Case studies on impacts of plug-in vehicle charging load on the planning of urban electricity distribution networks

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Abstract— **In this paper, the impact of plug-in vehicle charging load on electricity network planning is investigated by means of case studies which are based on statistical PHEV charging load modeling work and co-operation with two Finnish distribution network companies. According to the case studies, the impacts of plug-in vehicle charging load on Finnish urban distribution networks are modest with low penetration levels, but with high penetration levels plug-in vehicles should be taken into account in long-term network planning. Also, needs and possibilities of "smart charging" were acknowledged from the calculation results.**

Keywords— PHEV, plug-in hybrid electric vehicle, electric vehicle, charging load, network impacts, distribution network planning

I. INTRODUCTION

Transportation has a very important function in today's society. Globally, the energy production of transportation systems is highly dependent on oil, and there are strong expectations that the price as well as the volatility of the price of oil will increase in the future. The transportation sector is also a significant consumer of energy and a significant source of greenhouse gases and other emissions [1]. Today's climate and energy policies imply strongly towards diversification of transportation fuels, improving energy efficiency and reducing emissions. The use of electrical energy in a broader manner by means of plug-in hybrid electric vehicles (PHEV) and full electric vehicles (EV) offers the potential to partly fulfill these challenging requirements. Emission reductions and the amount of primary energy conservation due to plug-in vehicles are, however, highly dependent on the energy system.

There are some barriers related to the high penetration of plug-in vehicles (PHEV and EV). It is widely believed that PHEVs and EVs will become common within some time frame, but there are differences of opinion about when and at what rate the market penetration will happen. The most important barrier is the battery technology. Technologically speaking batteries are fairly good at the moment, but batteries suitable for transportation appliances are very expensive. However, the prices are expected to go down remarkably in the future [2]–[3]. Secondly, a lack of adequate charging infrastructure is a major barrier. It is fairly expensive to construct extensive charging infrastructure especially in the existing densely populated areas.

Many Finnish utilities have shown interest in the investigation of the impacts of charging of plug-in hybrid electric vehicles and full EVs on their networks. The distribution networks of Finnish distribution system operators (DSO) are generally fairly old, and significant network renovation work will be carried out by many companies in the following years. As the construction of distribution networks is a long-term investment, i.e. the lines and other components will probably be in use for many decades, the DSOs have to somehow assess or approximate the long-term changes in the loads of the networks in the planning process. Thus, there is a practical demand for PHEV load modeling already today.

To assess the impacts of plug-in vehicles on a power system, the effect on the electrical load of a plug-in vehicle fleet in a power system has to be modeled. The studies of this paper are based on the modeling methodology of the charging load profiling presented in [4]. The methodology is strongly based on the use of National Travel Survey (NTS) [5] data. NTS is used to model the car use habits of people. The main idea of the methodology is to track the trips of a car and calculate the electricity use and state-of-charge (SOC) of the battery pack and then calculate the related charging events during the day. Then the algorithm calculates the hourly charged energies of the car.

In this paper, the network impacts of charging load of plug-in vehicles on two real Finnish distribution networks is investigated. The networks are owned and managed by two DSOs: JE-Siirto Inc. and Tampereen Sähköverkko Inc. The calculations were made by the DSOs' staff and two M.Sc. theses [6], [7] were done during the studies. This paper is based mainly on these theses. As the two different studies were made independently from each other, their modeling and calculation principles were partly based on the possibilities of the used calculation tool (i.e. network information system, NIS), assumptions and the way of presenting the results differ from each other in some ways. However, the main statistical network power flow calculation principles (short description is presented in [4]) were the same in both cases. The whole distribution network was modeled: primary substations, medium voltage networks, secondary substations and low voltage networks. Distribution systems are different in different countries, and to our knowledge the paper presents the first network calculations made in Finland with statistical charging load models similar to regular statistical load models used today by every DSO in Finland.

During the last few years, different kinds of "smart" charging schemes have received a lot of attention from the scientific community and plenty of different results and ideas have been published, cf. for example [8]–[17]. In the calculations of this paper, a case in which charging is started immediately when the vehicle is parked at a charging place is considered. This concept is sometimes called "dumb" charging. From the car usability point of view, dumb charging represents the most favorable charging principle, as the state-of-charge of the batteries would be as high as possible at every moment. This kind of charging case offers a good reference point in order to see the possible *needs* for charging control, the worst case scenarios for network planning purposes, and also the *possibilities* of plug-in vehicles to produce different kinds of ancillary services for the electricity system [8]–[9]. This is because in order to control plug-in vehicles one must know when the resource (controllable load or energy storage) is available in the network. This paper's main scientific contribution is the use of statistical charging load models in real DSOs' NISs and to get an overall view of the impacts of EVs from network capacity and planning perspective in real urban networks.

The paper is organized as follows. In section II, the case networks and the case scenarios are presented and charging load modeling is discussed. In section III, the results of the calculations are presented and discussed. In section IV, conclusions are made and future work is proposed.

II. CASE NETWORKS, SCENARIOS AND CHARGING LOAD MODELLING

A. *The case networks*

1) *JE-Siirto*

JE-Siirto Inc. operates as a DSO in the city of Jyväskylä in Central Finland. In 2011, the yearly transferred energy was about 0.64 TWh. In the area there are five primary substations, 367 km of medium voltage lines, almost 500 distribution transformers and 980 km of low voltage lines. As the network is a city area network the cabling degree is high. The cabling degrees (proportion of cable kilometers of all line kilometers) of the medium voltage network and low voltage network are 78 % and 95 %, respectively.

2) *Tampereen sähköverkko*

Tampereen Sähköverkko Inc. operates as a DSO in the city of Tampere and some surrounding areas, but in this paper only the load flow calculations of the city area are investigated. The city area covers roughly about 1/3 of the whole distribution area. The whole distribution area is showed in fig. 1, and the network area under investigation is circled. In 2011, the total transferred energy was 1.8 TWh. In the city area, which is under investigation in this paper, there are 10 primary substations which comprise 15 main transformers, 750 km of medium voltage lines, 1150 distribution transformers and 2000 km of low voltage lines. The number of medium voltage and low voltage feeders in the city are 109 and 8212, respectively.

B. *Penetration levels and electricity use of vehicles*

In order to assess the impact of charging load on the electricity grid, it is necessary to define the penetration levels and the electricity use of the vehicles.

1) *JE-Siirto*

A rough assessment of future traffic flows inside the distribution area and through its boundaries was made based

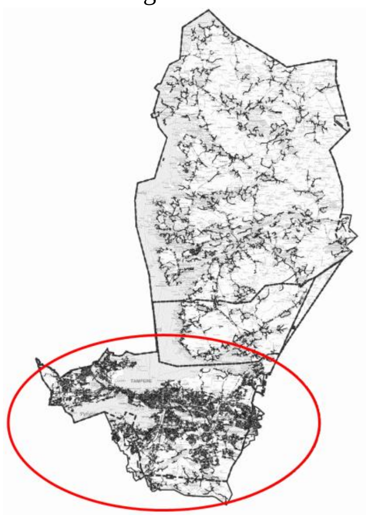

Figure 1. The distribution area of Tampereen sähkönsiirto Inc. The part of the network under investigation is circled.

on local traffic data. Fig. 2 presents the assessed traffic flows during work days. It is estimated that about 48,500 cars are located inside the distribution area (DA) of JE-siirto in 2030. About 20,000 cars are travelling daily between homes and workplaces inside the DA. Also about 5,000 cars travel between homes inside the DA and workplaces outside DA, and in addition to that about 12,000 cars travel between homes outside the DA and workplaces inside the DA. This allows rough approximations for the amounts of cars in workplaces and homes inside the DA during work days to be calculated.

It is useful to assess the average yearly electricity need of the cars. According to NTS, in the central part of Finland passenger cars are driven about 19,000 km/a on average. If it is assumed that all the kilometers can be driven using electricity and a specific electricity consumption of the EVs was 0.2 kWh/km, the electricity use of a regular car would be 3.8 MWh/a. It is assumed that about 70 % of the driven kilometers of PHEVs would be driven using electricity, and the corresponding electricity need would be about 2.7 MWh/a.

In the calculations of this paper, five different scenarios are presented which differ from each other in the penetration levels. Penetration levels of PHEVs and full EVs are quantified separately. Different penetration levels also correspond to different levels of yearly total charging energy. These scenario parameters are presented in Table I. The last scenario, 100 % of full EVs, is mostly a theoretical one. It, however, works well as an interesting baseline to which other results can be compared.

TABLE I. THE SCENARIOS OF JE-SIIRTO'S CALCULATIONS.

Sce-nario	*PHEV penetration level (%)*	*Full EV penetration level (%)*	*Yearly total energy (GWh)*	*Yearly total energy (% of the total transfer in 2011)*
1	2	1	5	1
2	15	5	30	5
3	40	15	82	13
4	50	30	125	19
5	0	100	192	29

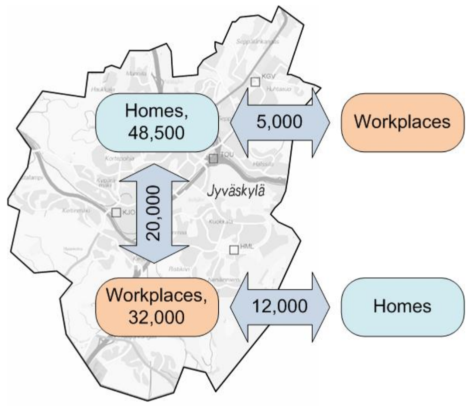

Figure 2. The daily traffic flows of the distribution area of JE-siirto Inc. during the work days.

2) Tampereen sähköverkko

It was assessed that there would be about 110,000 cars in the distribution area in 2030. In the study one PHEV type and two different types of full EVs (EV1 and EV2) were modeled. The average yearly mileages of PHEVs, EV1s and EV2s were 15,000 km/a, 10,000 km/a and 5000 km/a, respectively, and the corresponding average specific electricity consumptions including all the losses were 0.20 kWh/km, 0.20 kWh/km and 0.15 kWh/km, respectively. Using these figures, the average yearly electricity consumptions of the cars can be calculated.

In Tampereen Sähköverkko's (TS) calculations two different scenarios were covered. These scenarios differed from each other in penetration levels. Table II presents the penetration levels and the total electricity consumption of the plug-in vehicles in the scenario calculations.

TABLE II. THE SCENARIOS OF TS'S CALCULATIONS.

Sce-nario	*PHEV pen. level (%)*	*Full EV (EV1 + EV2) pen. level (%)*	*Yearly total energy (GWh)*	*Yearly total energy (% of the total transfer in 2011)*
1	20	11 + 6	76	4
2	31	16 + 9	115	6

C. Load curves

1) JE-Siirto

In addition to yearly energies of the vehicles, the distribution of the charging energy during the year has to be modeled. Network planning in Finnish distribution network companies is at present strongly based on customer class based hourly load curves. Each customer is modeled with a customer class specific load curve which contains mean and standard deviation values for electrical energy consumption in all hours of the year [18]. To apply these models the following data is needed: the class of the customer, the customer's yearly energy and the location of the customer in the grid. All this is stored in the information systems of the DSO. Customers are typically grouped into 20–50 customer classes. To model a certain customer, the customer class load curve is scaled in accordance with the customer's annual electricity consumption. It is also possible to make an outdoor temperature correction. These curves present the total consumption of a large amount of customers fairly well. The scaling principle mentioned above is also applied in the plug-in vehicle load models of this work, although its applicability is not verified [3]. However, we think that this approach gives fair results.

In this paper, simple load curves based on the algorithm presented in [4] are used. Only PHEVs are investigated in [4], but we think that PHEV load models can also be used to roughly model full EVs. In our studies different curves were used for workdays, Saturdays and Sundays. This corresponds to the daily load modeling principles of Finnish distribution network companies. As car use habits depend on the season, the year was also divided into two different parts, summer and winter, for which curves for different day types were formed. Also, network customers were divided into two different groups. The first group includes network customers with detached houses and semi-detached houses, and the second one includes other dwelling types.

Fig. 3 presents an example of the curves for the first mentioned customer group for winter time. The curves present the charging of a typical car during different types of days. Curves include mean and standard deviation values of the charged energy during all hours of the day. When the load curves were formed, a stack of assumptions had to be made. Average usable battery capacity of the cars was chosen to be 18 kWh and the average specific electricity consumption of the cars was 0.2 kWh/km. It is assumed that charging is carried out only at homes and workplaces. In both places the charging power was assumed to be 3 kW. Nowadays, sockets for pre-heating car engines in winter are very widely available in Finland in all types of houses and also in workplaces. These sockets could be used to some extent to charge plug-in vehicles. It is assumed that most of the charging would be made at homes and workplaces because the cars are parked in these places for long times and we already have some "charging", i.e. preheating, infrastructure ready in Finland in these locations. Also, it is assumed that roughly fourth of the electricity need would be charged at the workplace [19]. The confidence level [4] of the calculations was 95 %. At the workplaces, it is simply assumed that on average the charging is carried out evenly during the hours 7, 8 and 9 of work days with a yearly energy of 0.9 MWh.

2) Tampereen sähköverkko

The load curves of plug-in vehicles were pretty much the same as in JE-siirto's calculations. However, there are some non-negligible differences in their use. These are briefly discussed in the following.

Firstly, in TS's calculations only the mean value curves were used in MV and LV network calculations, and standard deviation curves were pressed down to zero. However, this simplification does not cause that big of an "error" because the currents in most of the lines and components consist of so many customers' load currents that the significance of the standard deviation is fairly low. However, in the parts of the network where there is a small amount of customers, the error can be non-negligible. Also, the confidence level of the TS's calculations for other loads than plug-in vehicles was 85 % (in JE-siirto's case the confidence level was 95 %), and this decreases the significance of standard deviations in the calculations [4].

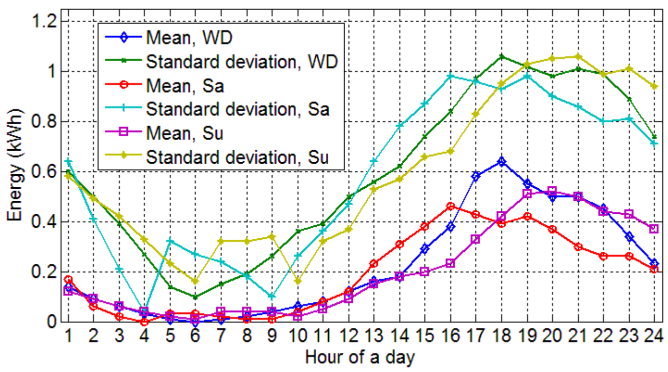

Figure 3. Curves for winter for a typical PHEV of the network customers living in detached houses and semi-detached houses.

Secondly, in TS's calculations it was assumed that in addition to homes and workplaces some charging takes place also in department stores and public car parks. In JE-siirto's calculations, charging was assumed to be carried out only at homes and workplaces, and also in the load curves produced by the methodology of [4], only home and workplace charging was assumed. In the modeling of department stores and public parking lots, certain home curves were used as it was assumed that as shopping is done mostly in the early evenings and during weekends, it resembles to some extent charging at homes. This is, however, a rough approximation.

The charging energy is divided so that 15% of the total charged energy is set for workplaces, 10% for the public parking and the rest for homes. In TS's distribution area there are 25 large department stores, shopping centers and public car parks, and the charging energy is divided evenly between these places. In scenarios 1 and 2, the yearly charging energies per spot for these places are 304 MWh and 480 MWh, respectively. For example scenario 1's energy corresponds to 185 cars charging 1.5 h at a 3 kW rate every day on average.

D. Placing the plug-in vehicle loads to the network

1) JE-Siirto

Vehicle loads were added to the homes and workplaces. In each scenario, plug-in vehicles were added randomly to the network customers until the assessed amount of plug-in vehicles was reached. The maximum number of plug-in vehicles in a household was restricted to one. It was noticed that when one car is added to all the households, the amount of cars corresponds with sufficient accuracy with the number of all cars in the distribution area. The number of cars in workplaces is a more challenging thing to assess. In this work, a rough assessment of the maximum number of cars for 45 different types of industrial or service sector customers of the network was made.

A simplification was made in the studies. It was mentioned previously that with plug-in hybrids 70 % of the kilometers could be driven using electricity. In practical studies this was taken into account so that N plug-in hybrids were modeled as $0.7N$ full EVs. In this way the practical calculation work could be simplified. This simplification, however, decreases the geographical diversity of the load and slightly increases the uncertainty of the results.

2) Tampereen sähköverkko

In TS's calculations the vehicle loads of homes were placed into the network pretty much the same way than in JE-siirto's calculations. Workplaces were divided into two different groups: industrial and non-industrial. In scenario 1 the yearly charging energies of these two customer groups per customer were 11.7 MWh and 0.9 MWh, respectively, and in scenario 2 the corresponding energies were 16.8 MWh and 0.9 MWh, respectively. In scenario 1 industrial charging load is set for every industrial customer and for non-industrial workplace customers the charging load was set for every third customer. Scenario 2 differs from scenario 1 in the way that for non-industrial customers the charging load was set for every second customer. This division between industrial and non-industrial workplaces is rough, but we think it leads to results with a reasonable order of magnitude.

III. THE RESULTS OF THE CASE SCENARIOS

A. The goal of the case study

The main goal of this paper is to assess the impacts of plug-in vehicles on the planning of electricity distribution networks. Planning is always a techno-economic process and the aim of the planning is to find technologically feasible solutions which have as low costs as possible within the planning period. In general, the aim of the network planning tasks can be presented as the following minimization task:

$$\min \sum_{t=t_1}^{t_n} \left(C_{inv}(t) + C_{loss}(t) + C_{out}(t) + C_{maint}(t)\right), \quad (1)$$

where C_{inv}, C_{loss}, C_{out} and C_{maint} represent the present values of investment, loss, outage and maintenance costs, respectively, of the sub periods $(t_1, t_2, \dots, t_n)$ of the planning period with a length of *T*. Of course, different technical boundary conditions such as electrical safety regulations have to be fulfilled. In principle, increasing the network load can increase all the cost components of (1).

In this paper the impact of plug-in vehicle load on (1) is not investigated in detail, but we simply study the impact of the load changes on the load levels and overloading of the network components and network voltages in different scenarios. This is a very restricted approach but it gives a rough overview of the impacts of plug-in vehicles on the network. In this paper, only the impact of the increasing plug-in vehicle charging load is considered and other possible changes in the network and its load are excluded from the studies. In other words the plug-in vehicle load is simulated in today's network.

B. Calculation results

1) JE-Siirto

Plug-in vehicle charging load can increase the peak power of the whole network. Table III presents the changes in the peak loads of the network in different scenarios. The peak loads are calculated by summing up the peak loads of the five primary substations. Change in energy losses is also presented in the table. It can be seen that in scenarios 1 and 2 the peak load rise is negligible. In scenarios 3, 4 and 5 the increase in peak load rises to a non-negligible level.

The most remarkable network impact of plug-in vehicle charging load is observed in distribution transformers (21kV/0.4kV). Table IV presents the sums of the need for additional transformer capacity, the number of overloaded transformers and the proportion of overloaded transformers of all transformers in different scenarios. Again, in scenarios 1 and 2 the need for new investments are very small, but the last three scenarios imply a need to replace at least some dozens of transformers with ones with bigger capacity. However, when compared to the total amount of distribution transformers in the network, the amounts are typically fairly modest. It was noticed that in some cases by shifting the time of charging to night, the overloading situations could be avoided. It should however be noticed that due to the electric heating systems of households, the total peak loads usually take place during very cold weather. During cold weather a moderate overloading of the transformers placed outside can be allowed.

TABLE III. CHANGES IN PEAK LOAD AND LOSSES IN DIFFERENT SCENARIOS

Sce-nario	***Change in peak load (MW)***	***Change in peak load (%)***	***Change in energy losses (GWh/a)***
1	0	0	0.4
2	1	1	1.2
3	10	8	4.1
4	18	15	6.5
5	31	26	11.0

TABLE IV. ADDITIONAL CAPACITY NEED AND OVERLOADING OF DISTRIBUTION TRANSFORMERS.

Sce-nario	***Total need for additional capacity (MVA)***	***Number of overloaded distribution transformers***	***Proportion of overloaded distribution transformers (%)***
1	0	0	0
2	0.7	7	1
3	3.2	28	6
4	6.5	55	11
5	16.2	100	20

The impact of the charging load on low voltage (LV) and medium voltage (MV) lines was also investigated. It was noticed that the overloading of LV and MV lines is practically negligible. There were a few overloading cases, but those could perhaps be managed by changing the configuration of the network.

The voltage levels of the customers' LV network connections were also studied. It was noticed that the voltages of the network customers remained at permissible levels very well even with the highest penetration levels. In scenario 5 there were only some dozens of network connections (out of 9340) with too low voltage.

2) Tampereen sähköverkko

In TS's calculations the impacts on primary substations' main transformers, MV feeders, distribution transformers and LV feeders were studied. The results are briefly summarized in the following.

Peak load levels of the 15 primary substations' main transformers increased only a little. Average increases in scenarios 1 and 2 were 2.4 % and 3.8 %, respectively. Maximum and minimum increases in scenario 1 were 4.3 % and 0.4 %, respectively. Corresponding figures for scenario 2 are 7.9 % and 0.6 %. These changes do not cause any problems.

The average increases of peak load levels of MV feeders in scenarios 1 and 2 are 2.3 % and 3.6 %, respectively. Also 86 % of the feeders have an increase of under 4 % in scenario 1. For scenario 2 the corresponding proportion is 58 %. In both scenarios the voltage drop in MV feeders is under 3 % apart from three feeders. However, in these three feeders the voltage decline is still under 5 %. According to TS's network design principles, the voltage decline of MV urban cable networks should be restricted to 3 %. This allows for a high enough transfer capacity marginal for back-up connection use to be ensured.

Changes in the peak load levels of distribution transformers were also studied. In scenario 1 the average increase in the load level of the distribution transformers was about 3.1 %, and in 91 % of the transformers the increase was under 6 %. In scenario 2 the average increase was about 4.8 % and in 80 % of the transformers the increase was under 6 %. However, in both scenarios there were dozens of transformers whose proportional load level increases were greater than or equal to 12 %. When these transformers were investigated, it was noticed that most of them are feeding industrial customers. In these transformers the absolute load level is often fairly low which partly explains the large proportional increase.

These industrial customers typically have a large "charging peak" in the morning as employees arrive in their workplaces. By dividing the cars of the workplaces into subgroups which charge their battery packs in different time windows, the peak load increase could be avoided.

The average increases of peak load levels of LV feeders in scenarios 1 and 2 are 3.0 % and 5.3 %, respectively. Also 89 % of the feeders have an increase of under 6 % in scenario 1. For scenario 2 the corresponding proportion is 80 %. In scenarios 1 and 2 a peak load level increase of greater than or equal to 12 % was noticed in 5.5 % and 9.8 % of the LV feeders, respectively. The changes in voltage declines are very small.

IV. Conclusions and Future Work

In this paper, load flow calculations were made to assess the impacts of plug-in vehicles on the network with two case studies. Five different scenarios with different plug-in vehicle penetration levels were defined and calculated in the first case study and two scenarios in the second one. The studies concentrated mainly on the load rates of different components. As a conclusion it can be said that plug-in vehicles would not cause serious problems in the case networks which are quite strong, i.e. it is possible to increase the loading of network components and line sections without violating any voltage limits etc. The networks are strong partly because there has to be some marginal in the network components for the possible back-up connection use. Generally, Finnish distribution networks are fairly strong because of the wide use of high power and energy loads such as electric heating and electric sauna stoves. However, in these two network areas, district heating covers some 90 % market share. In the studies of this paper many approximations and simplifications were made, but we think that the results are fair and give a proper overview of the impact of the charging load on the distribution networks. Also, the calculations showed in a preliminary manner that it could be beneficial to control the real charging loads or other resources in order to reduce the network impacts in some cases. Also, using the methodology of this paper, one can assess the availability of plug-in vehicles to be used as controllable loads and energy storages. Many topics and issues for future work arose in this study.

It would be useful to conduct a more holistic study on the impacts possible changes of the loads can have on network planning. In such studies other types of new loads besides plug-in vehicles should also be taken into account. In Finland there are a lot of households with direct electrical heating, and in the future some proportion of them will be totally or partly replaced by heat pumps. In long term this can cause a remarkable decrease in electricity consumption in some network areas. There are also plenty of houses today in Finland which are heated by heating oil. Some proportion of these households will probably replace the oil heating system with a system which consumes remarkable amounts of electricity, for example heat pumps. This load change can increase network loads in some parts of the network.

In future studies, financial factors concerning network planning presented in (1) should also be taken into account to some extent. In the calculations of this paper, mostly the loading levels or possible overloadings of network components were investigated. However, replacing for example a line with one with a larger cross-section might be economically feasible before possible overloading of the line.

In this paper it was mentioned that charging load curves could be improved in many ways. This could also be realized in future studies. Also, different types of investigations concerning the use of plug-in vehicles and controllable loads or energy storages could be made by means of network calculations.

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