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Evaluation of Technical Integration of Electric Mobility into the Grid

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Abstract

*Heavy research activities in electric mobility technology like fleet tests of Plug-in vehicles in different countries, show the high interest in vehicle-to-grid concepts (V2G). V2G concepts link the supply of the transportation system with the electricity system in order to increase energy efficiency and mitigate greenhouse gases. The different existing integration concepts lack still a broad evaluation. This study simulated the impacts of a high share of electric mobility on the electricity grid and identify possible differences. In consequence of ambitious CO_2 reduction targets and rising oil prices, all kind of stakeholders look out for alternatives to fossil fuel dependency of individual transport. At the same time government, research institutes and different players on the liberalized energy market focus on ensuring the safe operation of the distribution grid despite the integration of the rising shares of fluctuating renewable energies. Only by supplying the **e-mobility** with with renewable energy a significant CO_2 reduction is achievable. As a medium-term solution, meeting both challenges, the terms vehicle-to-grid (V2G) and/or **e-mobility** came up recently and are equivalently used. The interests of stakeholders: reducing CO_2 emissions, increasing energy efficiency in the transportation sector, reducing the dependency on crude oil imports and the creation of an adjustable load, or an adjustable storage for the rising share of fluctuating renewable energy. A lot of concerns are addressed by the concept of **e-mobility**. The expected extension of the electricity grid due to increased renewable energy production will allow to implement the sustainable supply of private transport. At the same time, the expected increase in renewable electricity generation [3] needs new measures to regulate power flow and grid stability [14]. So-called vehicle-to-grid (V2G) concepts allow to supply the individual transport with renewable energies and use the created load and capacity to compensate fluctuations of renewable energies [11].*

Keywords: V2G (vehicle-to-grid),smart grid, simulation

1 Introduction

In order to reach the ambitious CO_2 reduction targets of the global society, politics is looking for paths to walk on. Beside bioenergy technologies, which have been as the saving anchor, *e-mobility* is discussed more and more to reduce the CO_2 emissions of the transport, especially in the field of individual traffic. The promising advantages of e-mobility are not only high efficiency, reduction of local *and* total emissions, but better integration of fluctuating renewables and the high efficient grid operation by the intelligent integration of *e-mobility*.
Another topic regarding the upcoming *e-mobility* is the future operation of the electricity grid. The expected expansion of wind power in Europe and other fluctuating energy sources lead to the discussion of energy storage and services for the grid. According to the VDE [1] [10], proper storage systems could provide amongst others fol-

[1]VDE: Verband der Elektrotechnik, Elektronik, Informationstechnik e.V.; the Association for Electrical, Electronic Information Technologies

lowing services:

- storage capacity for fluctuating renewables
- relocatable load for active load shifting
- positive and negative primary control (provision within 30 s, for a period of up to 15 min),
- positive and negative secondary control (provision within 5 min, duration of delivery: up to 1 h),
- positive and negative minutes reserve (provision within 15 min, for a period up to 4 x 15 min),
- Reactive power compensation (possibly even without delivery of active power - phase shifter operation)

Besides the proposed services of upcoming *e-mobility*, there are other reasons to look for a possibility to reduce the peaks within the load profile. The pricing of electricity is directly coupled to the height of the drawn peak load. Peaks generate not only high transmission costs but also require expensive peak-load electricity generation plants. Therefore the utilities are not interested to generate new or higher peaks with a new big demand.

At the same time the expected immense expansion of renewables, beginning in the mid-term, will generate a high supply of fluctuating energy in the grid (cp. figure 1). Already today there is the requirement of derating wind turbines in high wind phases and shortage in grid capacity or to provide positive or negative controlling power, which is practiced already in Ireland [10]. In spite of the increasing accuracy of wind prognosis it is necessary to have a relocatable load, a storage system or controllable decentralized power plants. Otherwise it is necessary to expand the existing grids.

The VDE is convinced that the expansion of the grids can be delayed or even avoided by using controllable decentralized power plants and/or storage systems [13]. In this context, avoiding grid expansion, providing grid services, the term *e-mobility* comes up more and more often. Following the research study of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety the share of wind energy is increasing until 2050 to 30% of total energy production or 209 TWh [12], which is more than 5 times the amount of todays value. This number makes clear that the load profile in 2050 can not look like the profile today. Figure 1 is visulizing the expected change in the energy mix until 2050. Energy supply can not always meet the demand curve, sometimes the demand profile needs to meet with the supply curve. Therefore it is necessary to implement adjustable load and/or storage systems. Both is provided by the solicited *e-mobility*.

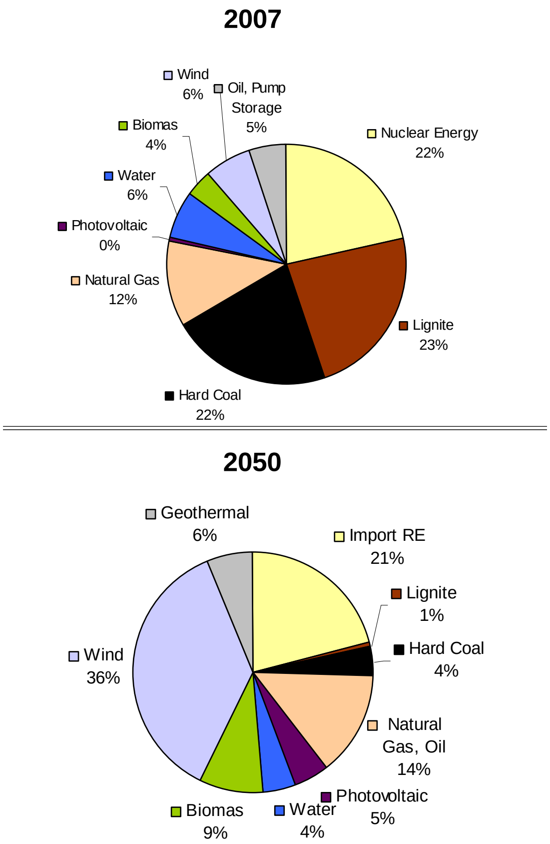

Figure 1: Comparison of the electricity mix in 2007 [5] with the expected mix in 2050 [12]

Besides all euphoric announcements and ”could be’s” it is still questioned what will happen if every passenger car is driven electrically. It is said, that 20% substitution of conventional cars by electrically driven vehicles (EV) would result in 10% more peak load in the grid [2]. But what influence on the demand profile will the technical solution of the integration have? How and where will the batteries be charged, at home, at public parking spaces, special electric filling stations or battery swapping stations and at which rated power of the connection? Where are the differences in terms of impact on the load profile, the coincidence factor of charging and the necessity and feasibility of load management.

This study is evaluating the differences in influencing the distribution grid between possible integration concepts of electrically driven vehicles in the town Freiburg i. Brsg., Germany. The upcoming *e-mobility* will modify the load profile of the local utility, the week of highest peak in 2008 is shown in figure 2, in a still unpredictable manner. To have an idea how the modified profile will look like, this paper is adding different simulation results to the profile.

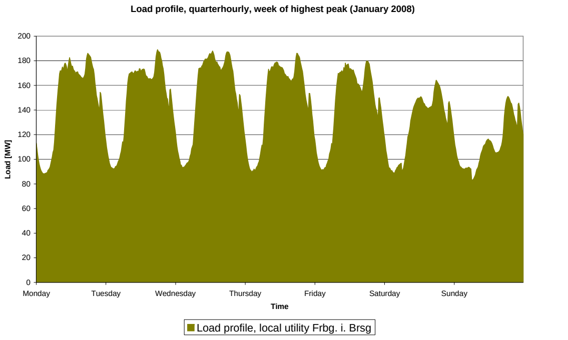

Figure 2: Load profile of local utility in Freiburg i. Brsg.

2 Methods of generating an energy demand profile of *e-mobility*

This chapter derives relations for the power profile of a regional e-mobility fleet and presents the results for Freiburg as a referenc

2.1 Theoretical energy demand of an electric vehicle fleet

The energy demand is following the driving profile of the region under research. When the number of vehicles is high enough it is possible to derive the energy demand of a certain time step by using the average driving distance and the mean specific energy consumption of the considered fleet. Hence the focus of this research is not only the impact on the whole grid of Germany, but on a specific town and as well on their distribution grid, it is necessary to have a look on the allocation of the number of trips and the distance of these trips. To be able to compare the statistically derived demand profile with the data of a local utility it is necessary to derive the total energy demand but the temporal resolution of the demand profile. Especially for smaller numbers of considered cars it is necessary to implement the effect of the distribution of the way lengths.

Figure 3 presents for the region of Freiburg the distribution of way length and their influence to the total energy demand. The data underlying that figure are taken from the data provided by the German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) [4]. Figure 3 shows that most of the ways are shorter than 50 km. But the energy demand is dominated by the rare ways with more than 50 km. With alternating battery capacity and/or alternating specific energy consumption the maximum range of electric driving is changing, hence the energy demand for electric vehicles within the region of the reviewed utility is constrained and restricted by consumption and battery capacity of the cars in the fleet. The simulation assumes that ways longer than the maximum possible driving range (cp. 3) will be summed in one way class, therefore the energy needed beyond the battery capacity is charged outside the considered region. The yellow columns in the graph display the share of energy consumption of each way class if battery capacity and consumption delimiting the maximum range to 200 kilometers. The maximum of energy demanded by one car is the amount of maximum storage capacity of its battery.

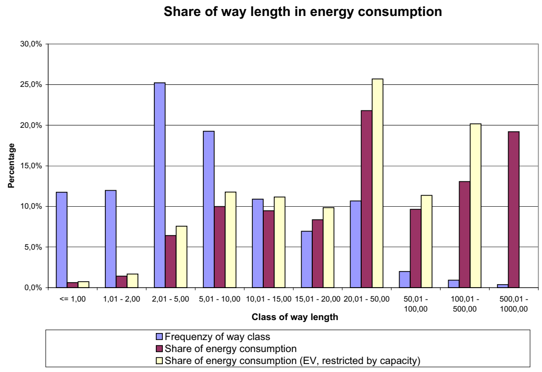

Figure 3: Correlation between energy demand and way class frequency (s_{max}= 200 km)

$$E_d = n_{HH} \cdot \sum_{t=1}^{d} w_{i,j} \cdot \overline{s} \cdot e_{Fhrzg} \quad ^2 \qquad (1)$$

$$\overline{s} = \sum_{n=1}^{10} p(n) \cdot l(n) \Big|_{l(n)<=s_{max}} \quad ^3 \qquad (2)$$

$$s_{max} = \frac{cap}{e} \quad ^4 \qquad (3)$$

Theoretically the energy demand for a certain electric fleet will be calculated by using equations 1 and 2. To estimate the energy demand of a day, the energy demand was derived with the mean way length. The result for Freiburg i. Brsg., with about 124,000 Households of which 74% hold at least one car [15, 6], was 960.4 MWh.
To derive a more accurate estimation of the energy demand profile the simulation assigns not only every way a certain way length following the distribution of way lengths (cp. table 1), but distinguish as well between the destination of ways. Daily ways ending at private household or commercial charging spots, like the place of

[2] t = number of time steps; n_{HH} = number of considered households; w_i=number of ending trips per time step and household; $\overline{s}$ = mean mileage per way; e = energy consumption of the fleet [$\frac{kWh}{km}$]

[3] n = way class; p(n) = probability of way class; l(n) = mean value of way class

[4] cap = mean capacity of fleet batteries, used for the simulation cap =40kWh, e = 0.20 $\frac{kWh}{km}$

Table 1: Distribution of way class

Way Class [km]	mean value [km]	Frequency
<= 1.00	0.8	11.8%
1.01 - 2	1.79	12.0%
2.01 - 5	3.83	25.2%
5.01 - 10	7.8	19.3%
10.01 - 15	13.07	10.9%
15.01 - 20	18.14	6.9%
20.01 - 50	30.7	10.7%
50.01 - 100	72.88	2.0%
100.01 - 500	213.82	0.9%
500.01 - 1000	785.33	0.4%

employment or shopping malls, vary not only in temporal distribution but as well in the probability of the mileage.
The simulation results into a daily energy request of 980 MWh for the traffic within the boundaries of Freiburg i. Brsg. without the commuter. Including the commuter the daily energy demand in the town of Freiburg will be about 1.3 GWh. It is assumed that the cars will be charged immediately after determination of each trip.

2.1.1 Energy consumption of simulated vehicles

The energy consumption of an electric or any other vehicle is a function of the driven velocity, the cross sectional area and the mass of the vehicle as well as rolling resistance and the drag coefficient. An estimation calculation shows that the energy consumption of an electric vehicle is in the range of 0.08 to 0.4 kWh per kilometer (cp. 2). The tank-to-wheel efficiency of η_{EV} = 0.86 for an electric vehicle is given by the former CEO of Tesla Motors M. Eberhard [7] and was marked at the state of art by Tomi Engel in his book "Plug In Hybrid" [8]. To calculate the energy consumption of a vehicle driving in the plain the following equations are giving a good approximation. It must be pointed out that

$$E_{roll} = F_{roll} \cdot s = m_{vehicle} \cdot g \cdot \mu \cdot s \quad {}^{5} \qquad (4)$$

$$E_{drag} = F_{drag} \cdot s = \frac{1}{2} \cdot A_{vehicle} \cdot c_w \cdot v^2 \cdot s \quad {}^{6} \qquad (5)$$

$$E_{acc} = F_{acc} \cdot s_{acc} = m_{vehicle} \cdot a \cdot s_{acc} \quad {}^{7} \qquad (6)$$

For the calculation the mean velocity of the MNEFZ cycle [8] was used, the values for the coefficients of rolling friction and drag was taken from [1].

Table 2: Energy demand of an electric vehicle ($\eta = 0.86$) for the MNEFZ cycle against the vehicle weight

$m_{vehicle}$ [kg]	1000	2000
E_{roll} [kWh/km]	0,04-0.14	0.08-0.27
E_{drag} [kWh/km]	0.03-0.05	0.03-0.05
E_{accel}[kWh/km]	0.00-0.01	0.00-0.02
$\sum$ [kWh/km]$\div\eta_{EV}$	0.08-0.23	0.13-0.4

Taking into account the overview given by M. Jantzen [9], electric vehicles are consuming between 0.04 and 0.2 kWh/km. But realizing that only small and city cars are mentioned, it is more likely that the average electric car will consume more. The *Forschungsstelle für Energiewirtschaft (FFE)* did a research about this topic in 2007 [2] and used as the mean energy consumption the value of 0.2 kWh/km. This is consistant to the own estimation shown in table 2.

2.2 Statistical Analysis of traffic data

The underlying data of the simulation is based on the statistical data of the German Federal Ministry of Transport, Building and Urban Affairs (BMVBS) [4]. The data is based on a questionnaire to the mobility behavior of private households in Germany in 2002 and comprises a sample of about 50,000 private households.

Using the characteristics of the sample it is possible to evaluate the data in order to be able to make a reasonable conclusion about the driving behavior for a town like Freiburg i. Brsg..

The data set gave an overview how many ways per household, driven by car, ended to a certain hour. The given dataset allows to make an estimation of the way destinations by analyzing the purpose of the ways. The assumption underlying the distinction of destinations is that all ways with the purpose work, job training and retail are ending at commercial charging spots, like parking lots, retail centers or places of employment. The rest of the ways is assumed to end at private households. To get an accurate estimation of the hourly energy demand, each way is multiplied by a way length following the distribution in table 1.

Because different connection power at the different charging locations (private households, commercial charging spots) can be assumed, it is interesting, whether the way is ending at private households or at commercial charging spots.

[5] E_{roll} = energy to overcome the rolling friction; F_{roll} = force on the car due to the rolling friction; s: covered distance; g: gravitational acceleration; μ= rolling friction coefficient

[6] E_{drag}: energy to overcome aerodynamic drag; F_{drag}: force on the car due to aerodynamic drag; $A_{vehicle}$ = cross sectional area of the vehicle; c_w = drag coefficient; v = velocity of vehicle

[7] E_{acc}= energy to accelerate the vehicle to velocity v; s_{acc}= distance that takes to complete acceleration; a = acceleration

To include the daily commuting vehicles from the neighborly districts it was assumed, that every way starting in the districts around Freiburg, ending at commercial spots within a range of 10 to 30 kilometers is ending in Freiburg i. Brsg.
The results of the statistical analysis result in the simulation outcome shown in figure 4.

3 Simulation of *e-mobility* impacts on the load profile of Freiburg i. Brsg.

The simulation of the impacts of *e-mobility* on the electricity grid of the local utility of Freiburg i. Brsg. was done in the first stage of the research for the 20 kV level. The impacts on the 400 V level will be done in the near future.

The intention of this research is to visualize how the load profile would change if there would be an electric fleet of passenger cars with the size of the actual fleet charging as their driving profile will request and to visualize the effect of the choice of infrastructure type. There is the choice of the rated power of connections as well as the choice of system.

One problem that occurs evaluating the results, is the big influence of simultaneous charging processes.
To make an accurate conclusion about the differences it is necessary to make assumptions about the simultaneity of charging processes. Because the statistical data underlying this simulation is based on a questionnaire where the times of ended ways are more a rough approximation, the accuracy is not likely to be better than 30 minutes. Assuming this, the data was taken as hourly and was distributed equally to the quarter hour values. Taking this instance into account, the most accurate prediction of a future load profile of *e-mobility* is lying in-between the two results shown in figure 5 and 6.

Since the total volume of the daily energy request by the electric fleet is not changing with the connection type or rated power, figure 4 is giving an idea about the extreme values that might occure, if a high concurrency is involved within the charging processes. The higher the rated power of the charging devices are, the higher is the difference between maximum peak-load the the mean power value of the considered quarter hour(cp. figure 4).

3.1 Immediate Charging

To supply an electric fleet with the requested energy amount there are different approaches suitable. It is conceivable, that the drivers will connect their cars always while not using, so the batteries can be charged immediately after finishing each trip.
That will lead to the effect, that the batteries will remain at relatively high state of charge (SOC) and that high amounts of requested energy per car are comparative rare. This is a scenario of uncontrolled energy request, generating a new load profile which will have increased peak at more or less the same daily hours, like the load profile without *e-mobility*.
Immediate charging stands for starting the charging process directly after finishing the trip. Since the underlying data does not allow to make statement about the concurrency of charging processes, it is necessary to generate extreme values to estimate the impacts in terms of energy demand and generated maximum peak loads. To generate the maximum peak load generated by *e-mobility* a high concurrency of charging processes was assumed. All charging processes are starting at the beginning of the considered time step. To simulate the other extreme, the energy demand within each time step was taken as degree of required power. The direct comparison is shown in figure 5 and 6. The difference between these figures is that in figure 5 the customers are starting to charge simultaneously at the beginning of the time step ($\frac{1}{4}$h). So the area below the load curve is not representing the energy demand, the curve is valid only to estimate the possible peak load effect of *e-mobility*. Figure 6 is neglecting this effect and shows the average energy demand per $\frac{1}{4}$h as well as the resulting load curve.
The figures 5 and 6 show very clearly that the grid is not benefiting from higher rated power connections. The transmission of energy to the cars is not that significant fast as expected. Hence the majority of charging processes belonging to short ways, the most processes are done within a few time steps even with lower fused charging devices. The conclusion of that instance is the higher charging line capacities are not favorable for the grid or the utility. Simply because the time frame of transferring the energy to the fleet batteries with high connection power is not significant faster than with smaller connection powers. But the higher power will have a considerable impact on the possible maximum peak load in the case of a high coincidence factor.

The marginal difference in the rate of transmitting the requested energy shows that the number of low quantity request are dominating the whole energy demand. Concluding the result of the immediate charging scenario it is obvious that a high diffusion of high fused charging devices is not necessary to meet the need of an electric fleet of passenger cars.

3.2 Controlled Charging

Under the point of view to provide safe grid operation and to avoid the necessity of expanding the grid, despite the appearance of a new strong energy demand by the *e-mobility*, it is necessary to control its energy demand.
To avoid increasing or generating new peaks in

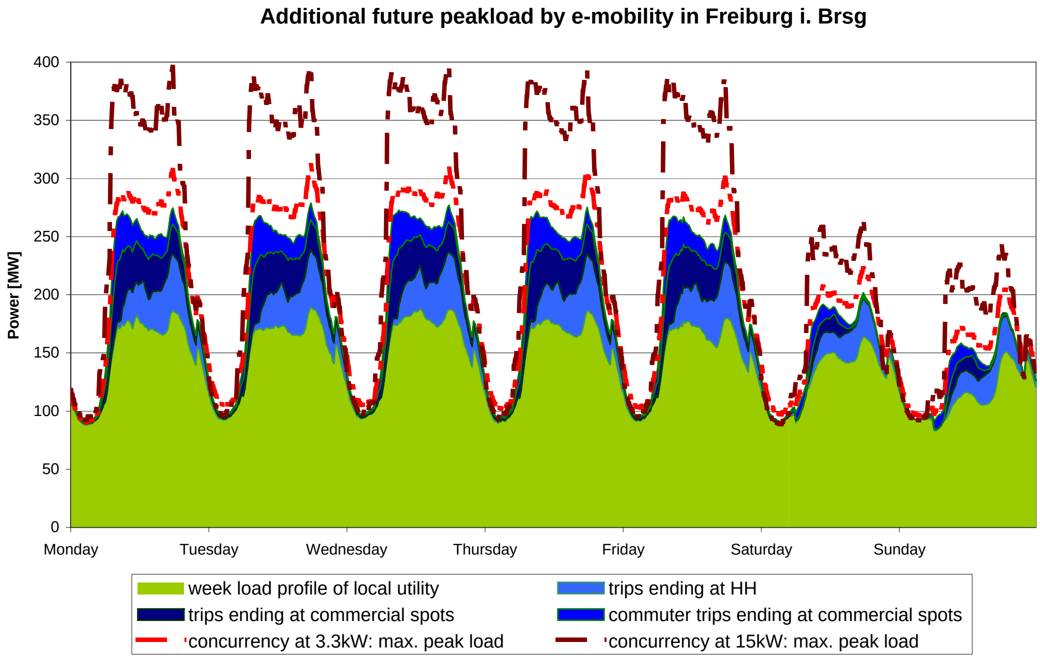

Figure 4: Energy demand profile of local utility in Freiburg i. Brsg., modified with simulation results, simulated rated power for charging. Display of maximum peak load in case of concurrency of charging

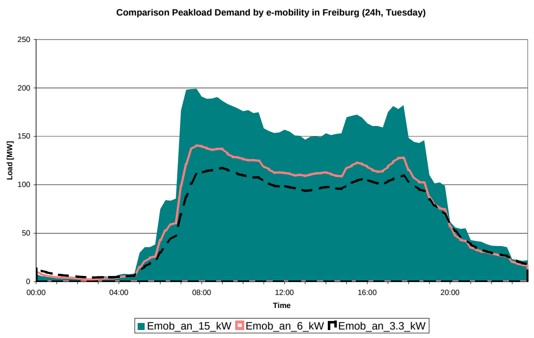

Figure 5: Comparison of different charging connection power, simultaneous charging at the beginning of each time step

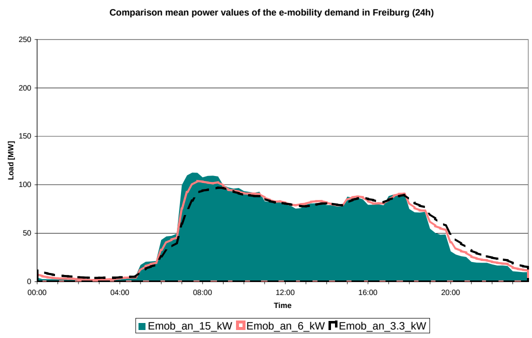

Figure 6: Comparison of different charging connection power

the load profile of Freiburg i. Brsg., it is possible to control the energy request. Generating new or higher peak load in the load profile of the distribution grid might lead to the necessity of expanding the grid. Different approaches to control the additional load are conceivable:

- Delimiting energy supply available for *e-mobility*
- Controlling the energy demand of the fleet to a energy band
- Delaying the energy demand by a number of time steps
- Tariff controlled charging

The ideal demand of a new load within the grid will not increase the peaks, therefore is restricted to the peak load of the former load profile (cp. figure 7A. To reach this ideal situation it is necessary to control/delay each single consumer, in this case the charging vehicle. Figure 7A shows that it is theoretically possible to shift the energy demand into the gaps of the existing load profile. In a future energy szenario with a high amount of fluctuating generation it might be usefull to follow the demand curve instead of making a band. To reach the same effect it is possible to limit the amount of energy available to supply a charging fleet of EVs. This means that if the limit is reached, any additional request is denied. So there is the need of an intelligent charge management infrastructure with either

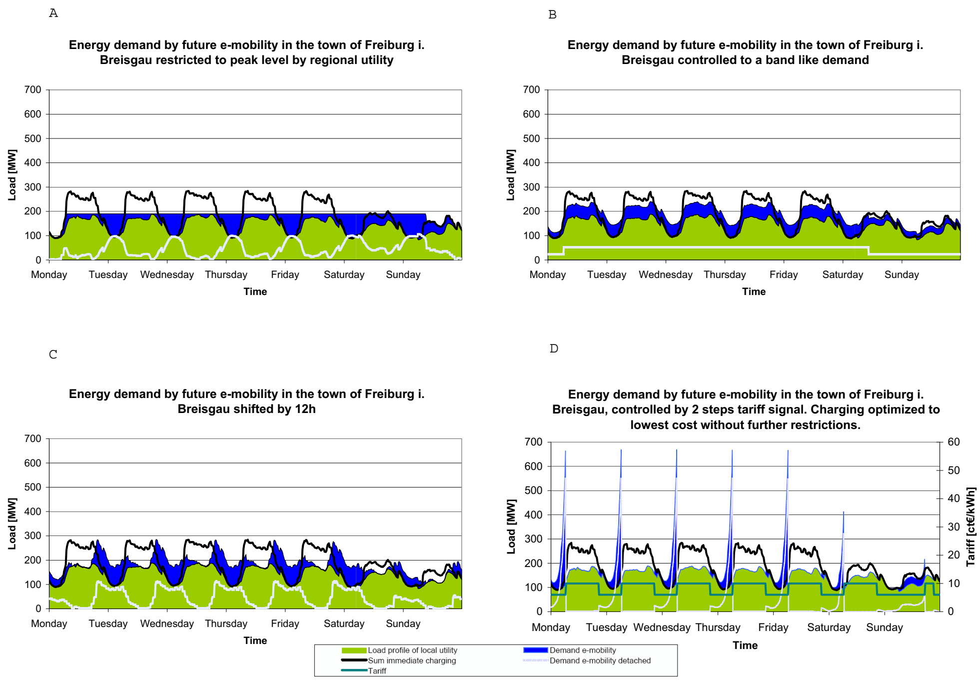

Figure 7: Energy demand by future e-mobility in the town of Freiburg i. Breisgau, comparison of different control approaches. A: restricted to peak level by regional utility; B: additional load demand controlled to a band; C: Shifting the demand; D: Tariff optimized charging

a communication with all participants or other incentives than restrictions, like dynamic tariffs. It is supposable to provide the EVs with a dynamic tariff following the energy demand, to avoid charging at peak times. An electric fleet charging optimized to lowest possible cost will have the effect of generating new peaks, hence everybody is charging at the moment of cheap energy (cp. figure 7D)[8]. To avoid this effect it is necessary to include a dispatcher device into the intelligence of each car which is randomizing the charging within the time frames of low energy prices or communicates with the utility which is controlling the access to the energy. The latter will be complicated and raise the infrastructure costs of the process. The simulation using this approach is shown in figure 8.

Considering that the load curve of the *e-mobility* is following more or less the same peak times as the load profile of the utility, it is imaginable to simply delay the request by 12 hours. The result of this approach is shown in 7C.

Another approach is the decoupling of the profile of driving and the profile of energy demand. Having a constant load by *e-mobility* will create no new peaks, but increase the existing ones (cp. 7B). This is a possible result in the case of providing the energy by battery swapping, assuming a sufficient number of batteries within the system.

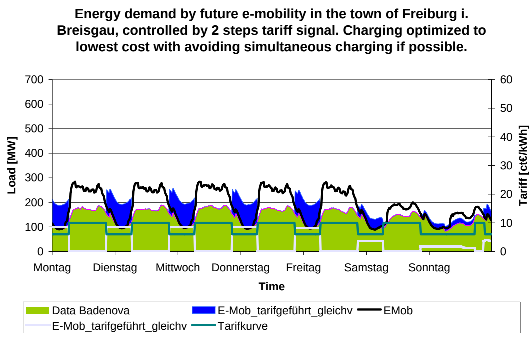

Figure 8: Energy demand by future e-mobility in the town of Freiburg i. Breisgau, controlled by 2 steps tariff signal. Charging optimized to lowest cost with avoiding simultaneous charging if possible.

4 Conclusion

Taking all results into account, it is to say that there is no silver bullet. The solutions to limit the effect of *e-mobility* are either complicated (communication, battery swapping) or not very effective. The most promising way is to provide the vehicles with a optimizing intelligence which is using tariffs provided by the utility and randomize its charging process within the

[8] Charging at lowest price or if necessary to make the next trip

frames of low costs. The realized simulations, in particular the cost optimized, tariff controlled scenario, show the resulting energy demand of the substitution of carbon based individual transport by electric driven vehicles is flexible enough to meet the upcoming challenges of the increasing supply with fluctuating renewables.

Providing tariffs alone is not solving problems like generating or increasing peaks. The time steps of provided tariffs will have a highly influence on the demand profile of electrified individual transport. Most likely a large number of vehicles will start charging at the beginning or stop at the end of each tariff step, respectively. To avoid this instance it is necessary to include either communication between vehicles and the grid operator or to include an randomization in the charging device to distribute the charging process equally within the time frames of the low cost phase. Another solution could be to provide different grid sections with slightly different tariffs to avoid to much impacts on the grid. It is to ensure, that vehicles will charge equally distributed within the phase of low energy prices, to avoid new and very high peak loads.

The simulations showed that the integration of electrified individual transport as a service provider or relocatable load is theoretically possible, even if real driving profiles are underlying the simulations. To achieve all promised advantages by generating this new, high demand, there is still a complicated way ahead.

To reduce the expense in building up a new infrastructure to supply the electrically driven fleet the Fraunhofer Institute for Solar Energy Systems is developing an embedded dispatcher which is sensitive for dynamic tariffs and avoiding the effect shown in figure 7D. Including the intelligence locally in the demanding car can avoid charging concurrency and makes it unnecessary to implement an expensive infrastructure with communication between all parties at the grid contenting spot. The dispatcher will be able to optimize the cost of the charging process, therefore the influence on the grid of the e-mobility is controllable by providing sufficient, dynamic tariff signals. This can lead to the necessary decoupling of driving and charging profiles in order to supply the electric passenger cars with the highest share of sustainable energy as possible without generating the necessity of a grid expansion or jeopardize the safe operation.

Authors

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