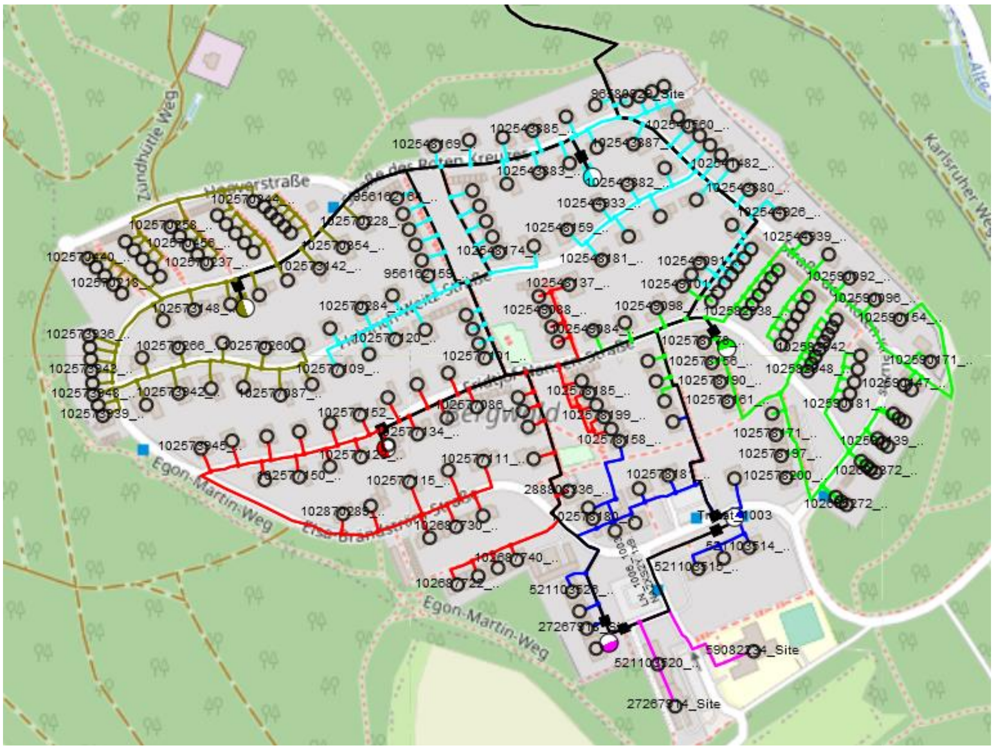

Figure 3 Generated Bergwald grid model

The optimization process yields the calculation of six 20/0.4 kV substations, each denoted by different colors, for the target area. Each substation is connected to a varying number of buildings based on the optimization outcome. The study area covers approximately half a square kilometer and encompasses a total of 241 buildings, including single houses, duplexes, townhouses, apartment towers, as well as non-residential structures such as a school, a community center, and several shops. The overview of the grid infrastructure within the Bergwald region is given in Table 1.

In terms of model elements, each of the six substations is equipped with a 630 kVA transformer. Consequently, the area includes a total of 253 busbars, 241 for buildings and 12 for transformers MV and LV sides. Since the lines are divided by internal nodes at the building connection points, there are 483 lines in total. Notably, the grid generation process for this area requires 311 seconds to complete.

Table 1 Overview of the grid infrastructure within the Bergwald region

Element type	Number of elements
Substation	6
Transformer	6
Busbar	253
Line	483

After acquiring the model, it's essential to assess its suitability for power flow calculation and evaluate its convergence characteristics. To this end, we conduct a standard power flow calculation in an example scenario, the results of which are depicted in Figure 4 showing the voltages in p.u. at each node.

Figure 4 Example power flow calculation of the model

This analysis provides insights into the model's ability to accurately represent the power flow within the grid and its convergence behavior under normal operating conditions. By examining parameters such as voltage magnitudes, phase angles, and line flows, we can ascertain the model's performance and identify any potential issues that may need to be addressed. This evaluation is crucial for ensuring the reliability and stability of the LV grid model in practical applications.

Once the model converges, it's important to analyze the voltage profile and line loading profile to assess the performance and stability of the LV grid. The voltage profile provides valuable insights into the adequacy of voltage levels across the grid, ensuring that they remain within acceptable limits and do not deviate significantly from nominal values. Figure 5 illustrates the voltage profile of the model for an example case.

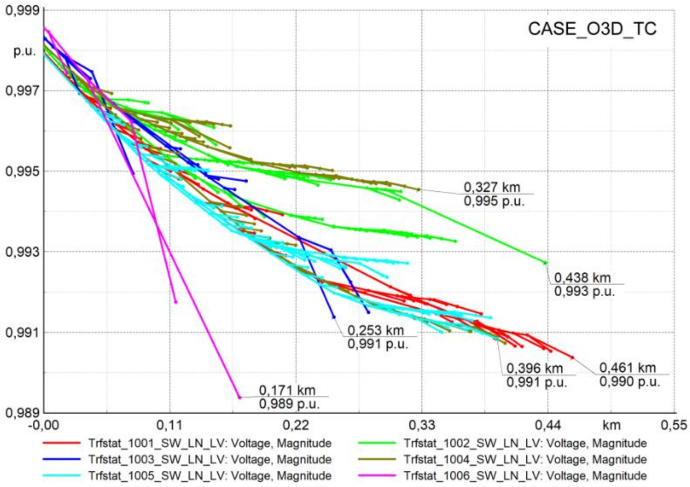

Figure 5 Voltage profile of the model for an example case

Upon examining the figure, it is observed that the voltage values range between 0.989 and 0.999 p.u. The variation in voltage levels is within acceptable bounds for typical operating conditions of the LV grid. It's important to note that the reference bus voltage value is set at 1 p.u. Following the voltage profile analysis, the statistical histogram of line loading is presented in Figure 6 for an example scenario.

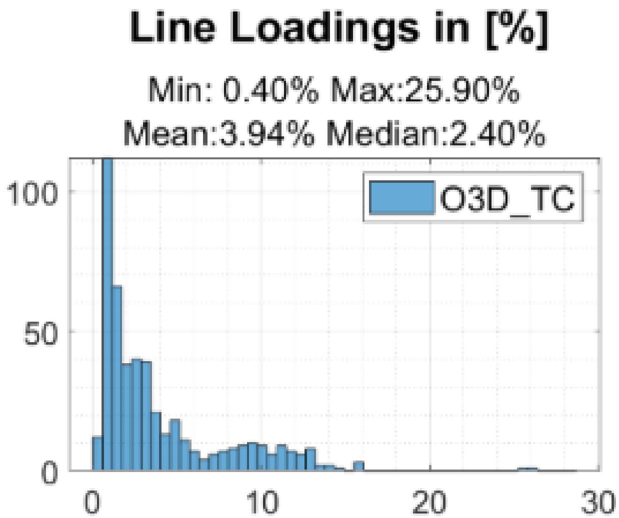

Figure 6 The histogram of line loadings for an example case

This histogram provides insights into the distribution of line loading across the grid, allowing us to identify potential areas of congestion or overload. When the figure is examined, it is noted that the maximum loading value for the example scenario is 25.90%. This value indicates that the loads are comfortably supplied within the created model, with sufficient capacity to accommodate the demand. It's important to emphasize that these loading values are subject to change under different load scenarios and operating conditions.

Indeed, the calculations and examinations conducted demonstrate the accuracy and effectiveness of this model in representing real-world LV grids. This approach offers the capability to generate LV grids efficiently with minimal data requirements, utilizing only open-source data. Additionally, it provides the flexibility to create and analyze different scenarios, allowing for comprehensive assessments of grid performance under various conditions.

Each building within the model can be customized to include specific elements such as residential loads, EVs, batteries, PV, or combinations thereof. This flexibility enables the examination of scenarios where DGs play a dominant role in the evolving network structure. Furthermore, it facilitates the exploration of opportunities for DG integration and their utilization in market-based operations.

3.2 Medium and High Voltage Distribution Grid Models

As outlined in preceding sections, a primary objective of this work package is to intricately model the LV distribution system. To accomplish this, the MV and HV distribution systems will be leveraged to establish a seamless connection between the LV distribution system and the HV transmission system. This comprehensive modeling approach ensures a holistic representation of the entire distribution network. In the modeling process, open-source data sources are utilized to create accurate representations of the distribution infrastructure. Additionally, collaborative efforts are underway with the distribution system operator in Karlsruhe to acquire load data at 110 kV level. By incorporating these datasets, the models can accurately reflect real-world conditions. Figure 7 illustrates the MV and HV grid of Karlsruhe, providing a visual depiction of the distribution network at these voltage levels.

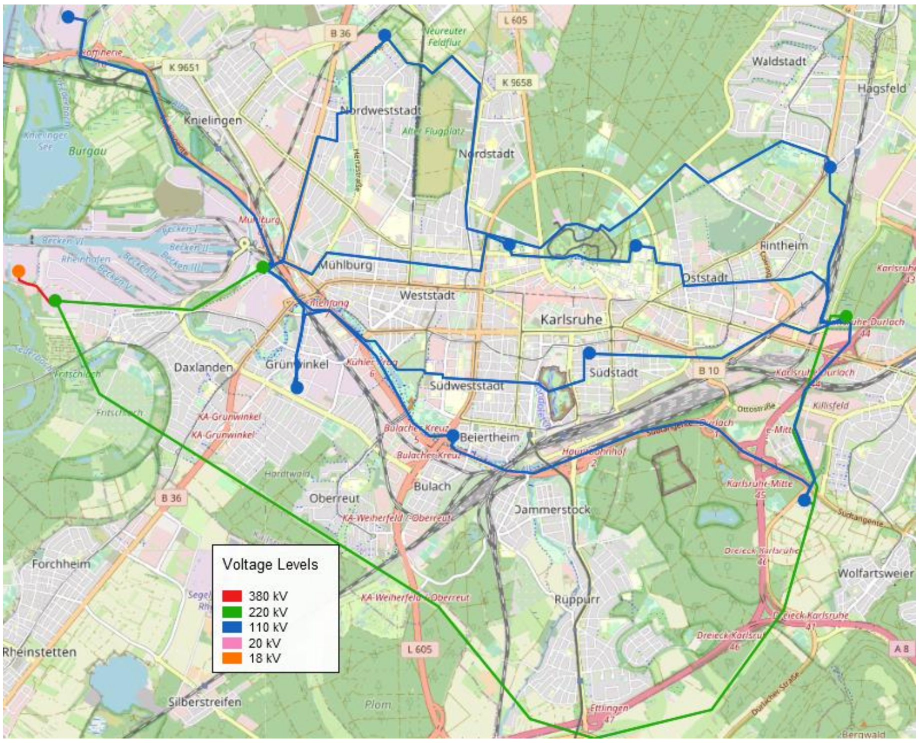

Figure 7 MV and HV grid of Karlsruhe

The figure showcases the operational structure of the Karlsruhe DS, which operates as a meshed grid. Notably, the grid comprises eleven 110 kV buses denoted in blue, symbolizing key nodes within the DS. Additionally, the connection points with the transmission system are highlighted by five 220 kV buses denoted in green, illustrating the interface between the distribution and transmission networks.

Moreover, the buses labeled as 18 kV and 20 kV signify the presence of conventional power plants within the region. In the modeling process, the focus lies on accurately representing the MV and HV distribution systems in Karlsruhe. However, to maintain model manageability and prevent excessive complexity, the complete 20 kV grid is intentionally excluded from the model and only partially modelled to link to the LV grid as explained in the previous chapter. This strategic decision ensures that the modeling efforts remain focused on key aspects while balancing complexity.

The creation of the Karlsruhe MV and HV distribution system models serves a crucial purpose within the project. These models provide the foundational framework for properly integrating the Bergwald LV grid, which is the subject of detailed examination within the project, with the HV transmission system. By establishing this connection, the project aims to gain comprehensive insights into the interactions and dynamics between different voltage levels within the power system, facilitating informed decision-making and effective network management strategies.

4 Generation of Transmission System

Within the project's scope, the analysis conducted on the transmission system (TS) will center on the DACH (Germany, Austria, Switzerland) region. This work package is dedicated to creating suitable models using diverse approaches and open-source data. Recognizing the varied needs of different project partners, multiple TS models are developed, each varying in complexity. This approach ensures that partners have access to models that align with their specific analysis needs and capabilities. By offering a range of TS models, the project aims to enhance collaboration and facilitate comprehensive analyses across various domains and research objectives within the DACH region.

4.1 DACH: Open Data Analysis

As a first step, the idea was to create a model from available open data. For this OpenStreetMap (OSM) was queried via Overpass Turbo for lines (keywords “line”, “cable”) and stations (keywords “station”, “substation”) at voltage level 380/220/110 kV [32]. The results were generated in GeoJSON and KML format (Google Earth) and visualized in Matlab as shown in Figure 8.

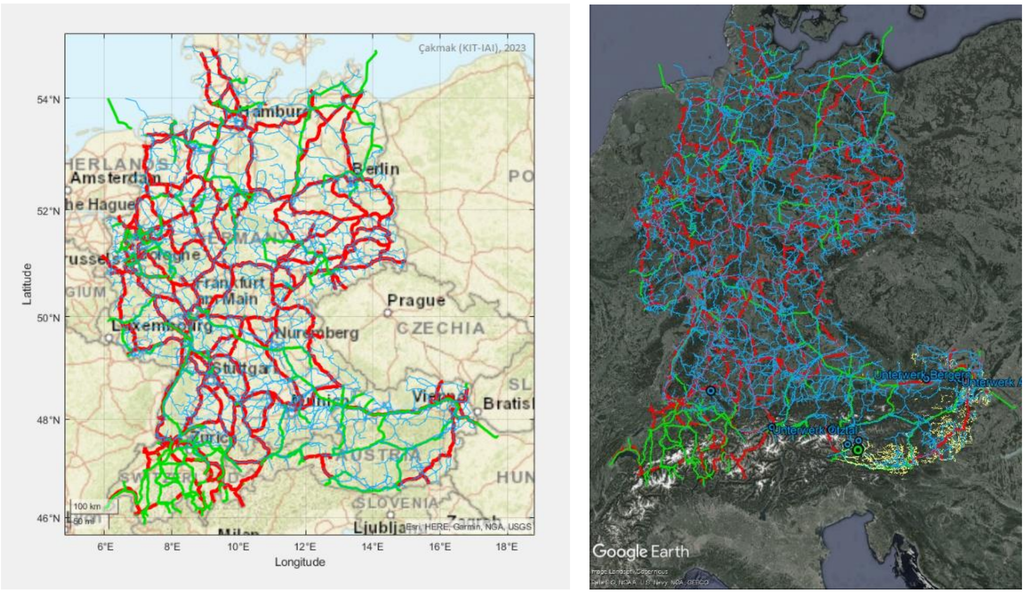

Figure 8 Matlab and KML visualization of the DACH transmission system based on Open Street Map data

However, when the resulting model is examined, it becomes evident that its complexity presents significant challenges for practical use in the developed methodologies. The intricacies of such a detailed model may hinder its applicability in scientific studies and analytical frameworks. Recognizing this limitation, there is a growing imperative to procure models better suited for scientific studies within the DACH region. This necessitates exploring alternative approaches to model creation that strike a balance between comprehensiveness and manageability.

4.2 Reduced DACH-Model

Today, the power system is becoming increasingly complex, prompting the creation of various initiatives and platforms aimed at managing this complexity effectively. These platforms not only enhance transparency regarding the transmission system but also provide crucial references for researchers. One such organization is the European Network of Transmission System Operators for Electricity (ENTSO-E) [33]. ENTSO-E, utilizing data from 40 TSOs, has developed a comprehensive map that represents the network structure predominantly for the European region [34]. This map includes the precise geographic locations of various network elements, offering a valuable resource for understanding and analyzing the European power grid. Moreover, additional data pertaining to the transmission systems of Europe, sourced from ENTSO-E, is accessible through the Python for Power System Analysis (PyPSA) community [35].

In addition, the countries and TSOs in the DACH region (Germany, Austria, Switzerland), which are examined in detail in this project, also openly publish data regarding the power system as part of their transparency initiatives. For example, critical data for modeling, such as production and consumption data for Germany and Austria, are readily accessible [36]. Similarly, Switzerland also publishes relevant data [37]. By utilizing these open-source datasets, it is possible to construct accurate TS power system models. Figure 9 illustrates the various open-source data sources used in this project.

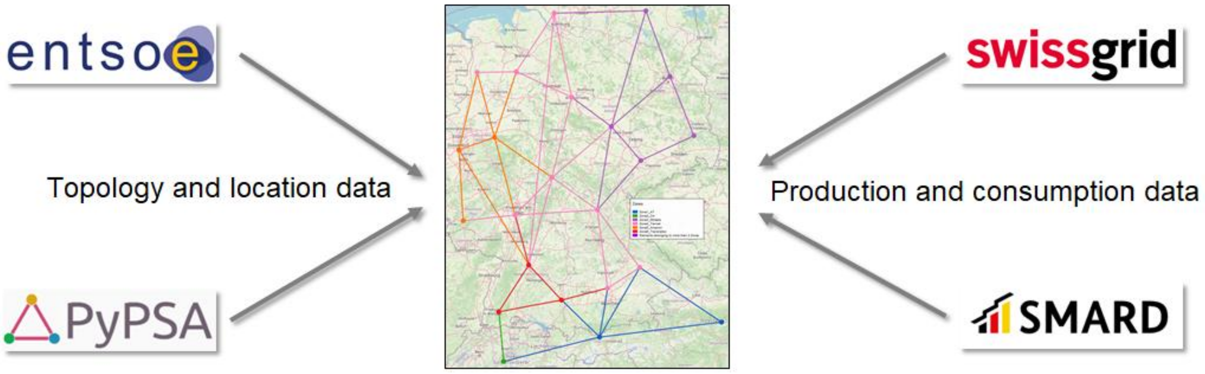

Figure 9 Various open-source data sources used in this project

These sources provide comprehensive data that are crucial for modeling and analyzing the power systems within the DACH region. By integrating these diverse datasets, researchers can develop robust models that reflect real-world conditions and facilitate detailed studies on the power grid's operation and management. The crucial aspect here is to create models that best meet the specific needs of the project partners. Given that project partners may require models of varying complexity, models with different complexity levels (low, medium, and high) are being created within the scope of this work package. For instance, medium complexity models of the DACH transmission system are shown in Figure 10. These models strike a balance between detail and manageability, incorporating essential features and data to ensure accurate representation without overwhelming computational resources.

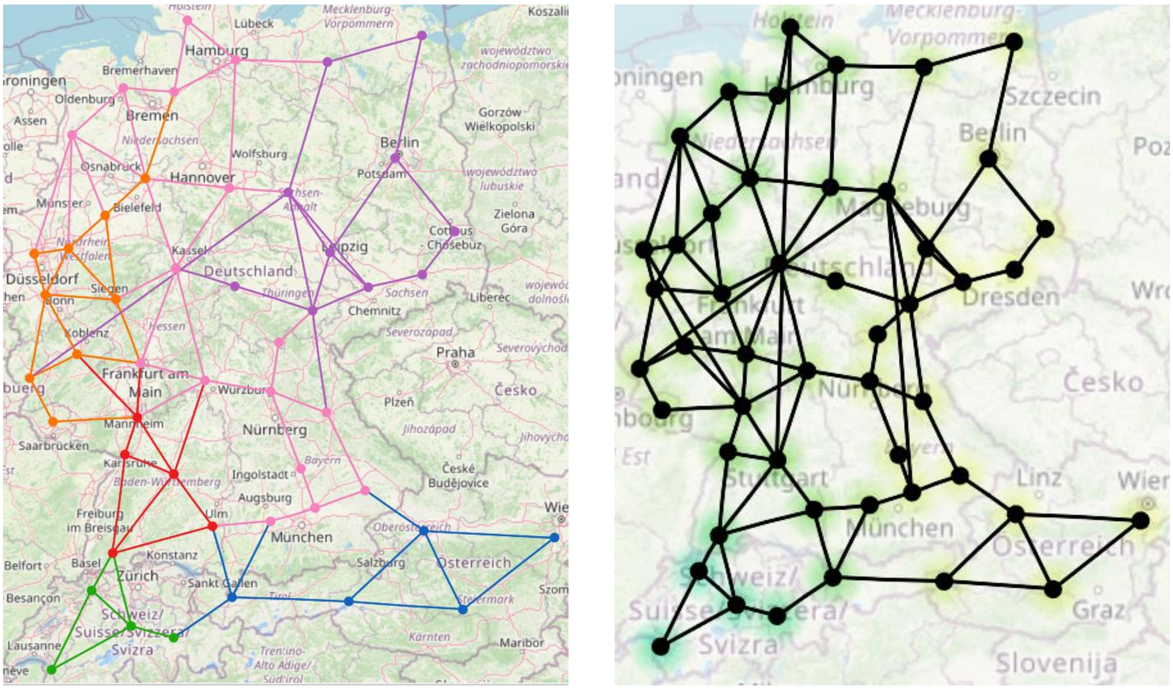

Figure 10 Medium complexity models of the DACH transmission system: Topology (left), Power flow results (right)

The low complexity model consists of 23 buses, the medium complexity model consists of 49 buses, and the high complexity model consists of 864 buses. These models account for the four transmission system zones in Germany (50 Hertz, Amprion, TenneT, and TransnetBW), Austria and Switzerland. By utilizing open-source data, production and consumption data within these zones have been realistically distributed to the buses. Furthermore, the capacities of the transmission lines are modeled to reflect the actual network. As a result of these processes, we have created network models that accurately represent the DACH region at different levels of complexity, tailored to meet the diverse needs of project partners. The development of these network models with varying levels of complexity ensures that all project partners can access the appropriate level of detail required for their specific needs. This approach not only supports effective collaboration but also enhances the ability to conduct comprehensive studies across the DACH region's power systems.

5 Model Conversion

With the dynamic evolution of the energy sector, ensuring interoperability among stakeholders from diverse domains becomes paramount for effective network management. For instance, the rising proliferation of DGs within DS elevates the role of DSOs in power system management. Additionally, economists must conduct comprehensive studies to assess the integration of these DGs into market-based operations. Given these multifaceted considerations, it becomes imperative to examine the network using various software platforms. Different stakeholders, each with their unique expertise and objectives, require access to the network model in formats compatible with their preferred software tools.

Ensuring interoperability among diverse software platforms and data formats is a critical challenge in collaborative projects within the energy sector. With the proliferation of various analysis software, each with its unique data format and features, effective collaboration becomes increasingly complex. To address this challenge and facilitate cooperation among participants from different domains, innovative solutions are imperative.

For instance, in projects requiring network modeling, bridging the gap between different software platforms is essential. The IEC Common Information Model (CIM) emerges as a key solution in this regard. CIM provides a standardized representation of power system information, offering compatibility across multiple software platforms. Software tools like PowerFactory often incorporate import and export functionalities compatible with CIM, enabling seamless data exchange. However, while CIM standardization significantly aids interoperability, it may not suffice for complete model format conversion. Additional approaches are necessary to effectively couple models from different software platforms and support diverse needs of project participants.

To address aforementioned problems outlined earlier and facilitate automated model conversions, we introduce a novel generic representation of power grids implemented as a new software tool called ePowCoRe [38]. This tool provides a versatile solution for converting power grid models between different formats while preserving accuracy. The ePowCoRe approach begins by incorporating a common data format. Thus, a generic data format is obtained, that simplifies conversion to various formats. Moreover, recognizing that network elements may be represented differently in various software, ePowCoRe adopts a flexible component model for converting these elements. In addition, the conversion process should be as transparent as possible. Transparency is key to understanding how each element is transformed during conversion, thereby contributing to correct analysis and interpretation. ePowCoRe achieves this by providing clear insights into the conversion process, allowing users to discern which elements were transformed and how they were modified. With ePowCoRe in place, models generated in PowerFactory, as demonstrated in the previous section, can be seamlessly converted to formats such as MATPOWER [39], Simscape Electrical [40], RSCAD FX [41], and GeoJSON.

By leveraging ePowCoRe, stakeholders can overcome the interoperability barriers inherent in disparate software platforms and data formats. This tool empowers users to efficiently exchange and utilize power grid models across different software environments, fostering collaboration and advancing research and development efforts in the energy sector.

For instance, within the project scope, other partners may necessitate the Bergwald model in GeoJSON format for integration into their demonstrator. Leveraging ePowCoRe, the Bergwald model is converted from PowerFactory to GeoJSON format. Figure 11 shows the GeoJSON format of the Bergwald model.

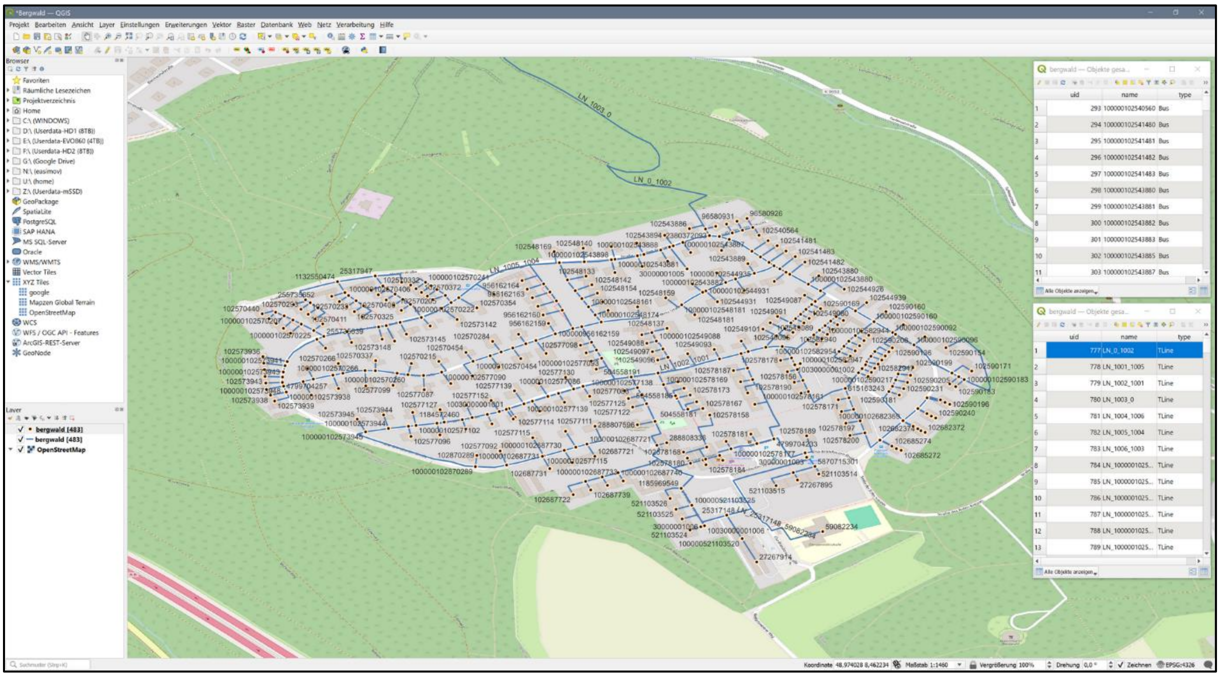

Figure 11 GeoJSON format of the Bergwald LV grid model

6 Conclusion

Within the framework of this work package, the primary objective is the development of comprehensive grid models leveraging open-source data. These models are meticulously crafted to encompass the entire spectrum of power distribution, spanning from low voltage (LV) to medium voltage (MV) and high voltage (HV) networks. Tailored to accommodate the diverse analytical needs of our project partners, these models are constructed with varying levels of complexity, ranging from low to high. This strategic approach allows for the flexible utilization of the models across a spectrum of analytical contexts.

The incorporation of high-complexity models facilitates in-depth analyses, enabling stakeholders to delve into intricate scenarios and assess system behaviour under diverse operational conditions. Conversely, low-complexity models offer a pragmatic solution for scenarios where computational efficiency takes precedence, ensuring swift and efficient execution of analyses without compromising on accuracy.

Furthermore, to facilitate seamless integration with the diverse software tools utilized by our project partners, the developed models undergo conversion into various formats through sophisticated model conversion techniques. This strategic initiative ensures that the models generated within this work package can be effortlessly incorporated into the workflows of different project stakeholders, regardless of their preferred software platforms.

By providing a robust foundation through detailed modeling, this work package supports numerous other work packages within the project. This enables the execution of many market-based analyses with models that accurately represent real-world power systems. Furthermore, the use of open-source data in model development mitigates data privacy concerns, facilitating greater collaboration and interoperability among stakeholders. Overall, this work package significantly contributes to enhancing interoperability in power system management by providing adaptable and privacy-preserving grid models.

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