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Analysis and prediction of electromobility and energy supply by the example of Stuttgart

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Summary

The increasing electricity demand of electric vehicles may become a major challenge for energy supply grids. This paper seeks to identify bottlenecks in the energy grid supply regarding different market penetration of battery electric vehicles (BEV) and plug-in hybrid vehicles (PHEV) in Greater Stuttgart. First, medium-term forecasts of electric vehicles xEV (BEV & PHEV) and the corresponding charging infrastructure are issued from 2019 to 2030. In the following, the associated energy consumptions and power demand of xEV are compared with different scenarios. Considering the spatial and temporal distribution of the further energy demand, load profiles and peaks of the subgrid with 349 households are microscopically simulated and generated, based on an individual driving and charging behavior. Furthermore, we analyze the impact of electromobility on the low-voltage grid using real grid data.

Keywords: BEV (battery electric vehicle), charging, infrastructure, energy, demand

1 Introduction

In order to achieve the emerging climate change targets coupled with managing traffic volumes, alternative vehicle concepts such as battery-electric vehicles (BEV) are offered by the automobile industry and require new infrastructure for electrical energy supply related to customer demands. Due to the increasing market penetration of electromobility and the resulting charging infrastructure, the use of electricity grid in particular on the low-voltage level is becoming more and more decentralized.

Previous work on the charging infrastructure indicated that the growing interest in electric vehicles has a strong influence on grid stability [1–4]. An increasing number of loading processes can cause a bottleneck in

the energy supply. The early detection of problematic areas is essential to detect possible weak points and to prevent a grid overload in the future. In this paper we present an investigation of the expanding market for electric mobility up to 2030 and its impact on the energy demand, carried out on the example of the network of the city of Stuttgart, Germany.

2 Prediction of vehicle number und charging points for an exemplary local area until 2030

The total vehicle fleet in Germany was analyzed and the potential market diffusion of electric vehicles (xEV) in the region Stuttgart in the year 2017 was estimated in our previous papers [1, 2]. This forecast is based on different current studies in consideration of the European CO₂ fleet emission targets (up to 59 gCO₂/km until 2030) [2]. It was also described that the current xEV share in Greater Stuttgart is twice as much as xEV share in Germany (0.56%). Based on the higher share in Greater Stuttgart it is suggested that at key industrial locations disproportionately high penetration of xEV can be expected in the future.

The vehicle fleet is subject to a continuous replacement by new vehicles. At the same time, the automobile manufacturers are under pressure to comply the average CO₂ fleet emission of the vehicles sold annually [5]. The development of the limit values for the different segments is shown in Table 1.

Table 1: Development of European fleet emission limit values in road traffic [5]

	2020	2025	2030
passenger car	100% (95 g/km)	-15% (81 g/km)	-37.5% (59 g/km)
light-duty vehicles	100% (147 g/km)	-15% (125 g/km)	-31% (101 g/km)
heavy-duty vehicles	-	-15%	-30%

The legal regulations will be disrupted by an EU directive that will come into force in 2021. In this directive, buses in particular are subject to a stricter requirement (see Table 1). Therefore, already by 2025, 22.5% of the total vehicle fleet should be as so-called emission-free concepts [6]. However, mainly passenger cars will be considered in the following.

First of all, a forecast of the medium-term penetration of electric vehicles for the passenger car fleet should be derived. The degree of fulfillment of the average fleet consumption achieved by the car manufacturers form the basis for the forecast. The limit value for cars will be sufficiently reduced from 2020 (as shown in Table 1). As a result, the efficiency enhancements concerning conventional drive technologies achieved to date will no longer be sufficient to meet the requirements. Switching to emission-free electric drives is a necessary consequence.

More than 58 million vehicles are registered in Germany, of which 46 million are passenger cars (2017) [7]. Comparing the importance of the vehicles according to their mileage, the share of the passenger cars with 630,481 million km covers almost 90% of the total annual mileage on the roads in Germany [8], as shown in Fig. 1.

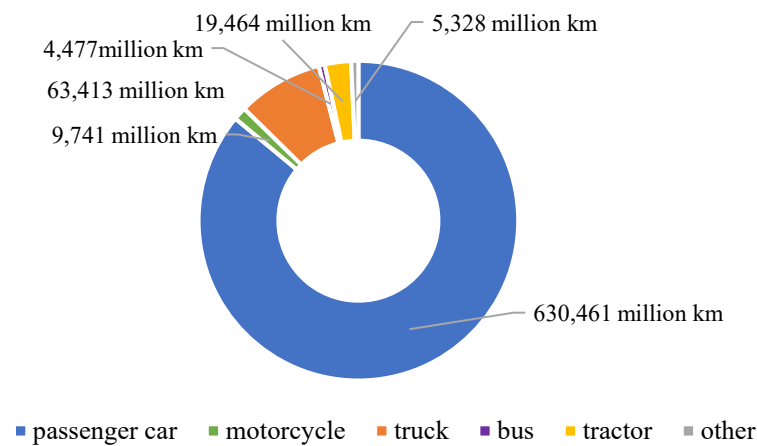


Figure 1: Total annual mileage in Germany [8]

Based on the analysis of the total vehicle fleet in Greater Stuttgart and the legal framework conditions, two electrification scenarios for road traffic in Greater Stuttgart in 2030 were created. The focus lies on passenger cars, as they have the largest share of total mileage and can be electrified more easily than duty vehicles due to their lower weight [2]. Hence, an xEV share of the vehicle fleet of around 27% in 2030 can be assumed in the Stuttgart region (see Fig. 2). This corresponds to approximately 480,000 xEV, assuming a sufficient market acceptance of the newly created offer of alternative drive concepts.

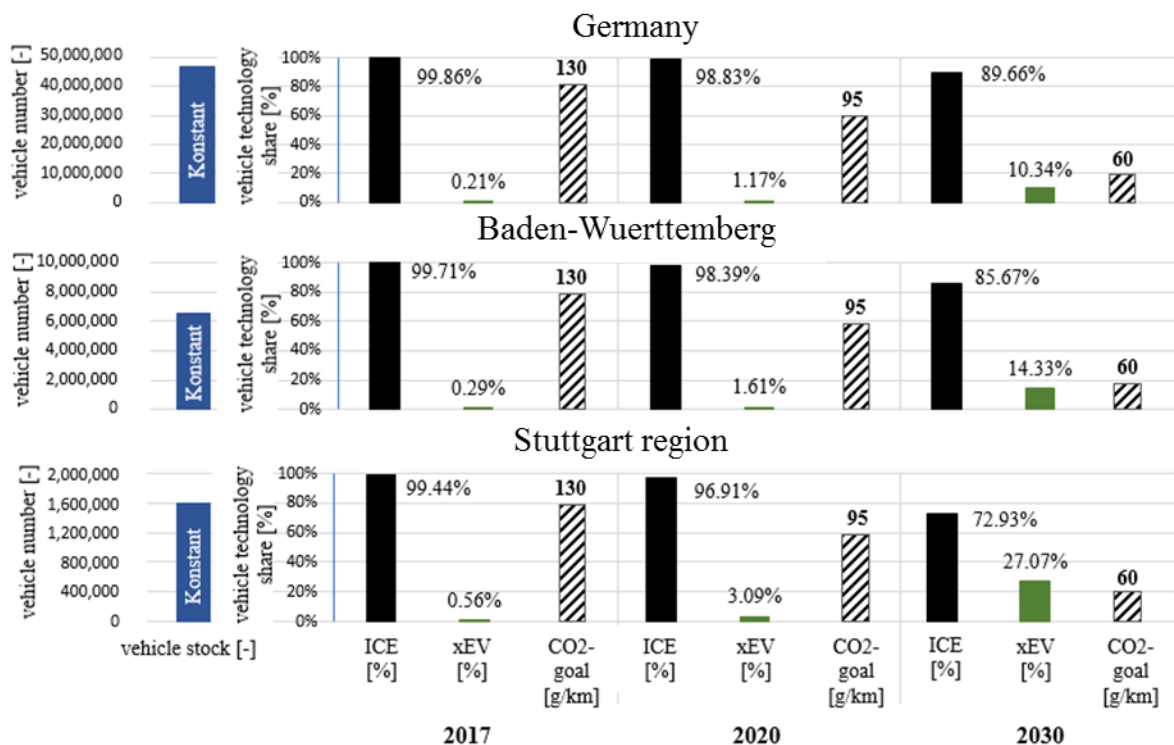


Figure 2: Forecast scenarios for the vehicle fleet electrification in Germany

According to the National Platform for Electric Mobility (NPE), 77,100 charging points have to be set up for one million xEVs, corresponding to around 13 xEV per charging point [9]. Extrapolating this recommendation into 2030, around 37,000 public charging points should be built by 2030 in Greater

Stuttgart. The costs for procurement and installation of these charging points were determined according to NPE roadmap charging infrastructure. This roadmap provides a forecast of the charging infrastructure costs in the categories "Smart charging box", "AC charging station" and "DC charging station" for 2020, as shown in Table 2.

Table 2: Charging station infrastructure costs for electric vehicles based on [10, 11]

	Smart charging box	AC charging station	DC charging station
charging station	1	2	1
investment costs station [€]	1,700	5,500	20,000
typical charging power [kW]	3.7	15.7	50
investment costs [€/kW]	459	350	400
grid connection costs [€]	0	2,000	5,000
grid connection costs [€/kW]	0	127	100
current costs [€/a]	500	750	1,500
current costs [€/a*kW]	135	48	30
assumption service life of charging station [a]	10	10	10
assumption service life grid connection [a]	40	40	40
lifetime weighted investment costs total [€/kW]	459	381	425

To determine the average costs, the specific costs per kilowatt of installed capacity of the charging stations and their electrical distribution, grid connections were determined as well as the specific investment cost for the charging stations.

A survey was conducted to investigate the distribution of public charging points' charging power. The investment for the target number of charging points was calculated based on the cost structure in Table 3.

Table 3: Total investment of public charging points in the Stuttgart area [12]

	distribution	number of charging stations	investment, €
3,7 kW	2%	738	1.3 million
11-22 kW	72%	26,585	79.8 million
≥ 50 kW	26%	9,600	204.0 million
total	-	-	285.0 million

The requirements for infrastructure, automobile manufacturers and electrification of road traffic are clearly driven by the current legal framework of the European Union. In urban centers such as the Stuttgart region in particular a strong increase in xEV is expected (around 480,000 xEV in 2030, corresponding to a share of

around 30%). In the following chapter, the energy system of the Stuttgart city will be analyzed and the future impact of electrified road traffic on the energy grid energy network will be shown.

3 Energy demand in Greater Stuttgart

In order to analyze the interactions between electric vehicles and the local energy system in Greater Stuttgart, an energy system analysis was carried out with the TIMES Local Stuttgart Model [13–15]. According to [1], this energy system model represents all processes for energy conversion and use in the area of Stuttgart. It covers the whole energy chain, which means energy supply (e.g. power plants, electricity imports), transmission and distribution, and energy consumption by end users.

From a mid- and long-term perspective, electromobility will play a key role in an urban energy and transport system. Consequently, with regard to the future development of electromobility, scenarios with different market penetration have been compared. As switching to public transportation can also be an effective instrument to reduce emissions, a scenario with light commercial vehicles (high: 11.6% or low: 4%) and buses (high: 21% or low: 7%) is considered. According to the master plan for the City of Stuttgart [16], the analysis is based on three hypothetical scenarios:

- "KLIM": reduction of 95% global greenhouse gas (GHG) emissions until 2050 (compared to 1990) and rapid implementation of electromobility (27% xEV in 2030)
- "KLIMPLUS": a falling demand for mobility in individual motorized transport due to increasing demand in public transport and rail traffic
- "KLIMPLUS-LOW": identical general conditions with "KLIMPLUS", but a significantly delayed expansion of electromobility (10% xEV in 2030).

Electricity demand distribution by sectors is shown in Fig. 3, indicating that in the KLIMPLUS scenarios, electricity demand in the sectors industry, trade and services as well as households declines by nearly 30% until 2050. The total electricity demand is almost stable from 2035 to 2045, while electricity demand for electric cars, trucks, and buses increases continuously. Apart from the transportation sector, electrification can also have a considerable impact on the other sectors such as households in 2050. Further comparison of the KLIMPLUS and KLIMPLUSLOW scenarios which total consumptions are comparable, show a shift from transport to the other sectors (KLIMPLUSLOW) in order to achieve long-term carbon neutrality targets.

Energy efficiency in industry and electromobility are important factors for electricity demand. In order to meet ambitious climate goals, electrification is considered as an obvious solution to decarbonize energy consumption.

The use of electromobility has multiple cost implications compared to conventional vehicles. This cost results primarily from the specific battery price and battery size. In addition, there are further cost effects due to the necessary expansion of the charging infrastructure and the regional energy system. Fig. 4 shows the differential costs caused by increased electromobility (KLIMPLUS) compared to the other scenario (KLIMPLUSLOW). Overall, this will be faced with additional total costs of around 600 million euro up to 2050. Taking a closer look at the majority of these costs, around 480 million euros will arise in the period 2023-2037. while in the following years costs will remain steady.

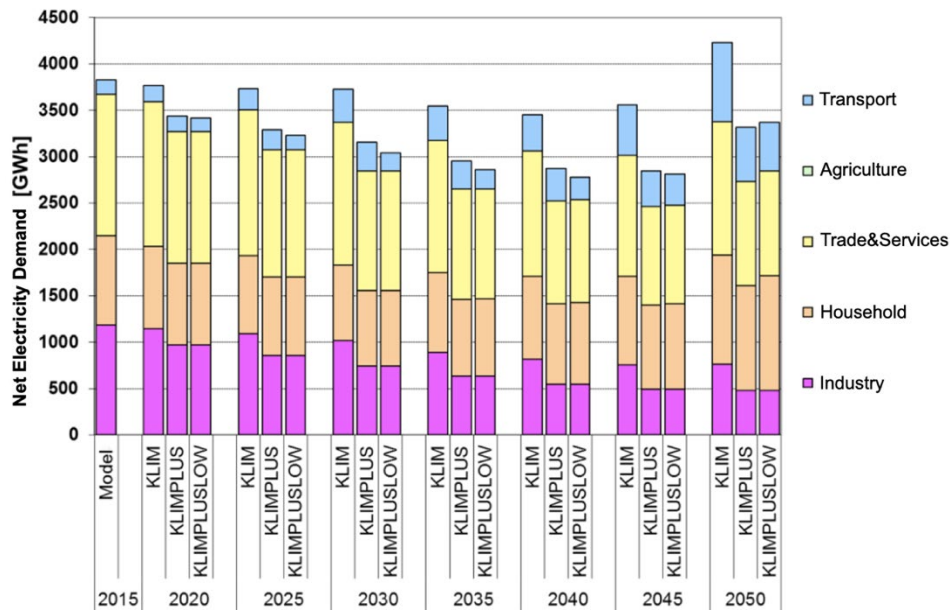


Figure 3: Electricity demand shares by sector in different scenarios

With regard to the cost components, the differences for the investment and operating costs between the conventional vehicles and the xEV are not significant, the additional costs are forecast to 35 million euros until 2027, meaning that the additional costs in the balance sheet are mainly due to the installation and operating costs of the charging infrastructure. In total about 880 million euros cumulate over the considered period.

The remaining differential costs in both parts of "Imports / Exports" (e.g. fuel and electricity imports) and "Other system" (e.g. energy system of industry and households) will stay relatively low until 2042. However, the "Other system" subsequently shows significant cost reductions compared to the KLIMPLUSLOW scenario. These is explained by the fact that greater efforts are required in the remaining energy system to achieve the greenhouse gas reduction targets, especially if the electromobility is rarely considered in the master plan of Stuttgart.

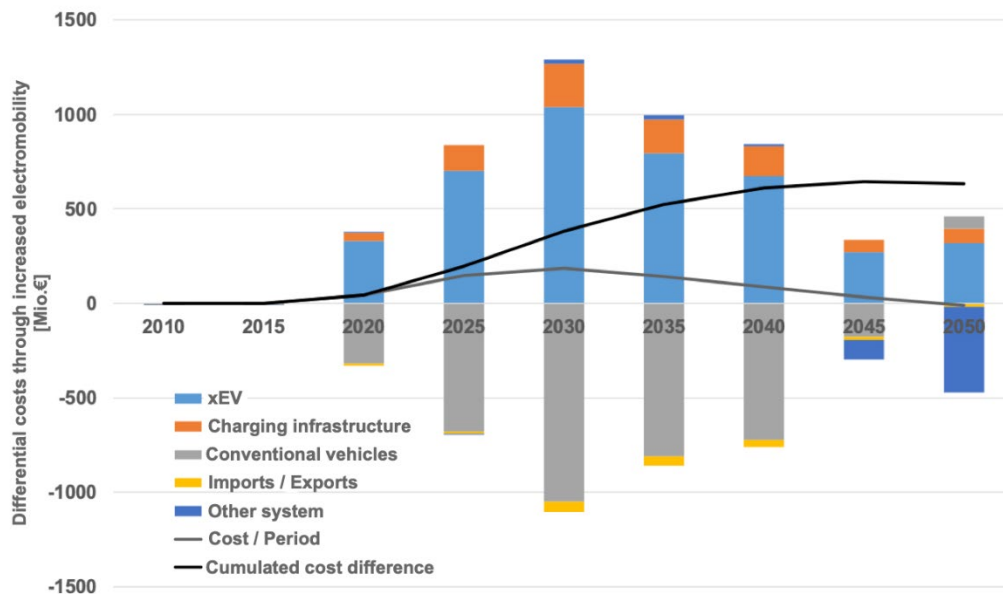


Figure 4: Discounted system cost difference due to increased electromobility (cumulated over 5-year periods), KLIMPLUS and KLIMPLUSLOW scenarios in comparison

4 Examination of network effects in the city Stuttgart based on a travel demand model including electric vehicles

To examine the temporal and spatial distribution of additional energy demand caused by electromobility we used the agent based travel demand model mobiTopp. mobiTopp is a microscopic multi-agent traffic demand model developed at the Karlsruhe Institute of Technology, Institute for Transport Studies, which simulates the movement of all people using all modes of transport exact to the minute over a period of one week [17]. Further, car use and charging patterns can be analyzed for different vehicle types including electric vehicles. In total, 5 scenarios with different patterns market shares for xEV and different charging capacities were simulated (see [2] for further details).. These results were used for further analysis within this project.

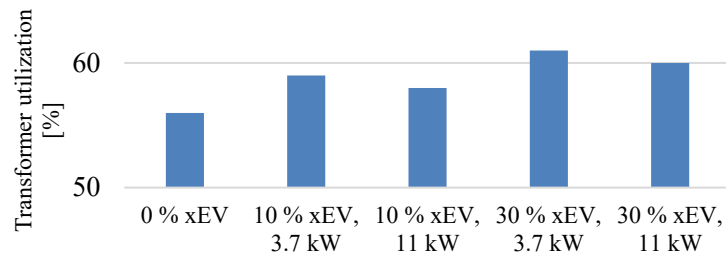


Figure 5: Transformer utilization for the different scenarios

First, a load flow analysis was carried out for a residential area with 433 households and 779 inhabitants in Stuttgart. For this purpose we analyzed the peak load of BEV charging and average household energy demand, assuming that agents recharge their BEV once they return home without any charging management in the simulation. We observed that a higher charging capacity can lead to a lower transformer utilization (see Fig. 5). This could be explained by a temporal fall apart of charging and household peak load. Due to the shorter charging time, a higher charging capacity can lead to a reduction in simultaneous charging processes. In summary, no thermal or voltage-related overloads could be identified independent of the scenario [2].

5 Analysis and prognosis of network load in the city of Stuttgart

Second, an analysis of the low-voltage grid including the additional demand from electromobility (resulting from the mobiTopp simulation) was conducted for the whole city of Stuttgart. As a local distribution system operator, Stuttgart Netze GmbH (SN) is responsible for the secure and safe operation of electrical distribution network in Stuttgart. The distribution network includes around 1,500 km of medium-voltage and 3,900 km of low-voltage lines. The structure of the distribution network is schematically represented in Fig. 6.

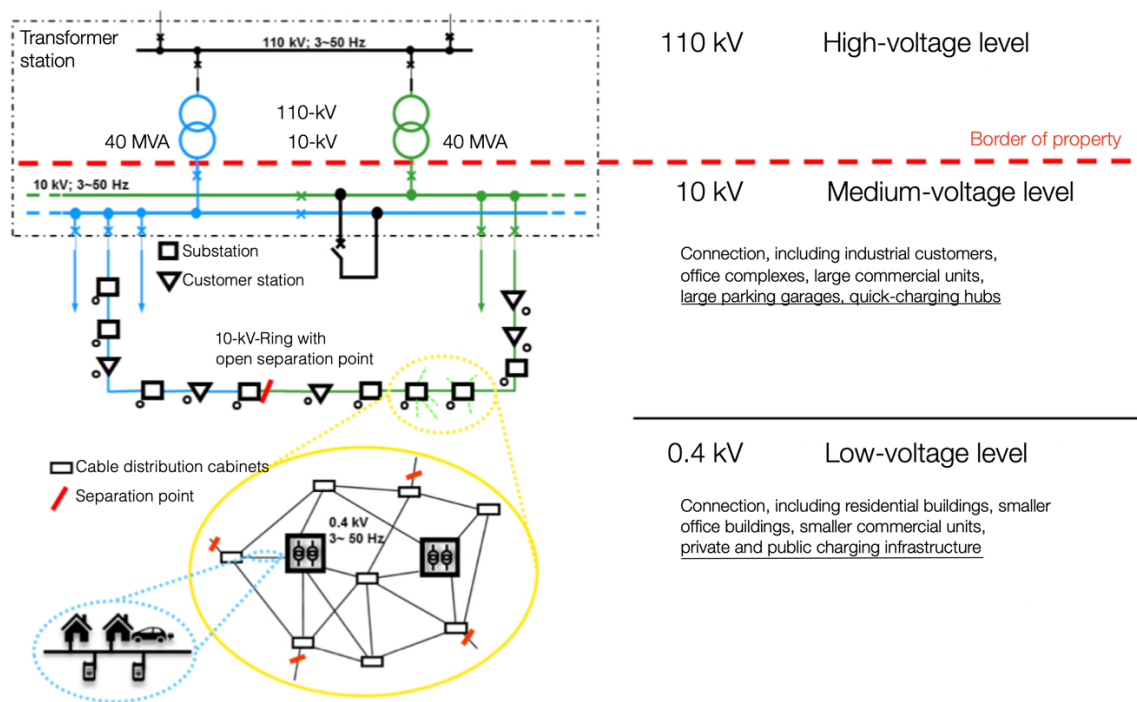


Figure 6: Schematic structure of electrical distribution network

The transfer points between the high-voltage and the medium-voltage network build total 24 transformer stations in Stuttgart. The medium-voltage network is basically operated in open ring configurations. Medium-voltage lines supply electricity to large customers directly through the customer substations. On the other hand, there are around 1,000 substations as feed points for the low-voltage network. The low-voltage distribution network consists of about 560 subgrids, which are supplied by one or more local stations depending on the required demand. The subgrid is the smallest network structure by means of galvanic connections at low-voltage level. As shown in Fig. 6, the cables and cable distribution cabinets are interconnected to form a mesh network.

Fig. 7 shows the distribution of the energy in megawatt-hours for different days of a week. The results are simulated using mobiTopp with a xEV market penetration of 30% and compared with the grid data in the supply area of SN. The chart helps to identify the variation of demand across the different hours of a day. There are two peaks across the day, first, the larger peak (yellow circle) occurs in morning between 08:00 and 10:00, reaching approx. 60 MWh. This correlates with the time vehicles arrive at work on a morning. Second, a smaller peak (green circle) is noted in the late evening, this is likely due to drivers plugging in their vehicles as soon as they arrive home at the end of the working day. Furthermore, the energy requirement in this model for each charging process is covered in a relatively short time due to a high charging capacity of 50 kW. And it also leads to a significant decrease in the midday from 11 a.m. This represents major potential to reduce simultaneous charging and peak loads with some appropriate measures, including delayed charging at home and workplace (until after the peak). Furthermore, in the simulated week, the energy consumption by charging was approx. 2,350 GWh, which accounts extrapolated about 4% of the total energy consumption in the medium and low-voltage grid of SN in 2018. The peak power is at least 60 MW attributable to charging processes. This corresponds to about 11% of the peak load in the supply area of SN in 2018 [1]. This means that electromobility is less an energy-quantity problem rather than a challenge to supply load peaks in areas with high densities.

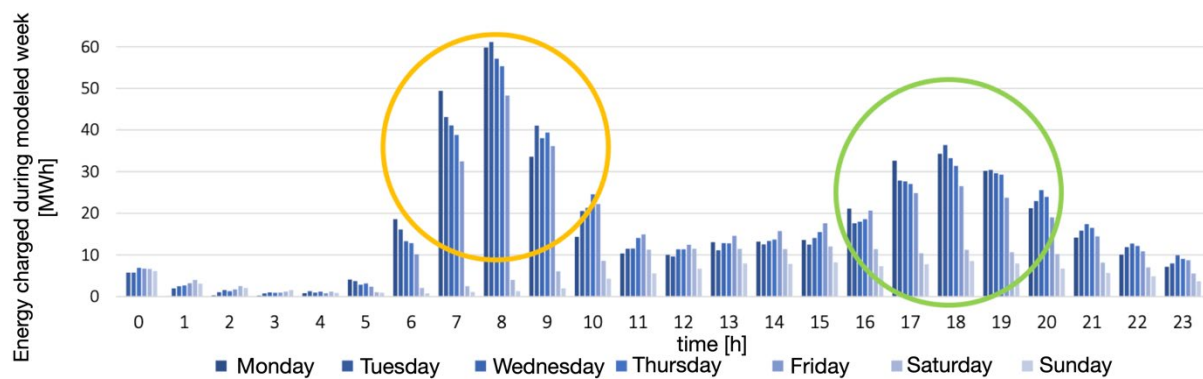


Figure 7: Temporal distribution of the energy charged during the modelled week (30% BEV, new charging points = 50 kW, public charging is possible everywhere)

To identify such hotspots the peak load of each low-voltage grid network was compared with their transformer reserve capacity. For around three quarters of networks, the currently available transformer reserves are sufficient. For a further 13%, more observations must be taken with suitable measuring technology, since utilization is expected to be just above or below 100 %. Only 10% of around 560 subgrids have a need for action. And more than 60% of these overloaded grids are characterized by industrial use (see Fig. 8). In this field high concentrated loads, such like car parks, are generally connected to the medium-voltage grid where load peaks are easier to handle. Furthermore, 30% of the overloaded grids are dominated by residential use paired with dense housing construction. Additional charging demand increases the typical load profile of households in the evening hours. Therefore, an intelligent charging management is necessary to optimize the utilization of grid networks.

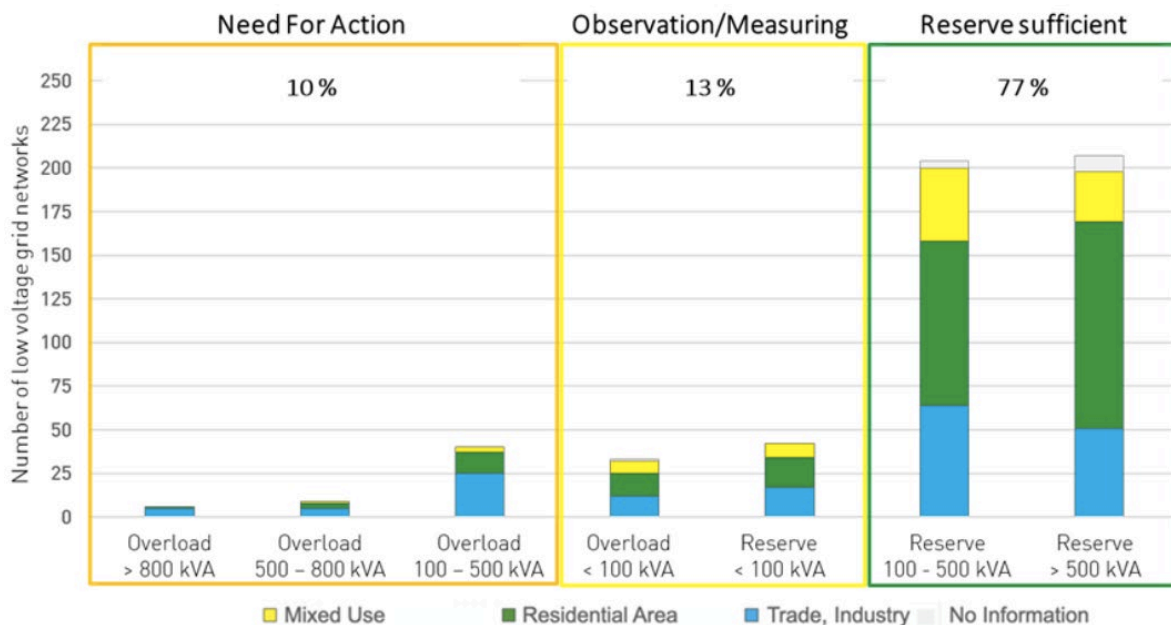


Figure 8: Analysis of the low-voltage grid including the additional demand from the 30% scenario

6 Summary

Respectively to these investigations, already in 2030 every fourth car in Greater Stuttgart will be equipped as an electrified vehicle (xEV). Therefore vehicle charging infrastructure needs to be expanded. Currently, about 400 charging points are set up in the city of Stuttgart (2019). The demand of the upcoming charging point needs will respectively to the given simulation results increase by a factor of 100. This increased demand of electrical energy might effect the electrical distribution grid, therefore a network analysis was carried out taking into account the "worst case" of xEV market penetration of 30% for a residential area of the city Stuttgart with 433 households and 779 inhabitants. By this investigation the maximum voltage converter load capacity did not exceed 61%.

Further, results of net grid simulation were compared with network data in the supply area of the local distribution system operator SN. Only 10% of the approximately 560 subgrids were identified as weak points in the investigated power grid, of which 60% can be identified by industrial use and 30% of the residential areas with dense residential construction.

Hence, it can be concluded that even assuming a market penetration of electromobility of 30% there is still no critical shortage of energy supply expected.

Acknowledgments

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Prof. Dr. Ralf Wörner became chair professor on the field of vehicle technology in the automotive industry at the Esslingen University of Applied Sciences by the end of 2016. In between of 1997 till 2016 he worked as leading Engineer at Daimler Company, whereof he was in charge for the development activities of powertrain systems applied in international cooperation programs from 2011 to 2016 and of different types of automatic transmissions at Daimler Company from 2007 to 2011. Before that he led the development activities of high performance powertrains at Mercedes-AMG from 2000 to 2007. His professional activities were started in the research & development department of combustion engines at Daimler Company between 1997 and 2000.