Integrated Expansion Strategies for Public Charging Infrastructure in Cities

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***Abstract*—The quality and demand coverage of urban public charging networks depend on a high number of on-site specifics comprising e.g. mobility behaviour, socio-demographics as well as technology and economics related parameters. This study presents a model that develops integrated expansion strategies for public charging infrastructure in urban areas taking into account the mentioned factors. First, the model quantifies the demand of normal and fast charging infrastructure. Second, it optimizes the placement of the charging points in order to cover the charging demand as best as possible. Third, the model investigates to what extent the local power distribution grid is prepared for a considerable increase in the share of electric mobility. Fourth, it examines if the power grid restricts the identified installation sites and whether controlled charging is able to relieve critical grid situations.**

The model is applied to the Pfaff area in the German city of Kaiserslautern. The exemplary district and its specifics are introduced. The resulting charging infrastructure demand and placement within the area are presented and discussed for an assumptive share of 30% of electric mobility. It shows that charging the electric vehicles doesn't cause critical grid situations even without controlled charging.

However, because of on-site specifics and suitable charging concepts being highly individual, solutions need to be developed case by case. It can be concluded that the necessary charging infrastructure expansion leads to multiple challenges for cities. The presented method addresses these challenges by developing integrated charging infrastructure expansion strategies in order to support stakeholders such as municipalities, distribution network operators and charge point operators in their planning and decision making processes.

***Index Terms*—Electric Mobility, Charging Infrastructure Expansion, Grid Integration, Urban Planning, Smart Cities**

I. INTRODUCTION

Nowadays cities worldwide are facing enormous challenges such as traffic-induced smog, noise pollution and climate change. One element to tackle these challenges is electric mobility. However, the total share of electric vehicles (EVs) is still low in the EU countries [1]. Besides problems as the low range of EVs, long charging times and limited availability of EVs, it is also the absence of charging possibilities which discourages people to purchase an EV [2]. Therefore, a demand covering charging infrastructure (CI) is necessary.

CI can be divided in private, semi-public and public CI. The three types mainly differ in terms of accessibility for different user groups, the ownership of the infrastructure and the space it is built on. Private CI is placed on private property and its accessibility is naturally restricted to few users. Semi-public CI is commonly installed at points of interest usually by the facility itself or in cooperation with service providers. In the case of semi-public CI, the charging stations are built on private space but are accessible to the public. Public CI is also accessible to the public or at least the customers of the service provider [3]. But in contrary to private and semi-public CI, public CI is installed in public space. Therefore, municipalities need to provide areas for the charging stations to charge point operators.

However, the planning of public CI in cities is an interdisciplinary and multidimensional task. The quantification of the demand is a trade-off between a sufficient demand supply from the user perspective and economic and ecologic considerations. As the demand also has a spatial resolution, it is also the placement of charging points that is crucial for the quality of the demand supply of a charging network. Additionally, the power grid need to be taken into account in the planning process as the expansion and operation of local distribution networks is seen as one of the major challenges caused by the increase of electric mobility [4].

This work presents a method to develop integrated expansion strategies. It quantifies the demand and computes the optimal placement of the charging points within an investigated area. Subsequently, the implications of the EV charging on the local distribution network are examined using a probabilistic approach. To illustrate the method, the Pfaff area in the German city of Kaiserslautern serves as an example.

First, the CI planning model is presented in Section II. Second, the district and its specifics as well as the database used in the examination will be introduced in Section III. Third, in Section IV, the model is applied on the exemplary area. The results of the quantification of CI demand by employees and customers are presented as well as the results of the placement of customer CI. Concluding, the results as well as methods on how to develop strategic solutions to grid issues are discussed in Section V.

II. DEVELOPING INTEGRATED CHARGING INFRASTRUCTURE EXPANSION STRATEGIES: THE OPTIMISATION MODEL

A. *Traffic volume*

In order to determine the CI demand of an area, information concerning the traffic volume is important. Especially, two quantities are crucial, on the one hand the number of vehicles originating and terminating per day and on the other

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hand the temporal distribution within the day. By means of these quantities it is possible to consider the simultaneity of parking vehicles. Therefore, the Bosserhoff method is used which is a common method to estimate the traffic volume induced by areas in Germany [5].

The method is divided in three steps. First, the number of users of the investigated area is estimated. It distinguishes between different user groups. These are residents, employees, customers and visitors as well as pupils and apprentices. By taking the different uses and their respective gross floor area (GFA) and specific zonal parameters into account, the estimation of the number of the different users is computed. Second, the total daily traffic volume is calculated. In general, traffic volume can be subdivided in four types: traffic within the investigated area (internal traffic), traffic going through the area as well as traffic originating and terminating in the area. The Bosserhoff method takes this as well as different modes of mobility and the location of the area within the urban context into account. Results of the second step of the method are the numbers of daily traffic volume of originating and terminating vehicles for every user group. Third, the temporal distribution of the traffic within the day is determined, i.e. the traffic volume per hour. In this work, the third step is executed by a statistical evaluation of the study Mobility in Germany which conducted a travel survey of 156,420 German households during 2016 and 2017 [6]. The driving profiles recorded in the study are filtered and evaluated according to socio-demographic factors and trip purposes. This results in the frequency of vehicles arriving and the length of stay according to user group and trip purpose.

B. Quantification of the charging infrastructure demand

For planning purposes the demand for CI need to be quantified and located. In order to quantify the necessary CI the queuing theory (QT) is used. The basic QT concept applied on the case of charging EVs is illustrated in Fig. 1. There are several servers which are in this case charging points. These are serving the users i.e. the charging stations are charging the EVs.

EVs arrive frequently and their service (charging process) begin as long as a charging station is empty. If at one point an EV arrives when there is no free charging station the vehicle is queued in the waiting area or it withdraws from the queue without charging. The method considers the simultaneity of parking vehicles through the frequency of their arrival and the length of their stay. There exist different variants of the QT considering additional parameters, e.g. concerning the period users are waiting to get served [7].

In this case, the QT model is parametrised with traffic volume data of the area, i.e. the frequency of arriving vehicles over the course of the day and the typical length of stay. Furthermore, it is assumed that users will not wait for an empty charging point and that the parking time equals the charging time. In order to avoid that the CI demand equals the maximum simultaneity of parked EVs, a quota of users being served is defined. Thus, it is ensured that the resulting number of charging stations will be a trade-off between a sufficient demand supply and on the other hand economic and ecologic considerations. According to [8] the ratio is set to 85%.

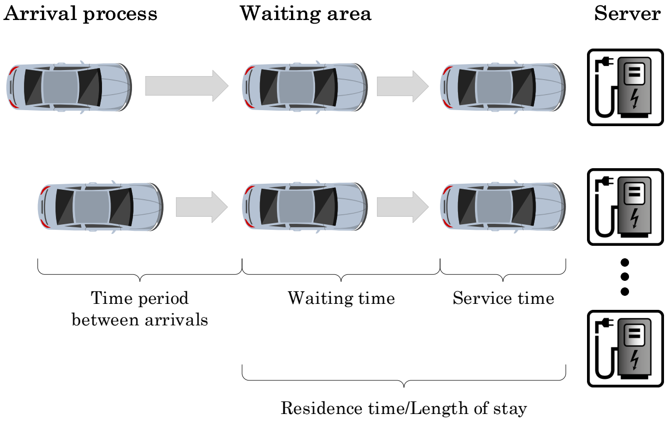

Fig. 1. Basic queuing theory concept applied on charging electric vehicles by using public charging infrastructure (illustration: ©Fraunhofer ISE)

CI differs in terms of the charging power, especially in terms of public and semi-public CI. The described calculation is carried out separately for different charging powers. An official classification for charging power ranges doesn't exist, but commonly it is differentiated between normal and fast charging. Normal charging applies to average charging power between 3.7 and 22 kW. Charging with high power is called fast charging which applies to charging powers of more than 22 kW [3].

In terms of the quantification of the CI demand, the described calculation is carried out separately for normal and fast CI. Fast charging is assigned for vehicles with a length of stay for 5 to 120 min; normal charging for a length of more than 60 min. The transition area between 60 and 120 minutes is attributed respectively. As a result, a number of normal charging points and of fast charging points for the investigated area are determined.

C. Charging infrastructure placement

In a subsequent step, the spatial distribution of the charging points is conducted by means of a utility analysis. In this method the frequency of arriving vehicles and length of stay of different uses in different buildings of the area is utilised again. The utility analysis leads to the assignment of a score for every single building in the area. Once again, it is differentiated between normal and fast charging i.e. there is one normal charging potential score and one fast charging potential score. According to the developed scores, the charging points are distributed proportionately within the investigated area in order to serve the charging demand as best as possible with a given number of charging points.

D. Power grid

In regard to electrical power grids, two criteria are important: power quality and a possible overload of operating material [9]. According to [10] the power quality is not critical in local distribution networks with short distances like in urban distribution networks. Therefore, the presented model examines the load of the operating material, i.e. the transformer stations' load. The local distribution network usually has to supply all loads within an area. Therefore, to

Fig. 2. The primary use of the buildings within the Pfaff area in 2029 (illustration: ©Fraunhofer ISE)

assess the grid load, load profiles of all electrical consumers besides the CI need to be known.

To describe the load by charging the EVs, information about the energy demand and the period of demand are essential. Driving profiles contain these information and are therefore used in this work. As all EVs within an investigated area will be usually supplied by the same power grid, it is necessary to have driving profiles for all user groups.

This work uses a probabilistic approach by using both synthetic load and driving profiles. In order to examine the power demand by the EV charging and its impact on the grid, load and driving profiles for one year are analysed. Potentially critical days with a high load are identified and investigated in detail.

For this purpose, a linear optimisation problem is developed. It simulates the grid load and the charging processes of the individual electric vehicles at the charging points. By means of different objective functions and constraints, different centrally coordinated charging strategies are implemented.

In this work, two different charging strategies are examined: uncontrolled charging and controlled charging with minimum grid load. Uncontrolled charging represents charging with maximum power from the begin of the charging process on. Controlled charging with minimum grid load means the charging power is distributed over the course of the parking time so that the peak of the grid load is minimised. At the same time the power grid restrictions and the energy demand by the EVs is taken into account.

III. Case Study: The Pfaff Area

A. *Past and future of the area*

Since 1894, the area was used by the company PFAFF to produce sewing machines. During the following decades the area of the factory grew and – besides the production halls – buildings for the administration and for housing of the company's employees were built. For about one century, the company was successful but in 1996 it began to make losses. Eventually, in 2004 the production was relocated to Shanghai. Since then, the Pfaff area was no more in use which led the city of Kaiserslautern to develop plans for how to use and revitalize the area. The new area development project shall create a smart and climate neutral quarter with little traffic. These goals shall be achieved through innovations in the fields of energy, mobility, buildings and digitisation as part of the living lab research project EnStadt:Pfaff.

In 2016, the dismantling of a part of the current building stock began. However, the construction of new buildings, the renovation of existing ones and the revitalization of the area as a whole is a long process which will last until 2029. When it will be finished, the district will be a mixed-used quarter accommodating about 1,500 inhabitants and approx. 2,700 employees on an area of 19 ha [11].

B. *Database*

1) Future use of the area: The type of the future commercial use of the single buildings is not definitely fixed yet as the land is still to be sold and the buildings to be built. Therefore, the probable future uses were assumed. In Fig. 3 the shares of the different area uses are shown, not considering the parking areas. In total, about 30.3% of the

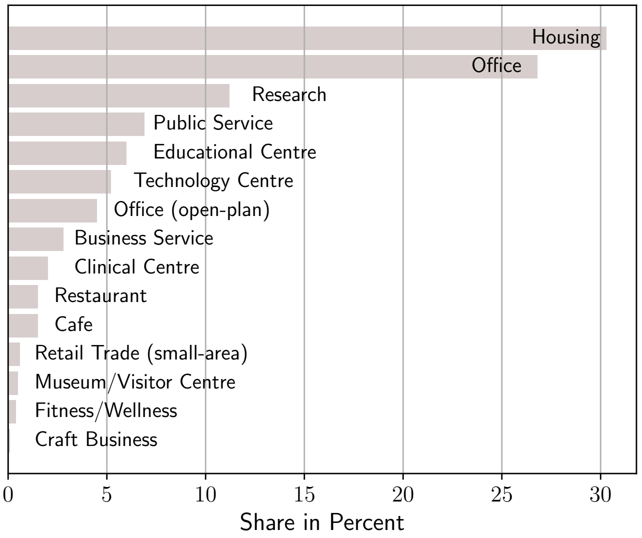

Fig. 3. Assumptive shares of area use in the Pfaff area in 2029

areas are used for housing, the other 69.7% are intended for economic purposes such as offices or public and business related services.

In Fig. 2, the primary use of the buildings within the area is depicted. It shows that some building plots have a relatively homogeneous use structure e.g. all buildings in building plot I are primarily used for housing.

Within the Pfaff area three multi-storey car parks will be built (cf. Fig. 2). Besides, there will be partly basement parking. Street parking will be implemented only to a lesser extent. Where basement and street parking will be realised is not determined yet.

2) Grid load: The method to examine the grid load presented in Section II uses a probabilistic approach. Therefore, it is working with synthetic load and driving profiles. These profiles are provided by a variety of tools which are presented in the following.

The model synPRO is a stochastic bottom-up model that generates electrical load profiles of German households. The model aims at the investigation of the influence of resident behaviour, building services and its efficiency on electrical load profiles of individual households. Probability distributions are used to get a statement about the frequency of the activity and its point in time. However, the duration of an activity is given as a probability density dependent on the start time [12]. In this study, the tool is used to generate load profiles for residential buildings.

synGHD is a tool that is used to create electrical and thermal loads for the trade, commerce and services sector also using a statistical bottom-up model. National standards are incorporated in the form of use data sheets on the occupancy, operation and equipment load. Finally, the investigation of the influenced factors enables the provision of electrical and thermal load profiles [13]. This work uses the electrical load profiles by synGHD for buildings related to trade, commerce and service.

KomMod, the abbreviation for Kommunales Energiesystemmodell (English: Communal Energy System Model), is a techno-economic bottom-up model that depicts the energy system of a district or municipality in its entirety with the sectors electricity, heat and transport. The model is used to optimise the design of generation plants and energy storage systems while at the same time considering their optimal operation [14]. In this work, electrical load time series of heat pumps computed by KomMod were used.

The model synPRO e-mobility generates probabilistic driving profiles of private households. For this objective, socio-economic factors are combined with technical and spatial factors. As a basis for developing the driving profiles, the route data set of the study Mobility in Germany [6] is statistically examined [15].

The project regional eco mobility 2030 (REM 2030) collected driving profiles of commercial vehicles from various economic sectors. The data were recorded by means of GPS systems deployed in the vehicles. The profiles contain data about the departure, arrival, driven distance of the different trips as well as information about the vehicle type and the economic sector [16].

The generation of the synthetic driving profiles of residential, employee and customer traffic for the investigated area is carried out using synPRO. To display the commercial traffic real driving profiles of the REM 2030 database were used.

IV. RESULTS OF THE CASE STUDY

A. *Traffic volume*

According to the future uses of the Pfaff area the first and second step of the Bosserhoff method as described in Subsection II-A is applied. The daily originating and terminating traffic per building plot is depicted for the different user groups in Fig. 5. It shows that in building plots IV, VI and IX the traffic volume is relatively low, varying between 108 and 227 vehicles originating and terminating daily. The rest of the building plots induces considerably more traffic with 1128 to 2148 vehicles per day. Besides the volume of traffic, it is also the type of traffic that varies. Customer traffic has the biggest share with 2750 customer vehicles arriving per day (cf. Table I).

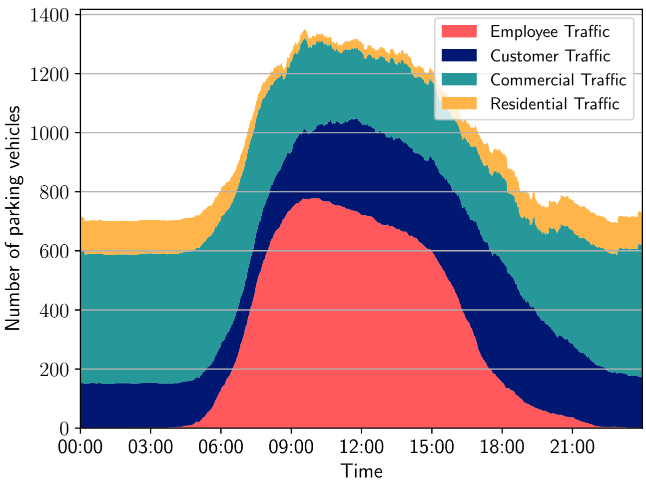

Fig. 4. Parking space occupancy over the day within the Pfaff area

Fig. 5. Daily traffic originating and terminating in the Pfaff area in 2029 (illustration: ©Fraunhofer ISE)

It is especially the building plots with a high share of customer traffic that induce the highest traffic volume. This is the case in building plots III, V and VII.

Corresponding to the different uses of the Pfaff area a characteristic profile of the parking space occupancy is obtained. In the case of the Pfaff area, the resulting parking space occupancy is displayed in Fig. 4. It shows that the peak is at about 10 o'clock in the morning when approx. 1,350 vehicles are parking in the area. At that time most of the vehicles are from employees working in the area. At night, there are still about 700 vehicles in the area which is also the minimum of the parking space occupancy over the course of the day. During night time, residential vehicles are representing the highest share of parked vehicles.

According to the assumption that 30% of the vehicles are electric, the number of EVs originating and terminating is shown in Table I.

TABLE I
PFAFF AREA: VEHICLES ORIGINATING AND TERMINATING PER DAY

	Residents	Employees	Customers	Commercial
All	632	1,215	2,750	671
EVs (30%)	190	365	825	201

B. Charging infrastructure demand and optimal placement within the area

In the Pfaff area, residents and business have private parking spaces. Therefore, vehicles by residents and corporate fleet vehicles are not considered in this study as these vehicles will be recharged by private CI. This study is about the demand of public and semi-public CI by customers and employees.

With regard to the Pfaff area, the process of quantification and location is carried out for customer and employee traffic assuming a 30% share of electric mobility. For customers the resulting CI demand is 64 normal charging points and 24 fast charging points. For employees, a demand for 167 normal charging points results. As the length of stay of employees is almost exclusively more than two hours, there is no fast charging station demand of this user group.

In order to serve the demand as best and as convenient for the CI users as possible the optimal placement of the charging stations within the Pfaff area is determined. For reasons of clarity only the placement of customer CI is presented in the following.

As described in Subsection III-A, it is not yet determined where basement and street parking will be implemented. Therefore, this study examines the CI placement by assuming that the parking is at the same position as the use itself i.e. at the position of the respective building.

The distribution according to the utility analysis (cf. Subsection II-C) is displayed in Fig. 6. It shows that building plots with a low share of customer traffic like building plots I and VIII tend to have a low demand for CI. But this is not the case at building plot III which has the highest traffic volume in total as well as related to customers. It has a relatively low demand with 6 normal and 3 fast charging points. However, the ratio of fast to normal charging points is one of the highest in this building plot. The highest demand is in building plots V and VII that together gather 37 normal and 12 fast charging points. This corresponds to 58 and 50%

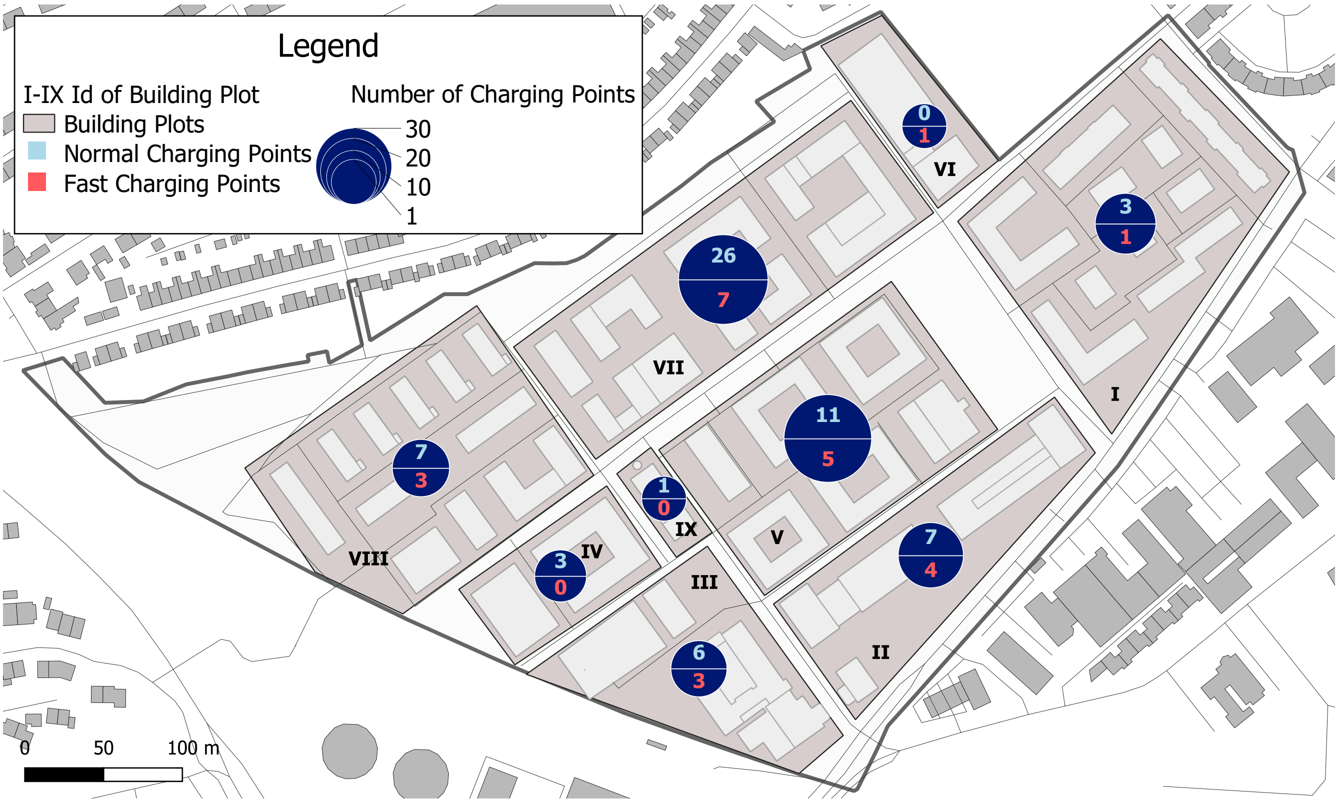

Fig. 6. Public charging infrastructure demand by customers visiting the Pfaff area, assuming a share of 30% electric mobility in 2029 (illustration: ©Fraunhofer ISE)

of the area's total demand, respectively.

C. Examination of the power grid

The investigation of the local distribution network results in several key performance indicators (KPI) for every transformer station. The KPIs for all six transformer stations within the Pfaff area are shown in Fig. 7. The maximum capacity utilisation of the transformer station varies between 23% and 48% without considering the charging processes of electric vehicles (I). With the additional electrical load caused by uncontrolled charging processes of electric vehicles, the transformer peak load increases to up to 52% (II). That represents a relative increase of 1.9 to 10.7% (IV). Using intelligent control of the charging, the maximum transformer load drops to 48% (III). In the case of two transformer stations, it was also possible to completely avoid an increase in peak loads by controlling the charging processes of the vehicles over time. Maximally, the relative increase in maximum transformer load using controlled charging reaches values of 2.1% (V). The peak loads of the transformer stations investigated in the Pfaff quarter could be reduced by up to 9% by controlling the charging processes (VI).

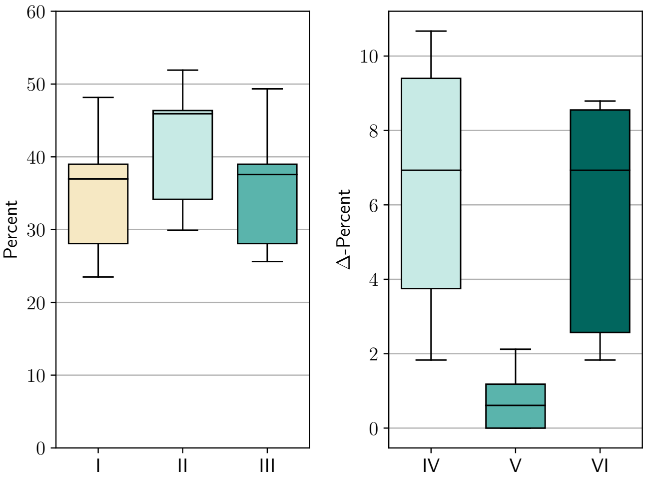

Fig. 7. KPIs resulting out of the local distribution network investigation: I: Yearly peak load wo. EV charging; II: Yearly peak load w. uncontrolled EV charging; III: Yearly peak load w. controlled EV charging; IV: Rel. increase by uncontrolled EV charging; V: Rel. increase by controlled EV charging; VI: Rel. peak shaving potential by controlled charging.

V. CONCLUSION

The quantification of the CI demand by customers results in 64 normal charging points and 24 fast charging points while 825 customer EVs arrive every day in the area. The resulting CI demand by 365 daily arriving employee EVs is 167 normal charging points. These correspond to a ratio of EVs to public charging points of 10.7 and 45.6%, respectively. As described in Section II-B the number of charging points ensures that 85% of the arriving EVs can be charged. The difference in the ratio can be explained by the typical length of stay of customers and employees. The latter typically stay much longer. Therefore, the simultaneity of parking EVs is higher and the CI demand as well.

Regarding the placement of the CI within the area, it appears natural that a high share of customer traffic results in a high number of charging points. Therefore, the low demand in building plot III may seem counter-intuitive. However, in terms of both CI demand and placement, it is not only the total traffic volume per day that is decisive but also the temporal distribution over the course of the day. In building plot VII the customer related uses are mainly an educational centre and coffee shops which are visited from the morning until the late afternoon. Building plot III is, besides a car park, a medical centre comprising medical practices, wellness and rehabilitation facilities. These are visited throughout the day including the evening. This means that in comparison to building plot VII the daily traffic is more distributed over the day. Therefore, the simultaneity of parking vehicles is lesser and fewer charging points are needed eventually.

There is also a variation of the ratio of fast charging to normal charging stations between the building plots. This effect is caused by the varying length of stay at different uses. Uses with a typically short length of stay induce a higher demand for fast charging stations and vice versa.

The results of the investigation of the power grid show that peak loads varies between transformer stations. In this case, none of the transformers risks to be overloaded in spite of an assumed share of 30% of EVs. However, this is mainly a matter of the transformer stations dimensioning and it is conceivable that the power grid of comparable city districts may not be developed to the same extent. Given a higher capacity utilisation, several solution approaches are possible. If the implementation of controlled charging isn't sufficient the power grid can be strengthened. Another approach to resolve the overload caused by EV charging is to relocate the charging points from a zone with high load to another zone which is connected to a transformer with lower peak load. Especially in areas with dimensions similar to the Pfaff area, this measure doesn't risk a significant loss of convenience for the charging station user due to the short walking distances. It can be concluded that under certain circumstances the combination of possible flexibility options through demand side management with intelligent placement of charging stations can avoid a cost-intensive expansion of the electricity grid.

OUTLOOK

In future works, the method will be developed further to examine the CI demand on the city level. At that point, more sophisticated CI placement algorithms will be applied. Furthermore, the effects of CI expansion on power quality in electrical distribution networks will be analysed by means of load flow calculations. Besides the technical aspects, economic investigations of the expansion and operation of public CI networks will be conducted. Concluding, holistic CI expansion strategies for cities will be developed, taking into account all mentioned factors as well as the optimal expansion development over the time, depending on the rising market penetration of EVs in the coming decades.

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