Local Energy Autarky with Decentralized Smart Grid Systems using EV Charging Management

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***Abstract*—Local energy autarky needs a permanent balance of generation and consumption which has to be coordinated by a smart grid system. This system has to ensure both the use of the flexible load should not be restricted and the curtailment of renewable power should be minimized. Since most of the renewable generation is naturally fluctuating, especially the load management has to be in the focus. Since EVs offer a high load control potential due to their storage capacity, they are ideal actuators for local energy balancing. In this paper an autarkic decentralized smart grid system is described which is able to balance the local consumption and generation while considering the grid condition (voltage, utilization) and the user needs. In this context, especially the flexibility and grid supporting potential of EVs is presented. To this end, a probabilistic mobility and charging simulation was conducted. Afterwards, the additional (non-EV) actuator need is calculated and assessed in the course of a case study.**

Keywords- Charging Management; Distribution Grid Automation System; Electric Mobility; Flexibility; Local Energy Autarky; Smart Grid

I. INTRODUCTION

Fighting the climate change is the main challenge of all parts of the energy supply sector in this age. In the recent decade the electrical energy sector was transformed by integrating a large number of renewable power plants which reduced the consumption of fossil resources in the generation of electrical energy substantially. Since these renewable power plants are mostly decentralized, the prerequisites for local energy autarky have been created also if generation and consumption could be balanced.

In order to balance generation and consumption, the generators and flexible loads have to be controlled by a smart grid system. Doing this, the system has to ensure both the use of the flexible load should not be restricted and the curtailment of renewable power should be minimized. Since most of the renewable generation is naturally fluctuating, especially the load management has to be in the focus.

Especially the mobility sector requires large quantities of energy which are still primarily supplied by fossil fuels. Although the share of biofuels increased, they are inadvisable for satisfying a high proportion of the total energy demand, because they directly compete with the food production. Therefore, it is reasonable to reduce the fossil energy demand by using electrical energy in the mobility sector too, so that the share of electric vehicles (EVs) probably will significantly increase in the next years [1].

Since EVs offer a high load control potential due to their storage capacity, they are ideal actuators for local energy balancing [2]. However, it has to be ensured that the charging control neither affect the local grid condition nor the users' mobility. Therefore, the smart grid system has to be able to avoid inadmissible grid conditions (limit violations) and impairments of the users' in addition to the energy balancing.

II. CHARGING FLEXIBILITY

To determine the charging flexibility, the mobility behavior of the vehicle users is required. Therefore, a simulation of the usage of EVs was carried out. In order to obtain valid results the simulation is based on data of a study on mobility in Germany [3]. Based on the provided data probabilistic driving profiles are generated by means of a multistage algorithm that was customized for utilizing data available in this specific mobility study. The main aspects of the algorithm are depicted in Fig. 1.

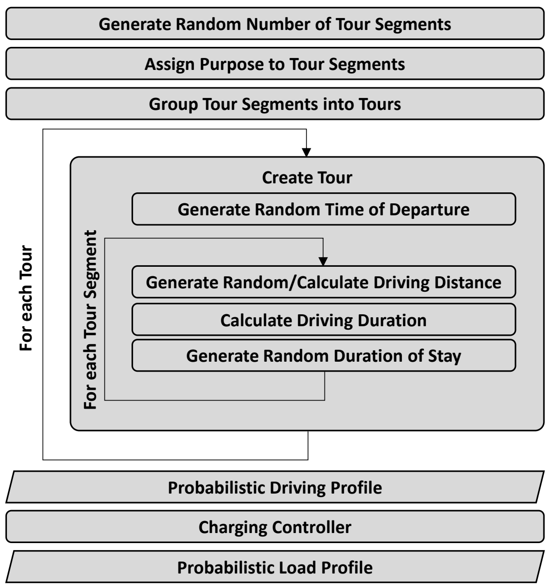

Figure 1: Simulation algorithm for generating probabilistic driving and load profiles

The simulation model was used to examine the load shifting potential of EVs via an analysis of generated driving and load profiles. Fig. 2 shows that the charging power of the majority of all EV charging processes can be limited significantly without affecting the users' mobility. So with a maximum charging power of 11 kVA in more than 80% of all charging cases, the charging power can be massively reduced by about 80%. This implicates a high flexibility potential, especially with a rising number of available EVs.

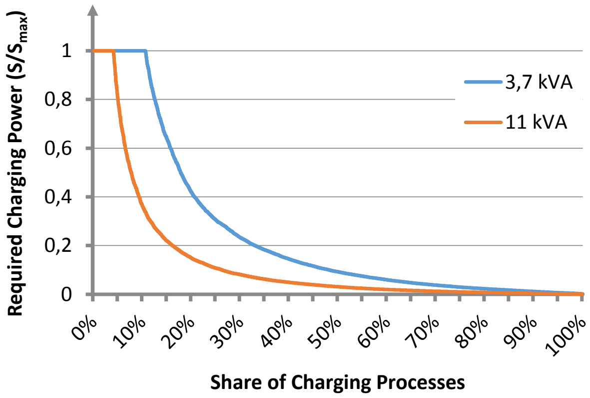

Figure 2: Required charging power for EVs without limiting the users' mobility

III. AUTARKIC SMART GRID SYSTEM

As mentioned before, local energy autarky needs a coordinative smart grid system. This system has to be able to calculate the grid state in real-time, balance generation and consumption and ensure a regular grid state.

Therefore, the smart grid system needs an autonomous control unit, several current/voltage sensors and controllable actuators. Fig. 3 depicts the concept of the system for a medium voltage grid in detail.

The smart grid system consists of an autonomous control unit within the medium voltage grid, several current/voltage sensors and controllable actuators. For cost-efficiency reasons only selected grid nodes are measured, voltages and currents at the other nodes are estimated [4]. Furthermore, (semi-) autarkic low voltage grid controllers could be integrated in the system which aggregate the control flexibility of the low voltage grids and supervise the local grid conditions [5]. In case of missing low voltage grid controllers, the charging stations connected to the low voltage level could be controlled by the medium voltage control unit too. Besides EV charging management the system is also able to control different actuators like wind or photovoltaic power plants, selected industrial processes or further local storages and controllable power plants. This way, off-limit conditions like overloads and deviations from the permitted voltage range could be remedied fast and precise.

As the local energy balancing needs ultra-short reaction times and the autonomous control unit and the communication or actuator response time is not fast enough to react within very few seconds, the "primary control" has to be provided by the inverters of the wind and photovoltaic power plants automatically. This adjustment potential, however, is limited to a maximum of few seconds [6], [7]. Afterwards, the control unit calculates the needed charging power adjustments or further actuator commands in case of insufficient charging flexibility.

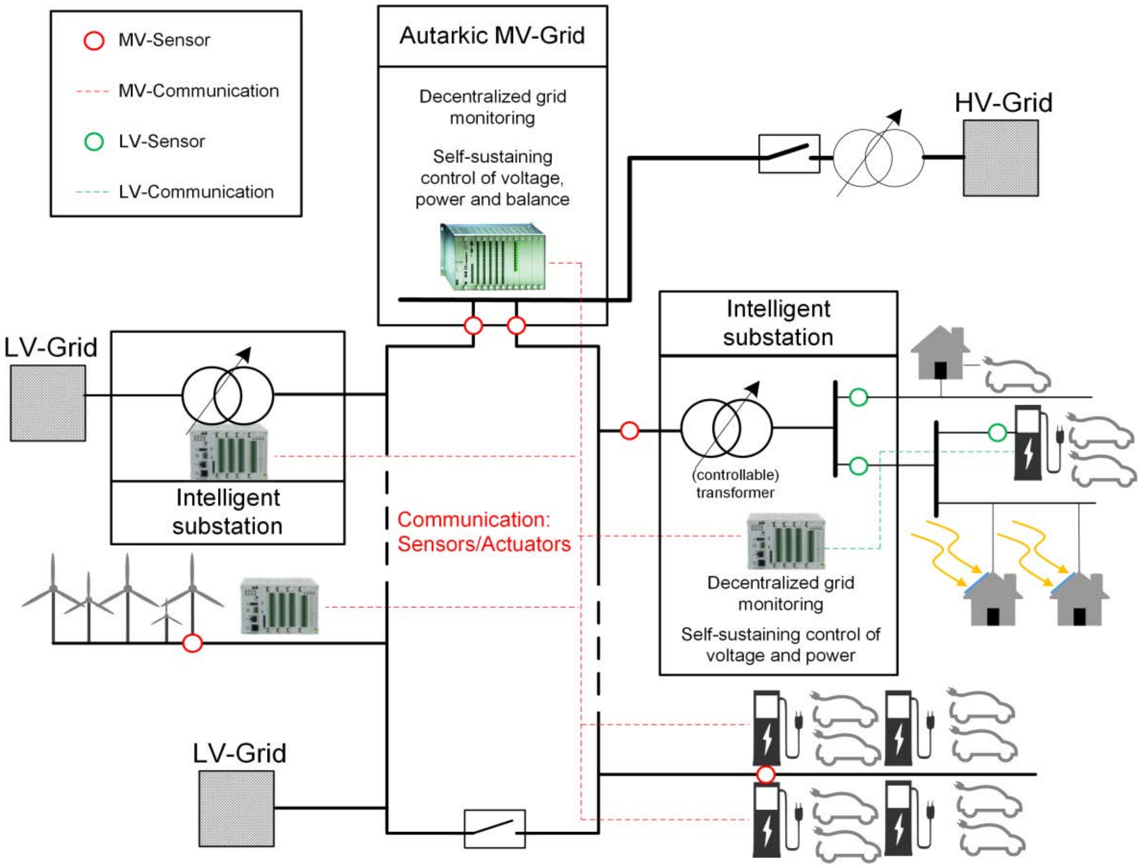

Figure 3: Concept of an autarkic control system on the medium voltage level

IV. BALANCING POTENTIAL OF EVS – CASE STUDY

The case study is based on an autarkic grid with 5,000 households with an average electrical energy demand of 3,000 kWh/a and the same number of EVs. On the basis of the mobility simulation, the average energy demand of the EVs is about 2,600 kWh/a. The total energy demand of 28 GWh/a is provided by wind and photovoltaic power plants only. This results in an installed wind power of 7 MW with 2,000 full load hours and 14 MW photovoltaic power with 1,000 full load hours per year. The EVs have an average battery capacity of 40 kWh and a maximal charging power of 22 kVA. For simplification, industrial loads and further power plants are not considered.

A. Available flexibility of the EV pool

The available charging flexibility of the EV pool was determined on the basis of the mentioned mobility simulation. This involved both, the power increase and power decrease potential of the pool, ensuring no restrictions of the users' mobility needs.

Fig. 4 shows the possible increase of the pool's charging power and its maximum duration. In the first 15 min the total charging power of the EV pool could be increased by 25 MW which exceeds the maximum infeed of the wind and photovoltaic power plants. Afterwards, more and more EVs are fully charged, so the total charging power decreases.

The daily energy demand of the 5,000 EVs is about 36 MWh. In contrast, the total storage potential of the pool is 200 MWh which is five times higher. Therefore, there is a usable flexible energy of 164 MWh. Compared to the daily energy consumption of the households (41 MWh), there is enough storage potential for four days. However, it should be noted, that the flexible energy is not equally distributed among all EVs, so the maximum power is limited.

Fig. 5 depicts the load reduction or vehicle to grid (V2G) potential of the EV pool respectively. It is shown that this exceeds the possible charging power increase many times. This is mainly due to the fact that the average state of charge is quite high (far beyond 50%), because the energy need of the average driving distance (7 kWh/day) is far below the battery capacity. It is possible to similarize the load increase and reduction potential by delaying non-needed charging processes. This, however, will reduce the possibility of spontaneous drives with the EVs and may reduce the acceptance.

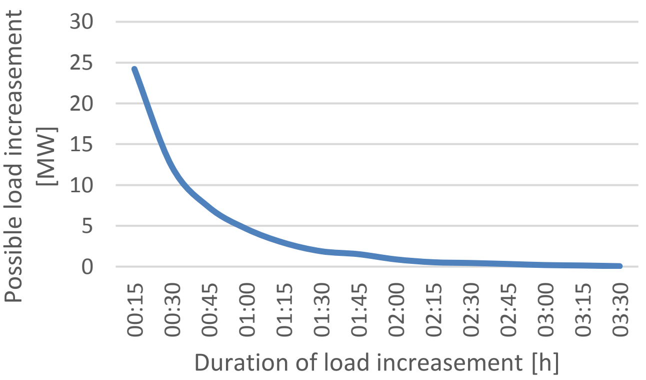

Figure 4: Load increasement potential of the EV pool

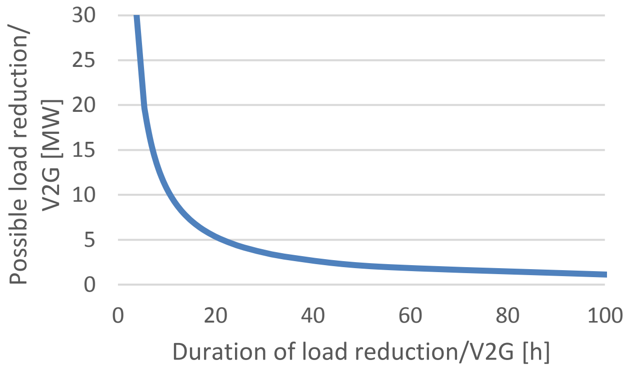

Figure 5: Load reduction resp. vehicle to grid (V2G) potential of the EV pool

B. Needed flexibility of the households

Since power fluctuations of single consumers balance at higher numbers, the total power demand of all households corresponds to a similar standard load profile each day. This total load profile is shown in Fig. 6 for average German households. It is depicted that the power demand ranges from 0.75 MW in the night to a maximum of slightly over 3 MW at Sunday noon. The maximum needed flexibility of about 2.5 MW could easily be provided by EVs (up to two days continually).

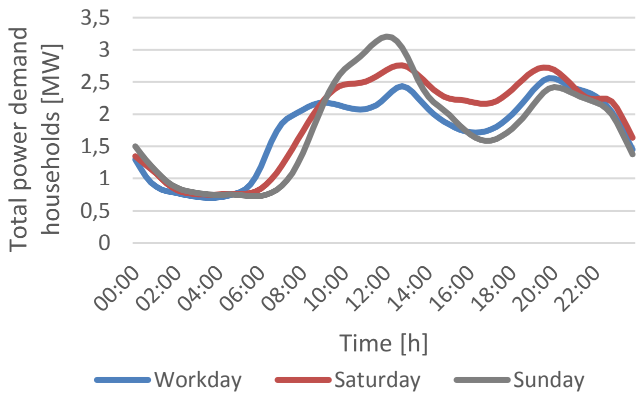

Figure 6: Total power demand of all households (summer day)

C. Fluctuation of renewable power plants

In this case study the total power generation is naturally fluctuating, so load balancing has to be ensured by storages. The storage dimension depends especially on the maximum power infeed, its duration and the maximum time of insufficient infeed.

On the basis of real photovoltaic and wind generation data in Germany, the actually maximum total power infeed in this case study is about 15 MW. Fig. 7 shows the temporal distribution of the total infeed. About a quarter of the year (2296 h) the total infeed is below 1 MW and less than 150 h over 10 MW.

However, the more decisive factor is the difference between load and infeed (residual load). Therefore, Fig. 8 depicts the distribution of consecutive power shortfalls and surpluses between the power demand of the households and the total infeed. The EV consumption is initially not included.

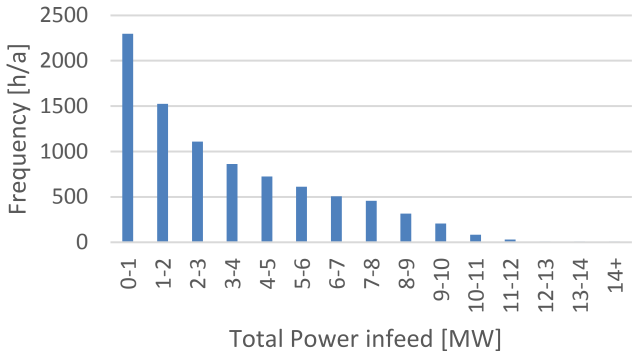

Figure 7: Distribution of total power infeed

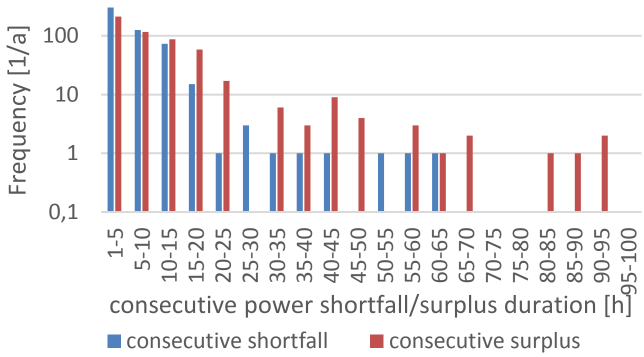

Figure 8: Distribution of consecutive power shortfall/surplus duration

D. Additional flexibility need

The maximum consecutive power shortfall is about 65 h, the maximum surplus 94 h. In total, there is a power surplus in 5,560 h during which EVs are charged and a shortfall in 3,200 h during which EVs are discharged. From the energetic point of view there is a maximum shortfall of 96 MWh and a maximum surplus of 510 MWh. Adding the energy need for EV driving, the maximum shortfall rises to 193 MWh (added total EV demand for 2.7 days) and the surplus shrinks to 369 MWh (subtracted total EV demand for 3.9 days).

Since the charging flexibility of the EVs is not sufficient to balance the system in these situations, additional flexibility is needed for permanent autarky. In particular, an additional long-term storage with a capacity of at least 200 MWh and a maximum charging power of 5 MW is needed. Although this is only needed few times a year (in this simulation 5 times), and high cycle stability is not required which massively reduces the storage costs, a permanent autarky cannot economically compete with a connection to the high voltage level (except for special cases like smaller islands). However, the EV flexibility is sufficient to balance the grid most of the year which reduces transfer losses and grid expansion costs and also increases the reliability.

V. Conclusion & Outlook

Local energy autarky needs a coordinative smart grid system which has to calculate the grid state in real-time, balance generation and consumption and ensure a regular grid state. Due to their high flexibility and storage potential, EVs are particularly suitable as actuators for this purpose.

This paper shows the structure and function of an autarkic smart grid system. In this context, the flexibility and grid supporting potential of EVs is depicted. Furthermore, on the basis of a case study, the local energy balancing potential of EVs is figured out. Their use means that the grid can be in an autarkic mode most of the year. Although the need of additional flexibility for permanent autarky is massively reduced, it still cannot compete with the connection to the high voltage level. Furthermore, this way the EV batteries loose life time which in turn causes costs. But since the total needed V2G-energy is about 3 GWh per year which results in about 15 load cycles of the EV pool, the loose of battery life time is very moderate.

Due to the further increase of volatile decentralized renewable energy production and decommissioning of central conventional power plants, temporarily local energy autarky will be more and more applicable. Especially the reduction of transmission losses and the increasing reliability of supply are likely to promote the local energy autarky. In case of a high EV penetration, the costs for local energy balancing could be decreased massively which probably also leads to economic reasonability. Nevertheless, there are many legal and organizational obstacles that have to be solved first and grid-specific economic calculations are imperative for each individual case.

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