Demands on the Electrical Grid due to Electromobility in Hamburg

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***Abstract*—Due to the planned conversion of today's vehicle drives to emission-free, especially electrically powered drives, new challenges for distribution grid operators are arising. In addition to the establishment of a suitable charging infrastructure, there will be additional demands caused by charging processes. These additional demands need to be supplied by the electrical grid and possibly modernization measures, like the expansion of transformer stations or the installation of new cables, need to be implemented. In this paper, we want to introduce an approach to estimate the future power demand due to electromobility in the medium voltage transformer stations of a city. For this reason, typical daily load profiles of electrically powered vehicles, which were split into specific sectors, were defined. Moreover, the vehicles of each sector were distributed over the transformer station areas by using distribution keys. By means of this approach, the demands on the electrical grid in Hamburg due to an increasing number of electrically powered vehicles were determined. Thus, for the first time, it is possible to find out which transformer stations are especially influenced by a significant number of electric vehicles. Selected results of the investigations are presented in this paper. It is shown that a higher market share of electrically powered vehicles will soon lead to a demand for action in several transformer stations in Hamburg.**

***Index Terms*—grid expansion, medium voltage level, high voltage level, electric vehicle, transformer station reserves.**

I. Introduction

The city of Hamburg is aiming for an aspiring reduction of greenhouse gases and fine particle emissions due to traffic by the use of emission-free drives. For this reason, approximately 600 charging points will be installed in the near future to implement a city-wide charging infrastructure for electric vehicles (EV) [1]. Furthermore, the local bus transportation companies Hamburg Hochbahn AG (HOCHBAHN) and Verkehrsbetriebe Hamburg-Holstein (VHH) are buying only buses with emission-free drives starting from 2020 [2].

The politically pushed market entry of EV leads to both opportunities and challenges for several involved parties. Practicability and economic efficiency of EV were investigated and published in several studies, especially concerning industrial fleets [3]–[5]. Furthermore, energy storage potentials of EV were considered, especially in combination with a higher integration of renewable energies. In that regard, it was examined how a critical mass of grid-connected EV can support the grid by providing ancillary services [6].

However, besides the potentials for the energy transition, an increasing share of EV also leads to new challenges for the electrical grid. The future grid needs to be able to supply an additional power demand caused by EV charging processes. The estimation of the future additional power demand is important for distribution grid operators in order to plan their future grid expansion. Here, a methodology is presented, that allows to assess the impact of a greater market share of EV on the workload of the electrical grid, using the example of Hamburg. Fig. 1 shows the model boundary of the region of interest. In this work, only the workload of the transformer stations on the medium voltage level and the bus depots points of coupling of HOCHBAHN and VHH were investigated. In addition, it is assumed, that all buses of a bus depot are replaced by electric buses. With the help of a politically defined development szenario for the EV market in Hamburg from 2015 to 2030, a scenario called META is developed. Following, two scenarios labeled MIN and MAX with a variation of ±30% regarding the scenario META were defined to investigate the impact of a change in the assumed market development on the power demand. Afterwards, the minimum, middle and maximum power demands at the transformer stations were examined for the years 2020, 2025 and 2030. Fig. 2 depicts the 110/10-kV and 25/10-kV transformer stations and their respective supply area on the medium voltage level in Hamburg. There are 53 transformer station areas. The reserves of the transformer stations at the present stage are classified in six different bins of reserve levels as shown in Fig. 2. These reserves serve as the basis for our calculations.

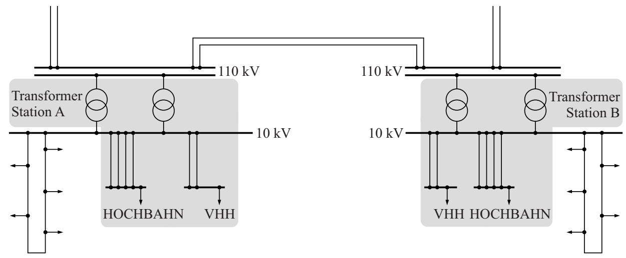

Fig. 1. Model boundary of the investigation: region of interests are the transformer stations on the medium voltage level and the grid connection of HOCHBAHN and VHH according to [7]

Chapter II describes the general methodical approach of our investigation, whereas in chapter III a total daily charging profile caused by electromobility is developed for Hamburg. In chapter IV the impacts of electromobility on each transformer station is analyzed. Finally, chapter V summarizes the investigation and draws a conclusion.

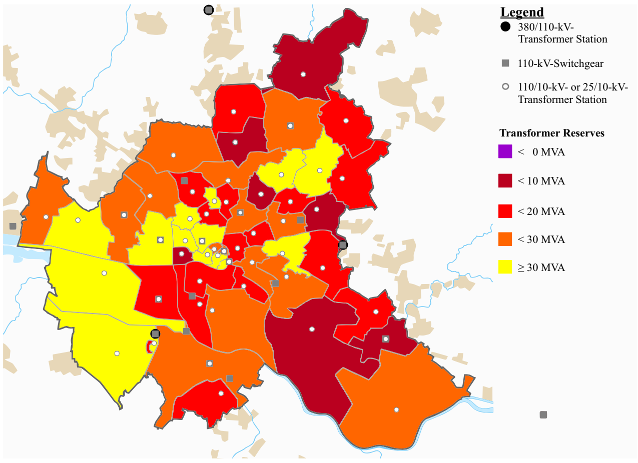

Fig. 2. Overview over the transformer station areas on medium voltage level and their current reserves in Hamburg (as of October 2016) according to [8]

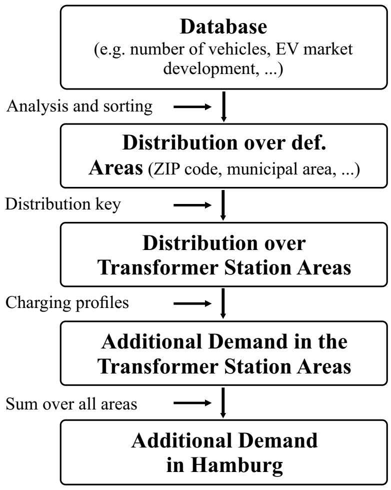

Fig. 3. Methodical approach of the investigations according to [7]

TABLE I
MODEL STRUCTURE OF GROUPED VEHICLES

Private	Industry	Local Public Transport
In Hamburg living, private users; Commuters from outside Hamburg	Trade and Municipal fleets; Car sharing; Multi energy stations	Electric Buses; Planned Subway U5

II. Methodology

A. Model Structure

The term “electromobility” refers to a variety of vehicles with different possible applications. To get a reasonable structure for our model, we defined three sections called: “private”, “industry” and “local public transport”, which describe vehicle groups of similar applications. Furthermore we divided each section into several groups of vehicles (from now on referred to as sectors) with a similar user behavior and thereby a similar drive and charging behavior. Thus, a sector is a pooling of vehicles with similar utilization. Table I is summarizing the used structure for our investigation.

B. General Approach

Fig. 3 illustrates the general approach of our investigation. After structuring the different types of EV into sections and sectors, a database for every sector was developed and analyzed. The information of each database is used to develop distribution keys for each sector. A distribution key describes how the EV of that specific sector are distributed over the area of Hamburg and where the EV are assumed to be charging respectively.

Depending on the sector, each database may contain a different set of information. E.g., the private sectors database involves information about the number of registered vehicles in different areas of Hamburg. Further details regarding the distribution keys may be found in [7].

With the help of these databases and the daily charging profiles the additional power demand due to electromobility in Hamburg in total is derived. To analyze the impact on every single transformer station on the medium voltage level, the above-mentioned sector-specific distribution keys were used to spread the EV across the areas of influence of each transformer station. The following is giving a short overview over the used data for the distribution keys of each sector:

- In Hamburg living, private users:
  average income, number of one and two family houses and registered private vehicles in the municipal areas of Hamburg.
- Commuters, trade and municipal fleets:
  registered non-private vehicles in the different zip code areas.
- Car sharing:
  todays operating area of the biggest providers.
- Multi energy stations:
  gas station locations of the five biggest chains of gas stations.
- Local public transport:
  locations of the bus depots and subway substations.

Addresses may be easily assigned to the appropriate transformer station area by locating it on the map. More complicated is the distribution of the vehicles of private users and commuters as well as the trade and municipal fleets, because there are no addresses for an exact allocation of these sectors. For this reason, a simple assumption is made: a power increase in a municipal or zip code area “a” due to an increasing number of EV leads to a partial power increase in the transformer station areas “x”, “y” and “z”. The share of installed transformer rating of a transformer station area on this specific municipal or zip code area “a” is defining how much the power demand in this transformer station area increases. This was possible with the help of the local distribution grid operator, who provided the necessary information.

After the distribution of the considered sectors on every transformer station area the additional power demand due to electromobility is calculated. A comparison of the peak load due to charging processes with the actual transformer station reserve allows the estimation of future reserves in each transformer station, respectively. Naturally, with this we only get a first vision of the impact of electromobility on the transformer stations.

C. Mathematical Implementation

For computing the additional energy demand in Hamburg and in every transformer station area, a mathematical model was implemented. The general approach explained in chapter II-B is mathematically expressed in (1) and (2).

$$P^a_{\mathrm{TSi}}(h) = \sum_{sector=1}^{5} (\langle \vec{A}_{\mathrm{TSi}}, \vec{n}^a_{\mathrm{sector}} \rangle \cdot P_{\mathrm{sector}}(h)) + \sum_{BDi=1}^{9} (b^a_{\mathrm{BDi}} \cdot P_{\mathrm{BDi}}(h)) + \sum_{SSi=1}^{11} (b^a_{\mathrm{SSi}} \cdot P_{\mathrm{SSi}}(h)) \quad (1)$$

$$P^a_{\mathrm{HH}}(h) = \sum_{TSi=1}^{n} P^a_{\mathrm{TSi}}(h) \quad (2)$$

$P^a_{\mathrm{HH}}(h)$ is the load profile of the city of Hamburg caused by electromobility, where a is the year of the scenario and h the hour of day. $P^a_{\mathrm{TSi}}(h)$ describes the respective load profile for each transformer station in a specific year a. The first term (sum over all sectors) is considering all sectors excluding local public transport, which is taken into account by the second and third term. The vector

$$\vec{A}_{\mathrm{TSi}} = (A_{\mathrm{TSi,A1}} \ldots A_{\mathrm{TSi,An}}) \quad (3)$$

is the so-called distribution key, which spreads the vehicles over all transformer station areas, as explained at the end of chapter II-B. Each entry $A_{\mathrm{TSi,Ai}}$ of the vector A_{TSi} describes the extent to that an increasing number of EV in the area Ai affects a transformer stations load. P_{sector} is the assumed daily charging profile of a specific sector. The vector

$$\vec{n}^a_{\mathrm{sector}} = (n^a_{\mathrm{sector,A1}} \ldots n^a_{\mathrm{sector,An}}) \quad (4)$$

contains the number of vehicles or multi energy stations in each area ($n^a_{\mathrm{sector,Ai}}$), whereby the kind of area is determined by the available data. The computation is described in the next chapter. The load profiles $P_{\mathrm{BDi}}(h)$ of each of the nine different bus depots in Hamburg were determined in [7]. The load profiles of each substation ($P_{\mathrm{SSi}}(h)$) describe the additional load due to the subway U5. The Boolean variables b^a_{BDi} and b^a_{SSi} indicate if a bus depot is converted for electro buses or a subway substation is in operation in a specific year a.

D. Distribution of Vehicles to Areas using the example of in Hamburg living Private Users

The expected number of EV in Hamburg was determined from market share scenarios. In order to assess the influence of a rising amount of EV in Hamburg on each individual transformer station, it was necessary to implement methods that distribute the charging spots of the EV over the area of Hamburg. Due to the nature of the used databases, the vehicles could only be allocated to discrete partial areas, e.g. postal code areas, of Hamburg. Using the example of the distribution of EV of the private users who live in Hamburg, the following shows one exemplary case for such a vehicle distribution, as performed in the meta-study [7].

TABLE II
PERCENTAGE OF THE MARKET SHARE OF EV FOR EACH SECTION

Section	Percentage
Very high electrification	55%
High electrification	25%
Medium electrification	10%
Low electrification	7%
Very low electrification	3%

Because of several factors that influence the buying decision of potential customers, e.g. purchasing price, private income or the possibility to charge the vehicle at home, it is not possible to use an equal distribution of EV over Hamburg. For this reason, the 100 municipal areas of Hamburg were examined regarding the average income [9] as well as the living structure, i.e. the number of apartments in one and two family houses [10]. The latter is important because a private parking place at home encourages the buying decision of EV due to possible and economic charging processes overnight. The 100 municipal areas were divided into five sections related to “income” and “living structure”. With a weighting of 60% to 40% for “income”, a new arrangement of the municipal areas within the five sections results. Each of the sections is given a percentage of the total market share of EV. Table II is containing the share of each section.

The absolute number of private EV in a municipal area MAi ($n^a_{\mathrm{pEV,MAi}}$) depends on the ratio of registered private cars in the municipal area MAi ($n_{\mathrm{prV,MAi}}$) to the total registered private cars in the specific section ($n_{\mathrm{prV,section}}$) and is calculated with (5).

$$n^a_{\mathrm{pEV,MAi}} = n^a_{\mathrm{MarketShare}} \cdot P_{\mathrm{section}} \cdot \frac{n_{\mathrm{prV,MAi}}}{n_{\mathrm{prV,section}}} \quad (5)$$

The total number of private EV in Hamburg for a year a is considered with $n^a_{\mathrm{MarketShare}}$ and P_{section} represents the percentage of a specific section, as presented in Table II.

With this, a transformation of the number of vehicles in municipal areas to one in transformer station areas is possible by using the vector $\vec{A}_{\mathrm{TSi}}$.

Further information about the distribution of the other sectors can be found in [7].

III. DAILY CHARGING PROFILES FOR HAMBURG

This chapter presents the results of the defined sector-specific daily charging profiles for the sectors listed in Table I. As a result of these charging profiles, the temporal development of the power demand in scenario META is presented.

A. Sector-specific daily Charging Profiles

For each sector, a daily charging profile is defined considering “typical” drive and park behavior. One assumption is, that there is no change in todays drive and park behavior due to longer charging time. This is reasonable because of the sufficient idle time of vehicles.

The defined daily charging profiles show an average charging behavior of bigger vehicle groups. These assumptions are based on investigations of the drive behavior as well as on charging profiles of actual electromobility regions. Basically,

TABLE III
SUMMARY OF THE TEMPORAL DEVELOPMENT OF SCENARIO META

Year	Number of EV	Peak Load	Energy Demand
2020	18,000	56 MW	0.25 GWh/d
2025	32,000	127 MW	0.46 GWh/d
2030	110,000	315 MW	1.48 GWh/d

many different charging profiles may be developed, both sector-specific and for subgroups within a sector. Further details may be found in [7].

B. Comparison of Scenario META in the Years 2020-2030

The superposition of the defined daily load profiles for the considered time horizons is depicted in Fig. 4. For this depiction, the defined sectors were summarized as their superior vehicle sections (see Table I) “private”, “industry” and “local public transport”.

Especially the changeover of the bus fleets and the expectable development in the section “industry” contribute to the power demand caused by electromobility, whereas the share of the “private” section is small. This is a result of the assumed electrification rate in the considered sectors. After 2030, the electrification of private vehicles will further rise, but this development is not investigated in this study.

Due to a power band of 55 MW, the planned subway U5 causes a rise in power demand, which is depicted as local public transport. The U5 is only involved from 2025 to 2030, since it is still at the planning stage and supposed to be in operation no earlier than 2025. Table III shows the most important results for the temporal development. The energy demand in Table III only takes the demand of EV and not the local public transport or multi-energy stations into account.

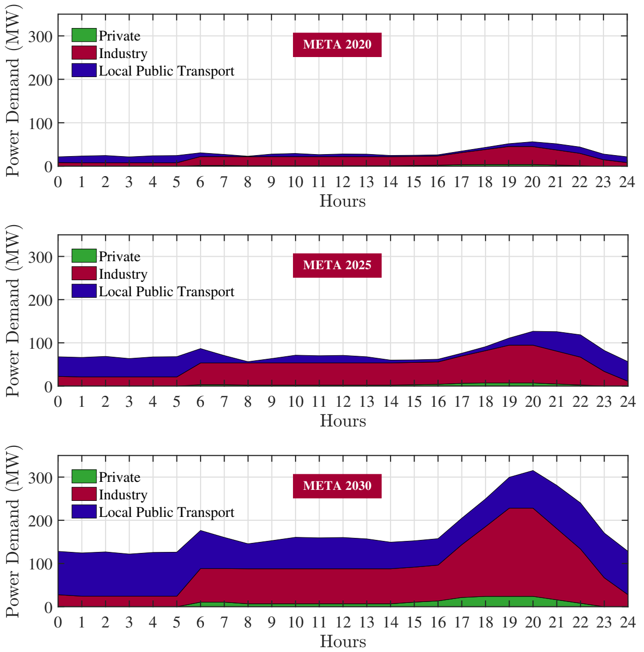

Fig. 4. Development of the energy demand in scenario META according to [7]

IV. IMPACTS OF ELECTROMOBILITY ON THE TRANSFORMER STATION RESERVES

The additional demand at each medium voltage transformer station due to electromobility is calculated as the sum of the demands of all sectors, by using the daily charging profiles and defined distribution keys. The peak load of each transformer station caused by electromobility is compared with its actual free capacity in order to determine the future free capacity. Here, no direct comparison between the daily load profile due to electromobility and the daily profile of the transformer stations is performed, hence it is assumed, that the transformer stations peak is in line with the peak caused by electromobility. However, the resulting error is supposed to be small as both loads typically peak in the evening.

A. Development of the Additional Load in the Transformer Station Areas due to Electromobility

The temporal development of the resulting additional demand is shown in Fig. 5 for each transformer station area, respectively. The additional demand is devided into four power bins (see legend in Fig. 5).

Transformer station areas with a higher additional demand are especially the ones that contain bus depots and subway substations of the planned U5. The demands caused by “industry” and “private” are spread over the transformer station areas of Hamburg, whereas the demands caused by “local public transport” concentrate on a few areas. The maximum additional power demand in scenario META 2030 occurs in the transformer station area Eidelstedt. It adds up to 16.7 MVA.

Fig. 6 depicts the impact of the considered scenarios on the additional demands for each transformer station area. This comparison shows the effect of a variance of ±30% of the market development assumed in scenario META on the additional demand of the transformer station areas. The section “local public transport” and the sector “multi-energy stations” remain identical in all three scenarios.

At a first glance, scenario MIN shows a lower additional demand in most of the areas. However, one has to keep in mind, that the color of an area changes only if the boundary of a power bin is exceeded. Fig. 6 does not contain any information about the actual size of the demand in- or decrease. In Fig. 6 several transformer station areas switch to a higher power bin when one compares the scenarios MIN, META and MAX. In order to determine whether this is caused by a high increase of the additional demand a sensitivity analysis is performed. With this, a reflection of the impact of the market development on the additional demand in the three scenarios is possible. Fig. 7 illustrates the results of the sensitivity analysis based on scenario META for the year 2030. For every transformer station area the decrease (MIN) and increase (MAX) of the additional demand compared to scenario META is depicted. Because only the market development changes by ±30%, but the local public transport and the multi energy stations are held constant, only slight differences occur between the values of MIN and MAX. Most of the transformer station areas have the same magnitude of power demand in both scenarios.

In scenario MAX, fourteen areas have an amount of more than 1.4 MVA compared to scenario META (see Fig. 7), but only three of these areas change the power bin in Fig. 6.

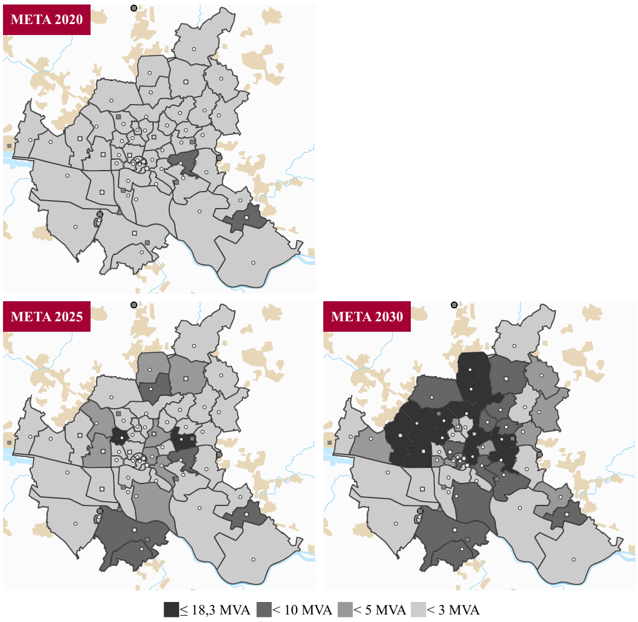

Fig. 5. Temporal development of the additional demands for each transformer station area in scenario META according to [7]

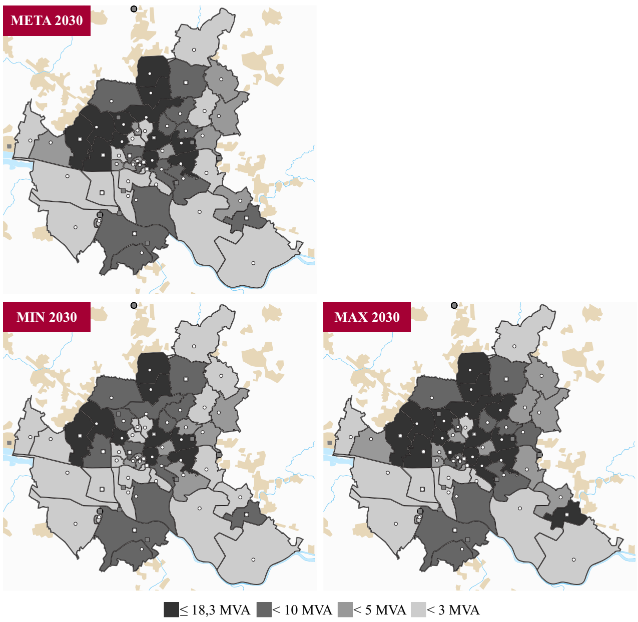

Fig. 6. Comparison of the scenarios regarding the additional demands in year 2030 according to [7]

Scenario MIN shows a similar situation. In both cases, most of the changes in power bins are caused by a small in- or decrease of the additional demand. This shows, that Fig. 6 can only supply a first indication of where an increasing amount of power demand is to be expected. A direct comparison of the scenarios is needed in order to determine the areas that are especially affected due to a change of the number of EV.

B. Development of the Transformer Station Reserves

The computed peak loads of every transformer station area are used to calculate the future free capacity of the transformer stations. Base value for the calculation of the future reserves are the present ones. As already mentioned,

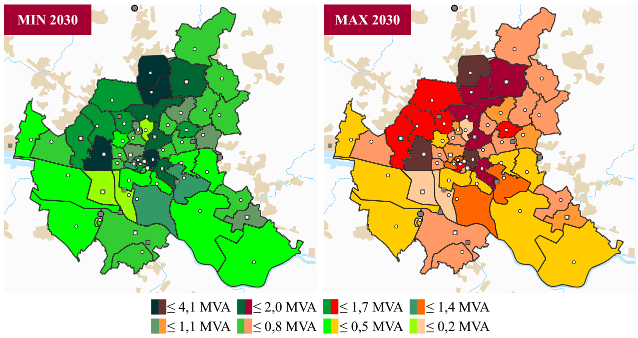

Fig. 7. Scenario sensitivity regarding the additional demands in year 2030 with META as base

the calculation does not involve a comparison of the daily load profiles, but of the peak loads. Fig. 8 shows the temporal development of the transformer station reserves of each area in META. A transformer station area is ranked critical if the reserves are used up or more specifically, the demand due to electromobility is greater than the actual reserves. With this definition and the used methodology, there are four critical transformer station areas in Hamburg in scenario META:

- transformer station Bergedorf
- transformer station Fuhlsbüttel
- transformer station Hellbrook
- transformer station Langenhorn

It becomes apparent that the transformer station Fuhlsbüttel is ranked critical even in 2025. In addition, 15 transformer stations have a reserve of under 10 MVA, of which eleven are new in this classification because of the power demand caused by electromobility.

To analyze how the development of the transformer station reserves depend on the underlying scenario, a comparison of the three scenarios is conducted. In scenario MIN three transformer station areas are ranked critical, while transformer station Langenhorn is still uncritical. Furthermore, only 14 areas have a reserve of under 10 MVA. The scenario MAX leads to a fifth critical area (transformer station Siemersplatz) as well as an additional area with low reserves.

V. Conclusion

This paper presents the results of a meta-study regarding the future demands on the electrical grid due to electromobility in Hamburg. For this purpose, the sections “private”, “industry” and “local public transport” were investigated.

The basis of the investigation is a political defined market development of electrically powered vehicles in Hamburg. Two scenarios labeled MIN and MAX were developed to investigate the impact on the electrical grid in the case of deviations from the assumed market development.

At first, crucial sectors were defined and distributed over the transformer station areas by using specific distribution keys. Afterwards, daily load profiles were defined for each sector.

The charging profiles lead to a peak load in the evening hours, because it is assumed, that no load management is used. Thus, the vehicles are charged as soon as they arrive at their respective parking place instead of using a load management.

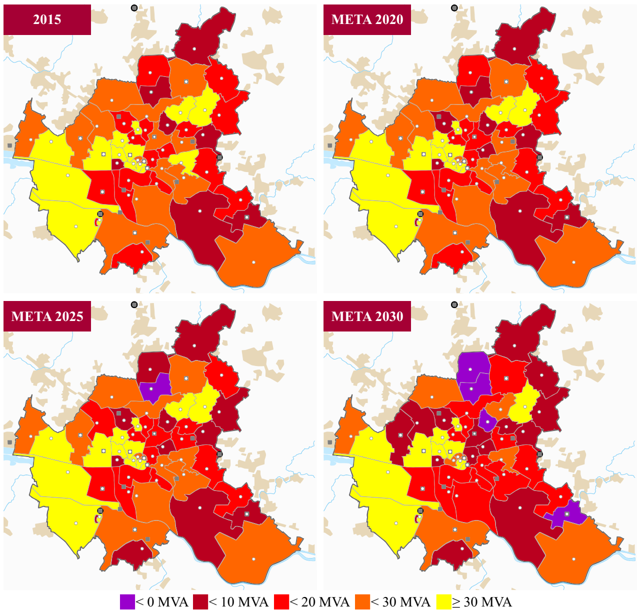

Fig. 8. Temporal Development of the transformer station reserves in scenario META according to [7]

To calculate the future transformer station reserves, actual reserves and future peak loads caused by electromobility were compared in each area. Especially in transformer station areas that contain bus depots and subway substations of the planned U5, high additional peak loads due to electromobility occur. Furthermore, the section "industry" has a big impact on the computed peak loads because a high increase of the market share may be assumed in this section due to daily planned tour lengths, a routinely usage with high mileages each year and resulting economic benefits for industrial vehicle fleets. A change in the assumed market development has a great impact on the reserves of each transformer station.

The determined transformer station reserves give some indication of the needed electrical grid expansion in Hamburg and show which transformer stations are affected by electromobility in particular. In this investigation, no controlled charging was assumed, but there is a great load shifting potential into the night hours, which will even allow for a greater penetration of EV without further modernization measures [11]. By using load management, less of the current transformer station reserves are used and the peak load in the evening can be flattened. For this kind of considerations, a comparison between transformer station profiles and daily charging profiles is necessary. In addition, agreements regarding controlled charging between the local distribution grid operator and charging station owners could help both parties: distribution grid operators can shift the peak load and therefore reduce the burden on the transformer stations, whereas customers could save money, if special "charging contracts" are concluded.

With this methodology, an estimation of the impact of future EV on the power grid is given. Nevertheless, it should be noted, that a more detailed database would lead to more precise results. Especially the database regarding industrial vehicle fleets offers high potential for a misinterpretation. This is because at headquarters registered vehicles often park and charge on several branches of a company.

Further investigations could be examined regarding the load shifting potential and the impact of EV on other electrical equipment of the power grid, e.g. if the installed cables can transfer the future load. Finally, distribution grid operators should keep an eye on the market development of electrically powered vehicles and compare it with the actual assumed developments. Thereby, time- and cost-optimized grid development can be achieved.

Acknowledgment

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