Need for and frame conditions of a load management for electric mobility in low-voltage networks

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Abstract:

Starting out from the research project "econnect Germany" this Paper examines the effects of electric mobility on low-voltage network. Assessed on the basis of a real-life rural and suburban local network it is appraised, at which penetration grade of electric mobility we need a load management to ensure the security of energy supply. Various charging strategies are developed and analyzed and evaluated by the simulation software NEPLAN subsequently. After that the results of the various scenarios are compared with each other to check, which of the operating resources can be judged as the limiting factors in the respective networks. Finally recommendations for optimized load management for the sake of the integration of electric mobility are offered.

Keywords:

Electric mobility, load management, dynamic energy prices, econnect Germany, traffic light concept, load profiles, charging strategies, low-voltage network

I. INTRODUCTION

Driven by the expansion of renewable energies and the goals of the Federal Government to bring one million electric vehicles onto Germany´s roads by 2020 and six million up to 2030, a corresponding energy transition involves a massive reconstruction of the existing power grid [1]. We accordingly observe the change from a centralized to a decentralized energy generation. To ensure the reliability of the electrical supply, the existing network infrastructure should be investigated and adjusted respectively. For this reason, seven different municipal utilities have joined to constitute a research partnership and have successfully applied for "ICT for electric mobility II" funded by Germany´s Ministry of Economics and Technology (BMWi). The aim of the project is to find out how electric mobility can be integrated in the intelligent energy supply (smart grid) of the future.
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II. STARTING POSITION

A. *econnect Germany*

As part of the research project "econnect Germany" a field trial in Aachen examines, how the grid responds to the electric vehicles (new loads) and whether it is possible to use these loads for demand side management (DSM). In addition the customers´ behavior concerning the usage of dynamic prices is another point of investigation. It is for this reason that STAWAG (Stadtwerke Aachen AG) has provided ten households in one local distribution system with a home demand management system and according electric vehicles for the period a half year. Besides the local network station has been equipped with a voltage regulated distribution transformer (VRDT) and measurements to analyze the influence of new loads. Additionally there are measurements in all cable distribution cabinets of the local network as well as in the house connection boxes of all participants in that field trial.
Figure 1 gives an overview over the suburban network area of the field trial mentioned. The black arrow marks the local network station, collecting all measurement results from the cable distribution cabinets (orange arrow) and house connection boxes. There are 180 household linked to the local network station by four cables.

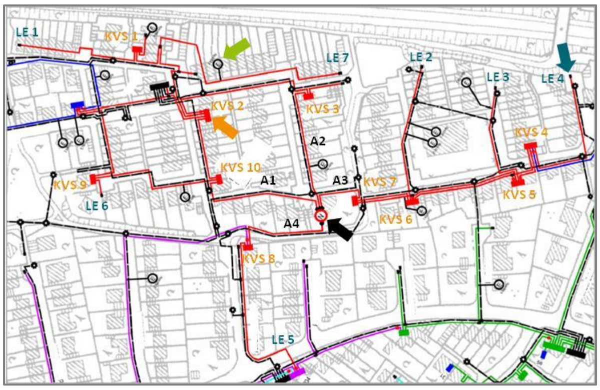

Figure 1: Suburban local network [2]

There are, however, different numbers of households connected to each of the 4 cables. Cable 1 (A1), for example, supplies 81 households with electrical energy and Cable 4 (A4) 10 households only. The green arrow indicates one of eight households with PV feed.

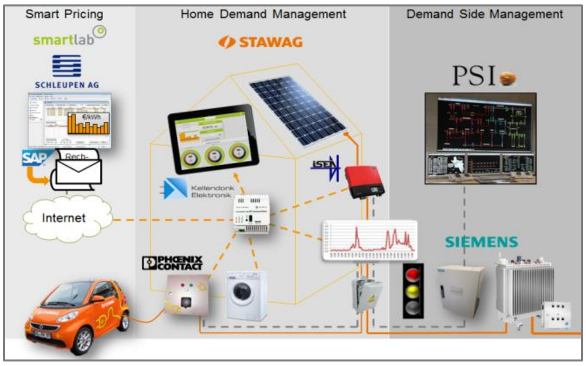

Figure 2: Management system [3]

Figure 2 shows that the overall architecture of the field trial can be divided into three sub-systems [3]:

- Smart Pricing
- Home Demand Management
- Demand Side Management

The first sub-system – Smart Pricing – deals with the development of dynamic prices for the participants of the field trial. First price forecasts must be created as a function of generation forecasts of renewable energies, load profiles and intraday market prices. These price forecasts for the following day have to be sent to the Home-Demand-Management system till 5 pm.

The subsystem "Home Demand Management" includes all components necessary for the participants to regulate the loading operations of the electric vehicle. The Home Demand Management system includes a wallbox (loading power up to 22 kW), a human interface (tablet), a smart meter and a home management gateway (HMG). The HMG serves as a central operator for the Home Demand Management system, controlling and coordinating the loading operations of the wallbox, so that the charging is taken at the cheapest electricity price.

To achieve this, the customer – by means of an app – sets a time by which the car must be fully charged. Due to the state of charge (SOC) of the battery the HMG calculates the required energy volume and selects the cheapest charging time.

The third subsystem "Demand Side Management" allows the distribution system operator to monitor the loading operations. For this purpose all measured values of the local distribution system are sent to the local distribution station by a power line connection (PLC). The intelligent local network station can autonomously reduce the charging power of the wall boxes, when an overload (cable, transformer) in the low-voltage grid will be given. The available charging power is represented in the form of a traffic light:

Green light:

None of the resources in the network is busy. No restriction for charging.

Yellow light:

High network utilization. Charging power is reduced as much as necessary in order to avoid overloading.

Red light:

Grid is currently overloaded. Loading is not possible.

The traffic light concept was developed by BDEW [4]. The measured values of the field trial are the basis of this thesis.

B. Charging strategy

In the simulation, three different charging strategies are examined and evaluated:

Uncontrolled charge upon arrival:

Uncontrolled charge upon arrival describes the currently conventional charging strategy. The vehicle charging starts as soon as the electric vehicles are connected to the wallbox. For the arrival of electric vehicles at home and correspondingly for the beginning of the charging process we used the last arrival at the private socket on the respective day. To do so the ten electric vehicles are equipped with GPS loggers.

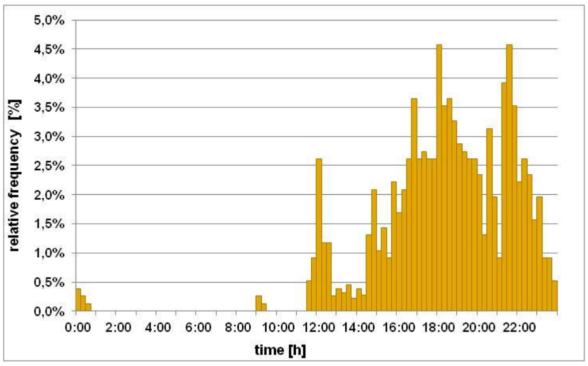

Figure 3: Relative frequency of the last arrival [own diagram]

Figure 3 shows the relative frequency of the last arrival of the participants. It becomes obvious that more than 70 % of the last arrivals are between 04.00 pm and 10.00 pm. This suggests that the peak load of the vehicles´ charges will probably overload with the peak load of the households.

Dynamic prices without network control:
In the scenario "dynamic prices without network control" an energy management system (EMS) selects the starting point of the vehicle charging. The EMS determines the economically optimal charging period based on the maximum loading capacity, the current state of charge and the dynamic prices. An evaluation of the electricity prices on the intraday market on the European Energy Exchange shows that the price of electricity is very low at night (10.00 pm to 06.00 am). A minimum is reached at 02.00 am, so that the vehicle charge is to begin at this time. In this scenario we assume simultaneity of vehicle loads of 75%.

Dynamic prices with network control:
In the scenario "dynamic prices with network control" the EMS is extended by a network control in the local network station. It aims at avoiding network overloads due to simultaneous vehicle charging. The network control is linked to the energy management system by PLC and it can reduce the load capacity in case of a network overload. Here two different scenarios are analyzed and compared with each other:

Variant A:
Even restriction of all vehicle charges in case of imminent overloads.

Variant B:
First-come, first-served (Loading operations start due to time of registration).

In Variant A, the electric vehicles are evenly throttled in case of imminent network overloads, so that none of the customers benefits or is at disadvantage. To grant this, the EMS sends information – i.e. number of connected vehicles or charging capacity – to the network control and then all vehicle loads are evenly throttled without any discrimination.

In Variant B the process starts with too many simultaneous charging processes at the same time (for example when the electricity price is very cheap) but initially with the vehicle loads that have first registered. As long as the first operating resources threaten to overload, the network control sends a clearance to the wallboxes. All other vehicle loads are lined up in the chronological order of their registration.

C. Reference Networks

Figure 1 offers an overview over the suburban network area. Within it 180 households are supplied with electrical energy. The total cable length is about 2066 meters in this local network, so that the cable length per household (HH) is about 11.5 m/HH. The transformer supplies power of 400 kVA. All in all there are four cables of the same typ (NA2XY-J 4x150SE). They are used for the transmission of the electrical energy up to the line end. In this local network the PV-supply is 47.7 kW_p.

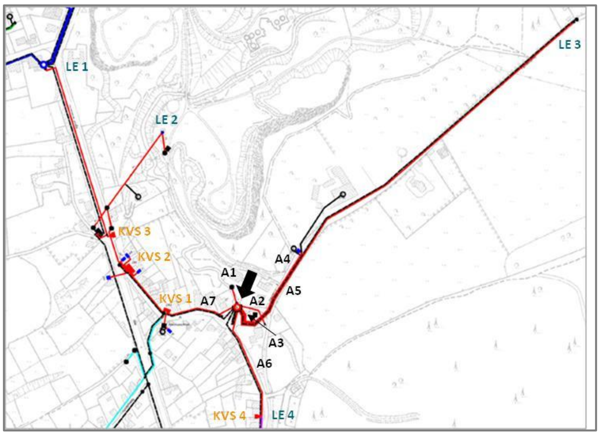

Figure 4: Rural local network [2]

Figure 4 shows the rural local network with a total cable length of about 1995 meters. The cable length per household is about 28.9 m/HH and by this almost three times longer as in the suburban area. The transformer provides a power of 400 kVA and supplies 66 households, one farm, one pump station and one parish hall with electrical energy. The PV-supply in the rural local network is about 226.5 kW_p, so it is four times larger than in the suburban grid area. The black arrow marks the local substation, which is equipped with seven cables. For the subsequent simulation, however, only three cables are relevant (A5, A6 and A7), which supply the household and the farm with electrical energy. Cable 3 supplies the pump station with electrical energy. The pump station is adopted by a constant power of 80 kW. Cable 4 is specially built for a PV system with power up to 205 kW. The other two strands each supply only one household with electrical energy and thus can be neglected.

Cable 5 is about 750 meters long and three households are pending on it. This strand, in particular, is expected to voltage losses as a result of line losses.

In both local networks will evaluated, which operating resources are the limiting factors in the respective networks. For this sake the utilization of the transformers, the utilization of the cables at the local network station and the voltage drop at the end of the cables (compare figure 1 and 4) are examined.

D. Development of load profiles

Households

For consumers without power measurement it can used standard load profiles (SLP). There are different load profiles used for the consumption forecasts each depending on the consumer group, the season, the weather of the day or of the week.

The Electricity Industry Association (VDEW) offers standardized load profiles for the different consumer groups. To perform a practical simulation, a peculiar load profile based on the measurement values of the suburban local network station is created. For this purpose the 15-minute averages of the electric power are used. From the 15-minute-average period of a certain weekday (f.e. 00.00 – 00.15) you evaluate an average value for the time from 01.12.2014 – 28.02.2015. This proceeding is repeated for each 15-minute-period of the weekdays mentioned. The calculated value is divided by the 180 households of the suburban grid and is the measurement for the load profile. Figure 5 shows the load profile H0 by VDEW as well as the load profile created by above mentioned measurements – on the one hand with and on the other hand without a factor. However, extreme load peaks, which arise on particularly cold days for example at Christmas, are not taken when using the average over the entire period.

For this reason, the load profile created has to be increase by an adjustment factor of 1.35. As figure 5 clearly shows the load profile arising by a factor of 1.35 is similar to the SLP and it can be used for the following simulation.

Figure 5: Load profiles households for one day [own diagram]

A comparison with respect to the annual consumption of the households as well as to the load profile of the local network station shows that for households in the rural grid area the same load profile can be used as for those in the suburban grid area.

Farm

The farm presents an exception, which is located in cable 5. As it annually consumes more than 70,000 kWh, an own load profile must be created for the farm. Figure 6 shows the load profile of the farm. Note that the base load of the farm is about 4 kW and thus significantly higher than the peak load of the households. In addition, there are peak loads up to 30 kW.

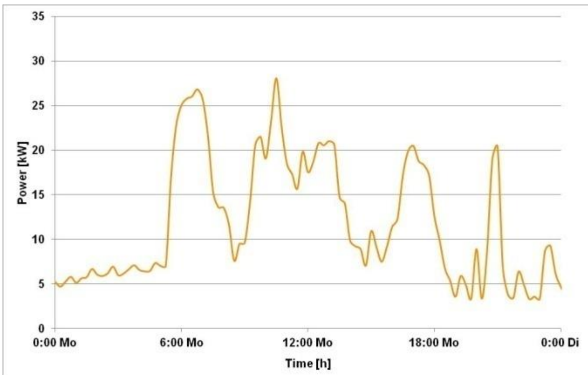

Figure 6: Load profile farm [own diagram]

Electric vehicles

Standard load profiles only make sense by considering a large number of loads. The objectives of the Federal Government strive for one million electric vehicles on Germany´s roads by 2020 and six million by 2030 and for this reason no SLP is used for the charging of electric vehicles. So a load profile is created by using the charging characteristics of the battery as a function of the distribution of arrival times for each load point.

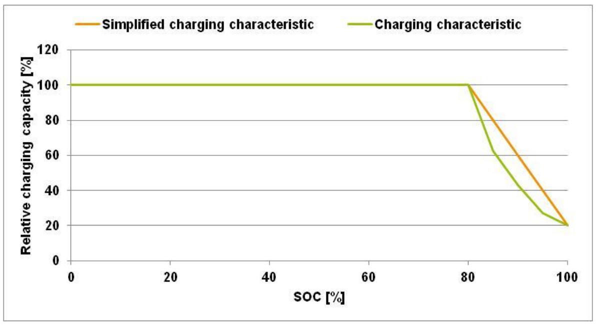

Figure 7: Charging characteristics of an electric vehicle [own diagram based on 5]

Figure 7 shows the charging characteristic of an electric vehicle [5]. Until reaching an SOC of 80 %, the battery will be charged with full charge capacity. From a state of charge of 80 % the charging power is throttled down depending on the SOC in order to protect the battery from overheating. For the creation of load profiles of electric vehicles it is assumed that there is a linear decrease starting from a SOC of 80 %.

As each electric vehicle greatly varies in terms of consumption, storage or charging technology, some further assumptions must be made:

- Battery capacity = 20 kWh
- Consumption = 25 kWh/100 km (charge loss included)
- average daily driving distance = 37 km [6]

Note that the load requirement is about 10 kWh per day. Depending on the scenario three different charging performances are considered: 3.7 kW, 11.1 kW and 22.2 kW.

III. SIMULATION

A. Rural and suburban network without electric mobility

Figure 8 illustrates the flow of the electric power at the suburban- and rural local power transformer from Monday to Friday. In the rural local network a PV feed of different levels is simulated.

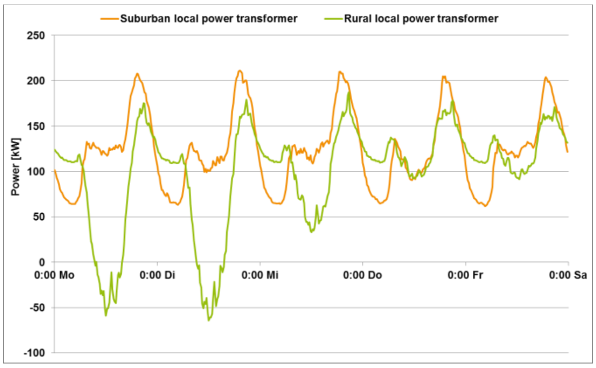

Figure 8: Course of the electrical power at the suburban- and rural local power transformer [own diagram]

As can be seen from Figure 8, the base load of the rural network is higher than that of the suburban grid area. On the one hand the farm needs significantly more electrical energy than the households and on the other hand the pumping station needs a constant power of 80 kW. Furthermore, it becomes clear that the local power transformers are charged with a maximum of 50 % (200 kW) during normal operation.

B. Uncontrolled charge upon arrival

First the scenario "Uncontrolled charge upon arrival" is simulated. Using the arrival times of the households the load profiles of the electric vehicles are randomly allocated to the house connections depending on the penetration of electric vehicles and the number of households per cable.

Figure 9 shows the maximum utilization of the suburban and of the rural local power transformer depending on the charging capacity and the number of electric vehicles. With a penetration of 100 %, every household owns one electric vehicle.

In figure 9, the red line marks the nominal capacity of the transformers, up to which it should be loaded to its maximum. Hereby, the reactive power is neglected in the low-voltage network:

$$P_{transformer} = 400\ kVA\ \approx 400\ kW$$

The yellow line marks the n-1 criterion for the low-voltage network. Local networks do not necessarily correspond to the n-1 criterion. However STAWAG tries to ensure that there is a reserve at which three stations provide each other. In consequence a local power transformer should be utilized to two thirds only.

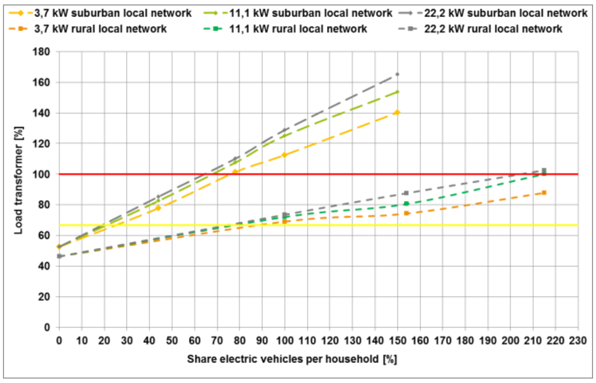

Figure 9: Maximum utilization of the transformers depending on the charging power and the number of electric vehicles [own diagram]

At a penetration of 20 % the n-1criterion is no longer guaranteed in the suburban network area. The transformer reaches its nominal capacity between a penetration of 63 % and 75 % in relation to the charging capacity. At this point the yellow line is initially achieved in the rural network.

Figure 10 shows the maximum utilization of the cable depending on the charging capacity and the number of electric vehicles. The maximum current capacity of the low-voltage cable used in the simulation is 300 A. The cables are secured by a 250 A-fuse, so that the maximum load of the cable is 83 % (red line).

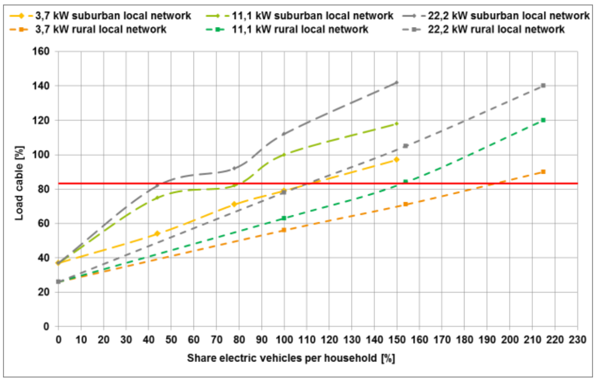

Figure 10: Maximum utilization of the cables depending on the charging power and the number of electric vehicles [own diagram]

In the suburban local network, the HRC-fuses solve to protect the cable from overheating between a penetration of 40 % (3.7 kW) and 110 % (22.2 kW). In the rural area network the bandwidth is between 110 % and 185 %.

Figure 11 shows the maximum voltage drop depending on the charging power and the number of electric vehicles. The red line marks the lower limit of the 10 % voltage band. However, the network operator tries to avoid voltage fluctuation >±7.5 % (marked by the yellow line in the figure).

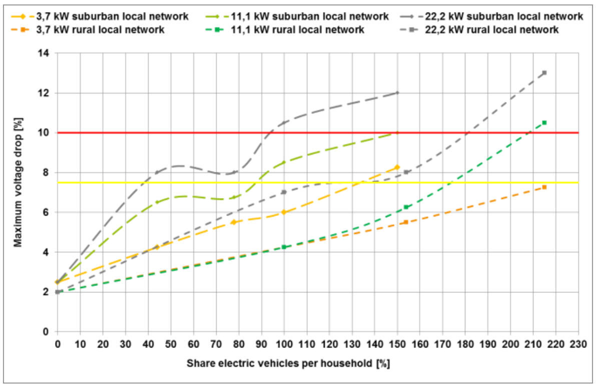

Figure 11: Maximum voltage drop depending on the charging power and the number of electric vehicles [own diagram]

Looking at the last three figures it becomes obvious that compared to the rural network the utilization of the operating resources rise more steeply in the suburban local network when increasing penetration of electric vehicles. In addition, the maximum load of resources increases with higher loading capacity.

The goal of the Federal Government is to bring six million electric vehicles onto Germany´s roads by 2030. This corresponds to a penetration of 15 % and is attainable in both of the local networks. Depending on the charging power, cables or transformers are the elements in the networks which tend to overload first of all. So the transformer is charged with its rated power at a penetration of 75 % and a charging power of 3.7 kW in suburban network, whereas in rural network the HRC-fuses solve at a penetration of 195 % and at no time the transformer reaches its rated power. In this scenario, voltage band problems appear at significantly higher penetrations only.

C. Dynamic prices without network control

The scenario “Dynamic prices without network control” has shown that due to high simultaneity operating resources are overloaded at low penetrations. At a penetration of 9 % with a charging power of 22.2 kW and at a penetration of 20 % with a charging power of 11.1 kW the HRC-fuses already solve. For this reason, a load management is urgently necessary to introduce dynamic prices.

D. Dynamic prices with network control

In the scenario “Dynamic prices with network control” two variants are examined:

Variant A: Even restriction of all vehicle charges in case of imminent overloads.

Variant B: first-come, first-served (Loading operations start due to time of registration).

In both variants, the electric vehicles are charged between 00:00 am and 06:00 am because the price of electricity is very low at night. In this scenario, only the suburban local network is investigated, because in this network the operating resources reach their limits sooner than in the rural grid.

Figure 12 presents the course of the electric power for the local power transformer for one day. The simulation shows that in both variants penetrations of electric mobility of 150 % are attainable. In Variant A the available charging power is evenly distributed to all load points. Here the transformer is constantly loaded with its rated power.

In Variant B, the power control grants the wallboxes, which have first registered a release depending on the available charge power. In this simulation the charging power is 11.1 kW. Due to the high charge power, it is not possible for the transformer to be charged with constant nominal power. Therefore, the course of the electric power swings about the nominal output.

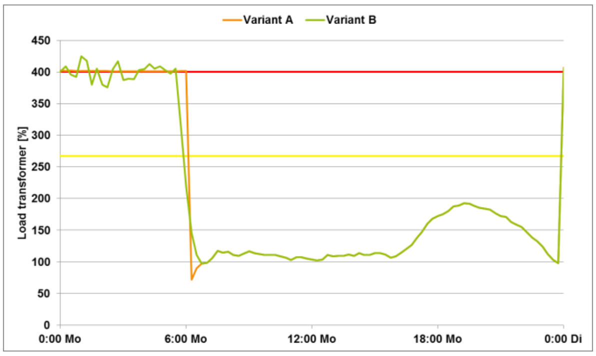

Figure 12: Course of the electrical power (150 % EV) [own diagram]

Furthermore the utilization of the other resources (cable, voltage drop at the end of the cable) is higher for variant B.

IV. EVALUATION

A survey within the econnect field trial shows that 2/3 of the participants accept charging times of up to 2 hours in the private sector. For this reason, charging power of 3.7 kW or a maximum of 11.1 kW will initially prevail. The current charging strategy "Uncontrolled charge on arrival" shows that a penetration of 75 % in the suburban and of even 195 % in the rural network is possible with a maximum load capacity of 3.7 kW. However, it can be seen that the n-1 criterion is already exceeded at significantly lower penetrations.

The traffic light concept developed by BDEW in combination with a load management can help to ensure the n-1 criterion with an increasing number of electric vehicles. Here, the loading of the electric vehicles represents flexibility. If an overload of the operating resources in the network occurs, the network operator is able to profit from flexibility. Thus the load capacity can be reduced depending on the load in the network. Intervention of the network operator on this flexibility should be associated with a corresponding remuneration. By this concept, the network operator can set a basis for the integration of renewable energies and new loads (electric vehicle) and in that way the network operators create a framework for introducing dynamic prices.

In Figure 13, the charged amount of the energy of the electric vehicles depending on the arrival times is shown for two weekdays in 2030 [7]. The bars indicate the hourly energy consumption of all electric vehicles. The color coding of each bar indicates the time by which the amount of energy for each hour can be shifted without affecting the users´ behavior. It becomes clear which amount of flexibility is provided by the loading operations. As average value there is a displacement of the load operations of around 11 hours. Especially in the evening at the peak of households (06.00 pm - 08.00 pm), more than half of the required amount of energy can be shifted for 12 hours.

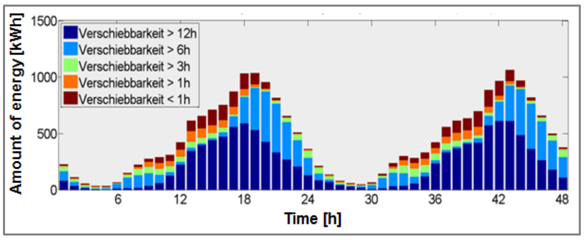

Figure 13: Mobility of the charged amount of energy for 2030 [7]

Operation mode of load management

A combination of intelligent load management and traffic light system allows for an even higher penetration of electric mobility without network expansion. For this purpose, the load of the local network transformer, the load of the cables and the voltage at various critical points are measured. The resulting values are transmitted to the intelligent local network station which is able to take advantage from the consumers´ flexibility (for example electric vehicles) to avoid congestion by reducing the load power in the grid.

The scenario “Dynamic prices with network control” has shown that a high penetration rate can be achieved by use of a load management. From the perspective of the network operator, Variant A has proven to be the more network-friendly behavior. Furthermore, in variant “first-come, first-served”, participants who are connected to one cable in connection with a lot of additional households, are disadvantaged, because this cable will be susceptible to earlier overload. In addition, in this variant those participants are disadvantaged, who - due to their working hours- can only select expensive charging periods.

As, however, the distribution system operator is obliged to operate its grid without any discrimination, Variant A is the preferable one.

V. CONCLUSION AND OUTLOOK

The paper concludes that the goal of the Federal Government to bring one million electric vehicles onto Germany´s roads by 2020 and six million up to 2030, can be obtained by the currently conventional charging strategy. Due to a growing penetration of electric mobility or for the purpose of an introduction of dynamic prices, a load management is urgently needed to ensure the security of energy supply. Introducing the traffic light concept by BDEW can offer successful conditions for a load management.

In the future the impact of a fast charging infrastructure on highways or in city centers should be investigated thoroughly. Besides, the effects of electric mobility on a municipal local network should be studied. As the number of vehicle loads per house connection is constantly increasing in densely populated settlements in downtown areas, the scenario “Loading in the parking garage” should be particularly analyzed.

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