Using Open Data for Modeling and Simulation of the All Electrical Society in *e*ASiMOV

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***Abstract*—The present study examines a future energy systems scenario, the so-called *All Electrical Society* (AES), which is defined by a very high number of active prosumers in the distribution grid in view of future 100% renewables-based energy systems. In this paper, we present data modeling methods that describe the power consumption behavior and power generation patterns via time series for 78 prosumers, each fully equipped with rooftop PV, two battery electrical vehicles and a heat pump. Quasi-dynamic simulations of a low voltage grid under stress conditions are performed using open data and free software. The simulatively determined increase in network utilization and congestion is also compared with the currently available grid capacity gained through extensive measurements in the examined distribution grid. The result is that in the AES scenario the current deployed electrical infrastructure of the distribution grid will be more than heavily overloaded, both the transformers and the respective power lines.**

***Index Terms*—distribution grid, grid overload, grid capacity, open software, open data**

I. Introduction

The challenges of the energy transition can be divided mainly into six categories. These are the investment, resource, political, societal, scientific, technological and the infrastructure challenges. The latter are coming into greater focus due to the rapid shift of renewables based power generation into the distribution grids and the strong electrification of the society already in place. Thus, congestion is expected due to the energy transition in the very near future also in developed countries as e.g., in Germany, which will be heavily affected by two important aspects among others. First, the extremely fast growing number of battery electrical vehicles (BEV) in Germany. According to the statistics [1] the number of BEV grew from 2,307 in 2011 and 83,175 BEV in 2019 up to 516,518 BEV in 01.10.2021. This exponential growth is reinforced by grants of the German Federal Office for Economic Affairs and Export Control (BAFA) for BEV [2]. Second, grants for energy efficient buildings [3], that cover photovoltaic installations with batteries and heat pumps ideally operated by renewable energy sources. As a result of these subsidies, PV holds a 28 billion kWh share of gross electricity generation with 292 billion kWh in Germany (9.6% in 2021) [4]. The number of battery installations usable for PV as well as for BEV increased from 5,000 to 272,000 in the period 2013-2020 [5]. A further consequence of these subsidies is that the number of heat pump installations in new buildings in Germany has increased from 0.64% in 2000 to 45.8%, i.e. one of two newly built houses is equipped with a heat pump [6]. These new developments are already affecting the distribution grid and intelligent solutions need to be implemented urgently. However, treatment must be preceded by diagnosis. Therefore, the impact of the so-called *All Electrical Society* (AES) on the utilization and the remaining network capacities must be examined for deriving respective measures for this future scenario. AES is defined by a very high number of active prosumers in the distribution grid. The contribution of the present paper is an analysis of the low voltage (LV) distribution grid (DG) capacities under stress conditions using open data and free software for quasi-dynamic simulations (QDS). The developed models comprise 78 residential prosumers that are fully electrified with two BEVs, PV solar generation, battery, heat pump, as well as the residential load. All results are compared to real measurements of the examined LV grid under normal conditions. The paper is structured as follows. Chapter 2 gives an overview of open data and open software initiatives in this field, but also introduces selected studies on the analysis of DG capacities. Chapter 3 presents our framework for the energy system analysis. Chapter 4 introduces data modeling methods for quasi-dynamic simulations that are presented in chapter 5. The paper concludes with a discussion of the results.

II. Related Work

A. Open Data and Software for Energy System Analysis

A vast number of open, mostly academic software and open data repositories in energy research exist, whose importance is discussed i.e. in [7]. In this context, [8]–[10] are important initiatives for the provisioning of open data including models, weather and power plant data covering Europe. The *Helmholtz Energy Computing Initiative* is a platform for open data and open academic software in the energy domain [11]. Beside this, various energy system analysis related software packages are freely available [12]–[15]. And last but not least, the *Helmholtz Open Science* initiative, which enables open access to research data [16].

B. Analysis of Distribution Grids

A literature review of congestion management with direct methods as reconfiguration, active and reactive power control, and indirect methods using market mechanisms formulated as optimization problems is given in [17]. A review on flexibility options for distribution networks based on concepts for planning and forecasting, monitoring and control in future power systems is presented in [18]. Many large-scale studies examine and discuss future scenarios in distribution networks [19]–[22].

The distribution system operator (DSO) Netze BW conducted several experiments on grid integration of electrical vehicles and analyzed the grid utilization for various grid types. For a rural supply area with 60 residential units, 43 house connections, 13 thermal power plants, 3 photovoltaic plants and 7 small BEVs supplied by 8 charging stations with max. 22 kW and a central battery storage, the behavior of customers and its effects on the on the power grid was analyzed in the project *E-Mobility-Chaussee* [23]. Three possible solutions for load reduction were tested: the use of preventive charging management, battery storage, and a string regulator that

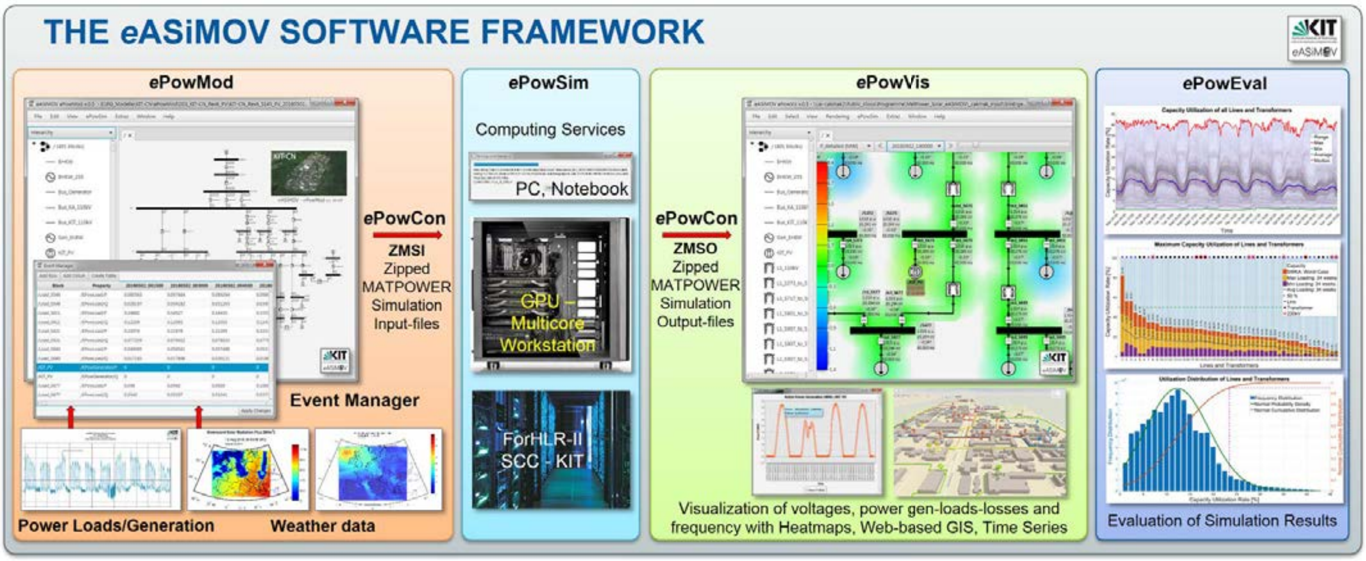

Fig. 1. Components of the *e*ASiMOV framework and the workflow for the electrical grid analysis.

can selectively raise the voltage in the power grid. In the project *E-Mobility-Carré* [24] with focus on urban quarters with predominantly multi-family houses and 45 BEVs, the demand power peak is at 175 kW in the night due to electrical heating. The maximum line loading is 120% with an exclusive substation power supply for the charging infrastructure. The project *E-Mobility-Allee* [25] comprises 21 residential units and 11 BEVs and various battery storage options combined with intelligent ICT for monitoring and control. With a current guided charging management the grid loading is up to 73% and for a voltage guided charging the loading increases up to 174%.

In this context, the present paper provides an analysis of grid utilization under future stress conditions in the AES using open data and free software.

III. Framework Description

The *e*ASiMOV software was initially introduced for the analysis of the power grid with the key idea to provide an open framework for grid modeling and visualization together with web-based data services that can utilize any open and commercial simulation engine with varying computing technology by defining appropriate data exchange and data conversion methods. Due to the emerging necessity of a holistic view of the energy system in the context of the requirements of a successful energy transition, the framework is now primarily expanded by a modeling and simulation component for the multimodal energy system analysis with regard to sector coupling. The extended framework is now known as *e*ASiMOV – *e*nergy system *A*nalysis, *Si*mulation, *M*odeling, *O*ptimization and *V*isualization. Its main components are described briefly in the following subsections in detail, followed by a list of applications where the framework was successfully deployed.

A. Framework Components

Fig. 1 shows the basic framework components and the workflow for the case of the electrical grid analysis. The framework components are in detail (1) *e*PowMod: JavaFX based interactive modeling tool for electrical grids with capability for hierarchical encapsulation of sub-models and support for schematics and geo-based modeling. The internal JSON-based model representation relies on Matpower (www.matpower.org). (2) *e*PowCon: Model conversion modules for converting between internal data representation to Excel, Matpower, OpenDSS (www.epri.com) and Powerfactory (www.digsilent.de). (3) *e*PowSim: Power flow computation engines implemented for CPU with Eigen, GPU with Arrayfire and a hybrid simulation with CUDA using various solvers, transient stability analysis and support for cluster computing. (4) *e*PowVis: Advanced visualization and interaction with simulation results. (5) *e*PowEval: Data analysis of simulation results delivering statistics and diagrams. (6) *e*DataServ: Web-based data services with REST-API for provisioning of weather data and power consumption data with intelligent data correction methods incorporated. (7) *e*CoSim: Co-Simulation framework with support for FMI/FMU model exchange and simulation coupling with a user-friendly graphical interface. The *e*ASiMOV software is freely available without any limitations on request from the authors. The licensed Java executable for modeling and visualization requires Matpower for power flow and optimal power flow calculations and GNU Octave (www.gnu.org/software/octave). No commercial licenses are required.

B. Applications in Energy System Analysis Research

The *e*ASiMOV framework was used for Open Street Map data analysis and graph optimization for automated generation of power flow simulation models [26], [27]. It was utilized for comparative power system analysis of large scale transmission grids together with model conversion to Matpower [28] and to the CIM format [29]. It was deployed in research on probabilistic power flow on the distribution grid using data-driven forecasts [30], distributed optimal grid partitioning for optimization of reactive power dispatch [31] and optimization with genetic algorithms for resilient and fair power distribution [32]. The framework was extended with transient analysis of the power system performance following a disturbance under balanced and unbalanced network conditions [33] with support for cluster computing [34] considering integrated renewable energy sources [35], [36]. To ensure simulations with high quality input data, a data driven method for time series imputation has been incorporated [37]. New framework extensions focus on co-simulation for energy system analysis comprising electricity, gas, and heating [38]–[40], but also consider coupled co-simulation with real-time simulators as the RTDS system [38], [41].

IV. Power Grid Model of the AES Scenario

This chapter introduces the simulation model generation with a strong focus on the data modeling as simulation input.

A. Power Grid Model

Based on OpenStreetMap data, Overpass-Turbo [42] is used to identify the buildings in the target grid area. The result is a JSON file, which is then processed with a Matlab script that extracts the data of the individual buildings; these are the geo-coordinates, the floor space and further information such as address and building type. Based on the analysis results, a KML file is created automatically. In a manual step, the cabling of the buildings with the transformer station is carried out, whereby the fail-safety is taken into account by means of appropriate distribution cabinets and switch elements. Using the visual information in the KML dataset and the available GIS-coordinates, the network is transformed into a geo-based grid model in *e*PowMod in a semi-automated procedure. The grid model includes one Lahmeyer station with a 20/0.4 kV transformer (0.63MVA DTTHL SGB 3phase) and seven radial feeders. The cables along the roads are of type NAYY 4x150SE 0.6/1 kV with a current rating of 0.27 kA, the residential unit connection cables are of type NAYY 4x35 with a current rating of 0.119 kA (1 kV). The cable and transformer specifications are converted into the per unit system and dimensioned according to the lengths of the individual cable sections using the GIS information.

Fig. 2 shows the visualization of the electrical network of the target area, which then has been converted into an electrical simulation model for quasi-dynamic simulations.

Fig. 2. Segmentation of residential buildings in the target area with Overpass in the Open Street Map data and automated KML generation for visualization and as an electrical grid modeling aid.

B. Data Modeling

In the *All Electrical Society* scenario of the future, overloads in the distribution grid are to be expected due to an extremely high proportion of electrical power consumption and distributed generation. Each of the 78 grid customers acting as so-called prosumers draws power from the higher-level grid and feeds in PV power. Specifically, the residual load of each prosumer in the model is composed of electricity generation with a maximally expanded PV system, two electric cars, a heat pump, and the regular electricity consumption. The following subsections summarize the data modelling for each of the components.

1) Battery Electrical Vehicle: Modeling the BEV behavior with time series generation is well published [43], [44]. However, for this study, we developed our own behavioral model where each residential unit is equipped with a TESLA Model 3 with fast charging capability at 11kW, a battery capacity of 75kWh and 7.5h AC-charging time. Further, as the secondary vehicle serves a budget BEV (Peugeot iOn) with slow charging at 3.7kW, a battery capacity of 14.5 kWh, and 5h AC-charging time, according to the specification data sheets provided in [45]. In our model, the charging time for the superior BEV can start between 6pm and 11pm, and at 9am-11pm for the budget BEV acting as a family car for daily use. To avoid uniformity in the time series, variability of the initial SOC and the time for recharging is considered.

2) Heat Pump: Heat pumps are devices that transfer thermal energy from a heat source - a medium with a low temperature level - to the heat sink, which is a medium with a higher temperature level using a reversed Carnot cycle. Technical details, implementation and evaluation of various types of heat pumps can be found in the literature. In [46] the working principle and optimization potential of heat pump heating systems are analyzed and a model for optimized scheduling is provided. In the context of decarbonization and greenhouse gas emissions reduction, the dependencies of the power demand of heating pumps are analyzed and in accordance electrical power load time series are provided in [47]. Optimal scheduling methods for a grid-supporting operation of heat pumps with demand side management control utilizing thermal storages aim at reducing the power peaks in the grid [48].

In the context of this study, we are less interested in the technical details, but rather in the development of a practically usable data model, that generates realistic and acceptable time series for typical heat pumps. These time series will be used as additional electrical loads of the single-family homes in the simulation model. The efficiency of a heat pump system is described either by the *Coefficient of Performance* (COP), which is relevant under standardized laboratory conditions, or by the *Seasonal Performance Factor* (SPF) that considers additional energy consumption for auxiliary energy in a time horizon of one year. Thus, the SPF indicates the annual ratio of the heating energy output to the electrical energy input [49]:

$$SPF = \frac{\int_{t_0}^{t_1} \dot{Q}_{therm}\, dt}{\int_{t_0}^{t_1} P_{el}\, dt} \tag{1}$$

In this study we consider groundwater heat pumps with a SPF of 3.8 that are significantly more energy efficient compared to air- and ground source heat pumps [50], [51]. We use standardized load profiles for heat pumps in combination with the energy consumption and the daily mean temperatures. As the authoritative temperature measuring point for the daily mean temperature, the utility provider EnBW determined the measuring point of the German Weather Service (DWD) in Stuttgart-Echterdingen, where the dataset for the past ten years is available [52]. The temperature data for the simulated period is combined with the daily parameter-dependent load profile for heat pumps (BW-WP1 EP1) provided by the DSO Netze BW [53]. As a reference, our model uses the typical electricity consumption of 7,076 kWh per 160 square meters of living space, which is transferred to our model according to the floor area of the residential units in the target area with varying SPF values.

3) Residential Loads: The residential loads are derived from a measurement campaign in the low voltage grid [54]. The power data measured at the 20/0.4 kV station are disaggregated and extrapolated to the 78 residential units considering the assumption of the dependency on the ground floor area of each building. In our model, semi-detached buildings have lower consumption than single family houses. The study target area contains only single-family homes.

4) PV Generation: In the AES model each building is equipped with maximum possible number of PV panels for solar energy generation. For setting up the model, we require the solar potential on each building, appropriate weather data and an approximation for the generated solar power. The weather data are provided by DWD [55] and compared to the in-house available commercial product Anemos [56]. The DWD dataset is of better quality, Anemos data are based on models. For the further analysis, we rely on DWD temperature data and Anemos radiation data although radiation data might also be available but major deviations are not expected. The solar energy potentials for the buildings in the study area are determined via the Energieatlas BW [57]. This delivers information on the building type, suitability class, possible suitable PV module area and the roof shape. Missing data were manually added using Birdseye-view map and an online tool for interactive area calculation on Google Maps [58]. According to the available roof area and the roof shape, the maximum number of installable PV panels and thus the peak power generation can be estimated. The output power P_s of a PV unit can be approximated as proposed in [59]:

$$P_s = \eta \cdot S \cdot I \cdot (1 - 0.005 \cdot (t_0 - 25)) \qquad (2)$$

In our model the efficiency of the solar panels is set η=15.7% [60]. The further parameters as the area of the PV panels S [m²], the solar radiation I [kW/m²] and the outdoor temperature t_0 [°C] are available as described above.

5) Residential Residual Load: In the time series for residential residual loads shown in Fig. 3 we can clearly identify the power export from the 0.4 kV to the 20 kV grid during active PV power generation phases and the power import in the evening and night mainly for BEV charging and heating.

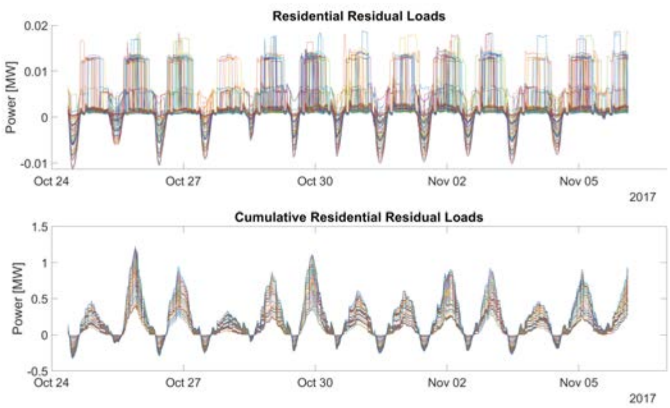

Fig. 3. Time series of the residential residual loads of the prosumers.

V. Analysis of the AES Scenario

A. Reference Study

The capacity on all voltage levels of the German electricity network was analyzed in [54]. Simulations were carried out on the highest and high voltage level, whereas high rate long-term measurements on the 20/0.4 kV voltage level were performed in 2019. According to this, the key findings for the distribution grid indicate a maximum capacity utilization of about 25% for the medium voltage grid and 13.5% (9.1% in average) for the low voltage grid. The analyzed suburb in the city of Karlsruhe comprises 74 residential buildings with a total 10 solar RE-devices and a maximum load of 83.3 kWp. These values are considered as a reference for the further analysis.

B. Quasi-dynamic Simulation in eASiMOV

The simulation model is setup in *e*PowMod whereas the aforementioned residential residual loads are defined as so-called *events*. Each object is assigned active and reactive power values using $cos\,\phi = 0.95$ for 1,225 quarter-hourly simulation steps representing the simulation period 24.10.2017 9am - 06.11.2017 3am. Since the model does not contain Li-ion battery storage models in a first step, each state is independent. Performing the task parallel power flow computation on a cluster computer does not make sense for the relatively small 174 bus, 79 generator and 189 branch model. The workflow as shown in Fig. 1 is initiated, the model converter *e*PowCon exports 1,225 Matpower model files into a so-called ZMSI-file (*Zipped Model Simulation Input*), which are transferred and simulated in the target computing environment and returned as a ZMSO-file (*ZMS Output*) to *e*ASiMOV, which invokes *e*PowVis for interactive visualization. Fig. 4 shows the simulation results in *e*PowVis for the grid load condition at 29.10.2017 10:15pm with the peak line loading value 266.5%.

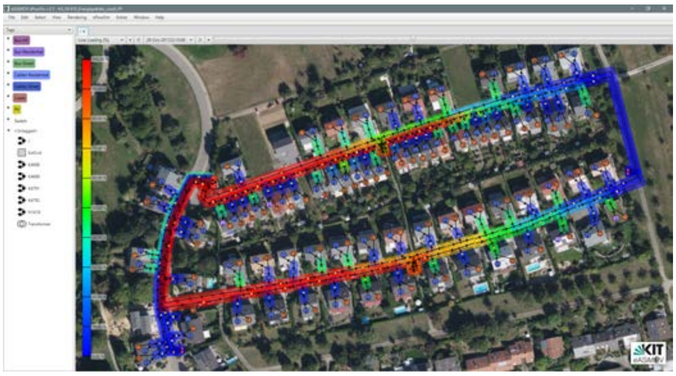

Fig. 4. Visualization of grid condition in *e*PowVis with peak branch loadings.

C. Discussion of Simulation Results

The heat map plot in Fig. 5 shows the loading of the branches in percent over the quarter-hourly simulated time. The mean branch loading value is 23.8%. The branches 1-27 represent inactive branches and switches. The branches 29-110 are cables along the streets with high loading and the branches 111-188 are cables to residential units with a relatively low branch loading. The summary statistics of the loading values related to the residential unit connection cables is as follows: min 18.8%, max 36.1%, mean 25.9% and median 24.3%.

The voltage magnitudes shown as a heat map in Fig. 6 correlate with the residential residual loads shown in Fig. 3 whereas high loads cause a voltage drop and vice versa. The voltage magnitude is in the range of [0.934; 1.046] $p.u.$, the mean value is 0.985 $p.u.$, and the median is 0.987 $p.u.$ The voltage limits are still in a valid range, since temporary voltage fluctuations of ±10% in distribution grids are acceptable according to international standard IEC 60038. Consider that in the model there is no control at all as automatic transformer tap settings or any consideration of active and reactive power limits.

The loadings and voltages are dependent on the power factor. Thus, with a selected $cos\,\phi = 0.9$ the maximum branch loading of 279.6 % is registered due to the increased reactance. The voltage magnitude

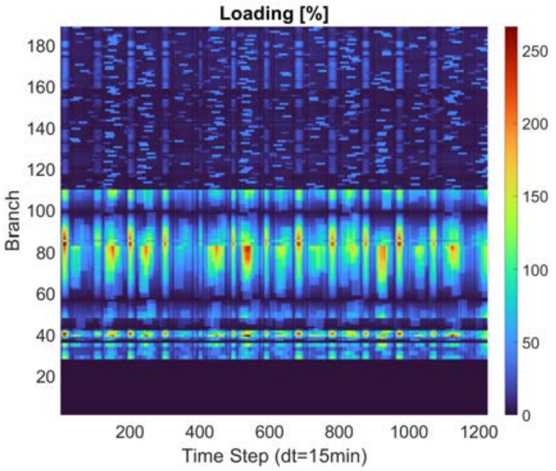

Fig. 5. Heatmap visualization of the QDS line and transformer loadings.

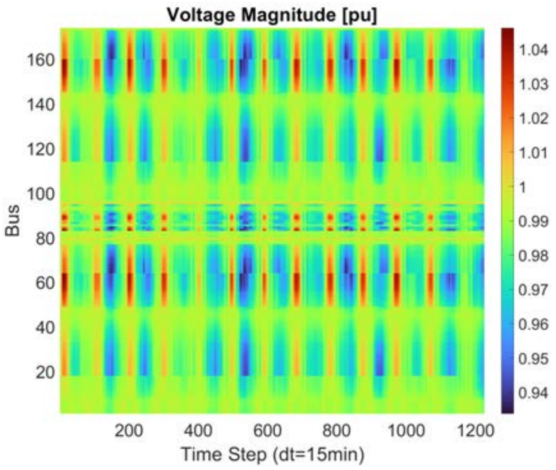

Fig. 6. Heatmap visualization of the QDS bus voltage magnitudes.

range drops to [0.926; 1.028] $p.u.$ As expected, the overall condition of the grid is deteriorating.

To analyze the effects of batteries, a further quasi-dynamic simulation with individually dimensioned batteries at each residential unit is performed, which results in the reduction of the average line loadings of up to 19%. The high residential loads, caused mainly by BEV charging in the evening, are partially compensated by the batteries, but the peak loading of the lines at midday still persist.

Compared to the measured data of the reference study in 2019, our simulations show an extreme increase of line loading from 13.5% up to 279.6% for the AES scenario. The severe congestion is plausible given that the model includes nearly 8 times the number of full-scale PV systems and the considerations of 156 BEVs and 78 heat pumps. The conducted experiments of the DSO Netze BW serve as a further good reference for comparison (see section II-B). For an experimental setup with 21 residential units and only 11 BEVs in combination with battery storage, they report a 174% line loading for voltage guided charging. Our simulation results display the same pattern, but of course they are quantitatively not directly comparable with the reported values. However, the trend is clear: distribution grid capacity will very soon reach its limits if necessary countermeasures are not undertaken.

VI. Conclusions

The introduced methods for grid and data modeling based on open data are well suited for the study of a future energy systems scenario, the so-called *All Electrical Society*. The simulation results indicate heavy congestion on distribution grid level due to the exponential increase of network loads and distributed generation in the low voltage grid. Without monitoring, intelligent control and other interventions as demand side management or flexibility options, the low voltage grid will not be able to handle the expected overload. The presented methods are a good initial starting point for further future research, using thereby the respective models of the free software *e*ASiMOV as a test-bed for developing novel optimization algorithms that can handle reduction of grid loading with optimal battery sizing and control strategies for battery and EV charging management. Future work will concentrate on automated grid modeling and a holistic analysis of energy systems considering heating and gas networks in a co-simulation environment incorporating high performance computing.

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