Increased Utilization of Residential PV Storage Systems through Locally Charged Battery Electric Vehicles

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***Abstract*- The goal of sustainable electro-mobility is to decrease its environmental impact by increasing the consumption of renewable energy. In this study, the opportunity for increased use of locally generated solar power is calculated, as it depends on the household profile, the pattern of usage of BEVs and the gain achieved using local batteries with various capacity. If the average driving profile of conventional vehicles in Germany is applied to BEV usage, a local stationary battery should at least hold 8-12 kWh energy content and the PV system should be 10 kWp or more to reach a contribution of 50% locally generated solar energy towards the demand of electricity for household use and BEV.**

Keywords*- *PV storage system; Battery electric vehicle; own-consumption; charging profile

I. Introduction

Charging the battery electric vehicles (BEVs) from renewable energy sources is key to improve the carbon footprint of BEVs. Hence, charging from a residential roof-mounted PV plant is a suitable proposition. Charging during evening hours will require a local stationary battery. Battery electric storage systems are installed in Germany in more than 50 % of all new residential PV installations [1]. Four person households have an average residential electricity consumption of 10 to 12 kWh per day (4,000 kWh/a). The utilization of their battery described by the equivalent of full cycles per year will reduce increasingly for battery capacities of more than 4 – 6 kWh [2]. The battery utilization can be improved, if the battery provides additional services for the network or for the customer. Hence charging a BEV during evening hours can take advantage of the surplus of stored electricity for large batteries. The following study will provide results regarding to battery utilization (in terms of equivalent full cycles per year), as it depends on PV system size, local electrical demand, daily driving distance and charging patterns.

II. Load Modelling

In order to simulate the impact of BEVs on the utilization of local PV storage systems, it is important to know the electrical loads and energy requirement of the households and vehicles considered. This section describes the load models used for this analysis.

A. Household Load

Two household load profiles with 1-minute resolution are used in the study, which represent two extreme cases, one with “evening-centered” and the other one with “noon-centered” energy consumption (Fig. 1). Those profiles have been derived in [3] by behavior-modelling people and their use of appliances for different types of households. The profiles are scaled to a yearly energy demand of 4,000 kWh. The maximum electrical demand of the “evening-centered” profile is during evening hours between 8 p.m. and midnight (red line). In contrast, the highest electrical demand for the second load profile is around 12 a.m. (blue line). Using the two load profiles in the subsequent calculations captures extremes and thus provide an insight into the dependency and range of results seen as the household load profiles vary.

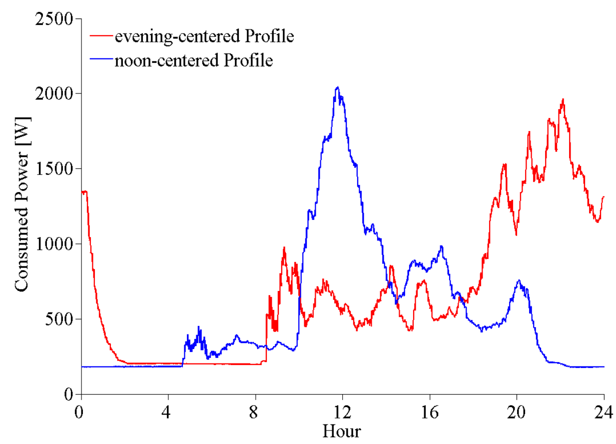

Figure 1. Average daily demand profile

B. *Electro-mobility Load*

Until now, there are only a few studies on electro-mobility behavior in Germany. The assumptions for arrival times and driving distance, which are used for the different calculated cases, are derived in this section.

For the case study, it is assumed that the 'first movers' charge their BEVs exclusively after work at home. Only the charging power at a standard socket (3.7 kW) and at a private charging station with 11 kW are considered. In order to create a charging profile for a single BEV, it is necessary to consider the daily energy requirements of the BEV and the start of charging in addition to the charging power.

So far, there are no surveys on driving distances and arrival times at home of battery electric vehicle owners, so that the current daily driving behavior of conventional vehicles owners also serve as the basis for electro-mobility. We use the summary of Probst [4], derived from the empirical study according to [5]. The amount of energy, which has to be recharged to a BEV, depends on the daily driving distances essentially and the energy consumption of BEVs (0.2 kWh/km) like in [6]. The maximum possible driving distance of the vehicles is limited to 300 km. This gives a maximum battery capacity of 60 kWh.

TABLE I. Survey Results For Daily Maximum Driving Distance

Driving Distance (km)	0	1	10	20	40	65	100	200	300
Probability (%)	29,9	2,5	17,1	12,7	14,7	9,1	6,1	4,7	3,2

Table I shows the daily driving distances and the related percentages of households, which have traveled the distance, according to Probst [4]. The second row shows the percentage of households, which have traveled the corresponding kilometers. It is noteworthy that nearly 30 % of the households do not move their car every day. The average daily driving distance of the remaining households is 50.1 km [4]. [4] and [5] also summarize the arrival time of German vehicle owners after the last trip per day. All arrival times are between 12 a.m. and 1 a.m. and have the highest probability of arrival at 6 p.m. The time of arrival at home after the last trip per day is assumed as starting point for the charging of the BEVs.

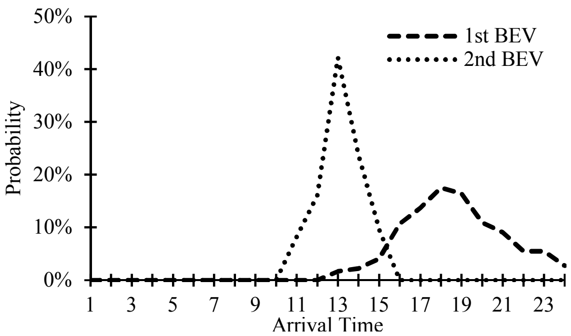

Figure 2. Probability of arrival time using for the analysis

The described input data are used to generate charging profiles for a single BEV based on the Monte Carlo method. For this purpose, driving distances and arrival times are chosen randomly for each day of the year depending on the probability distribution function.

Fig. 2 shows the probabilities of arrival times and Fig. 3 the driving distances which are used for the charging profiles. If the household has a 2nd BEV, it is assumed to be used during workdays only.

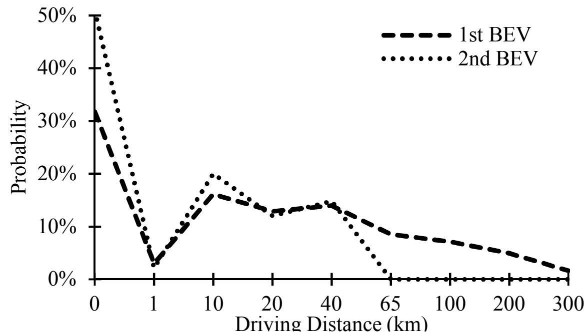

Figure 3. Probability of driving distance using for the analysis

The charging profiles for each BEV is considered rectangular. The charging power is 0 kW before charging and 3.7 kW or 11 kW during the charging process. The charging power changes back to 0 kW once BEV is fully charged.

III. Solar Power Production And Use

This section describes details of the assumed operation and control of the PV system and local battery.

A. *PV Storage System*

The measured output profile of an almost south facing PV system for the year of 2012, located in Southern Germany is used as input data. The specific average solar yield is set at 1,000 kWh/kW$_p$. DC powered batteries with a capacity from 2 to 14 kWh and a SOC swing of 90 % are assumed for local battery storages. They are located between MPP-Tracker and DC/AC converter with an efficiency of 94 % for the charging and discharging processes. The charging and discharging power differs between c-rates of 0.5, 0.75 and 1. The battery management systems is assumed to provide a constant loss if the battery is not fully discharged. Further details can be found in [3].

B. *Algorithm of Control*

At every point in time, solar power generated by the photovoltaic system is used in the first instance to cover the electricity demand of the household and electro-mobility. Surplus power is stored in the local battery storage. Energy from the battery is used, if the solar power falls short of the power needed from household and electro-mobility. Once the battery is empty, the public grid supplies remaining electricity demand. Surplus energy from the PV system is fed into the grid. The described algorithm makes sure, that the battery is not charged or discharged into the grid.

IV. LOAD FLOW SIMULATION

A MATLAB simulation model from [3] is used to analyze the utilization of residential PV storage systems through locally charged BEVs for one household. The described load models and the solar generation profile are entered as input data. Altogether five different scenarios are presented. The observation period corresponds to one year each and the simulation resolution is 15 min.

Of the many scenarios calculated, the following are selected to discuss the dependence of the results on input parameters. The first scenario ("w/o BEV") simulates the case without electro-mobility. Three PV sizes (4, 7, 10 kW_p) with the two defined household load profiles and battery storage capacities from 0 kWh to 14 kWh (2 kWh steps) were considered. The second scenario ("BEV (Monte Carlo)") assumes one BEV per household. Results are shown for a charging power of 3.7 kW and 11 kW, respectively. The driving distances and arrival times of the BEV are chosen for each day randomly with the Monte Carlo method to fit the respective probability density functions (Fig. 2 and Fig. 3). The sum of driving distances results in a yearly energy demand for charging the BEV of 2,700 kWh/a. For the third scenario ("Commuter 6 pm"), a commuter behavior is simulated. The daily driving distance on workdays is assumed to be 50 km, which correspond to the average driving distance of German vehicles, [4]. The daily arrival time at home is at 6 p.m. (highest probability of arrival according to Probst [4]). The driving behavior at the weekend remains unchanged compared to scenario 2. The energy required to charge the vehicle for one year is 3.450 kWh/a. The fourth scenario ("WE-charging Commuter") assumes a different charging behavior of a commuter. The amount of energy consumed on workdays is no longer recharged on the day of consumption, but at the weekend. Both on Saturday and on Sunday, the BEV is recharged starting from 9 a.m. On both days, half of the energy consumed during the week - i.e. 25 kWh - is recharged from 9 a.m. onwards. In addition, 5 kWh will be recharged from 7 p.m. on both days. This corresponds to the driving distance on Saturday and Sunday. This scenario has an energy demand for the BEV of 3,150 kWh/a. The fifth scenarios ("Two BEVs") considers two BEVs per household. The first BEV corresponds to the driving behavior from Scenario 3 ("Commuter 6 pm"). The second BEV shows the driving behavior of a half-time worker. The arrival times at home are between 11 a.m. and 3 p.m. The probability of arrival is normally distributed. The daily driving distance is between 0 and 40 km and the probability is based on Probst [4]. The driving distances and arrival times for the second BEV are also chosen randomly for each workday of the year with the Monte Carlo method (Fig. 2 and Fig. 3). The 2nd BEV will not move on weekends. The use of these two BEVs results in an energy demand to recharge the vehicles of 4,150 kWh per year. The number of full battery cycles and the absolute amount of solar energy used for household and BEVS (own-consumption of PV) are calculated for each simulated scenario.

TABLE I. ELECTRICAL DEMAND FOR INVESTIGATE SCENARIOS

Scenario	w/o BEV	BEV (Monte Carlo)	Commuter 6 pm	WE-charging Commuter	Two BEVs
Yearly demand for BEV and household (kWh)	4,000	6,700	7,450	7,150	8,150

V. RESULTS

Fig. 4 shows the equivalent number of full battery cycles per year and the own-consumption of locally produced solar power for the investigated battery storages in a "evening-centered" household with a 10 kW_p PV system and a storage system with a c-rate of 0.75. All shown scenarios in Fig. 4 refer either to a charging power of 3.7 kW (a & c) or 11 kW (b & d).

For the base scenario "w/o BEV" and an average residential electricity consumption of approx. 10 to 12 kWh per day, the local battery capacities of 2, 4 and 6 kWh are within or even above the optimum in terms of profitability (250-280 equivalent full battery cycles per year [2]). With larger battery capacities, the number of full cycles decrease sharply and do not lead to sufficient gain in own-consumption in order to pay for the additional invest. Scenario "BEV (Monte Carlo)" shows charging a BEV can make better use of the surplus of stored electricity in large batteries. The additional electrical demand for the BEV is approx. 7.4 kWh per day. An even better utilization of large battery capacities is achieved by charging a BEV during evening hours, as shown in scenario "Commuter 6 pm". The additional electrical demand for the BEV is about 9.5 kWh per day. The additional BEV ("Two BEVs") does not increase the number of full battery cycles further. Due to the charging at midday of the second BEV, the full cycles decrease lightly, although the additional amount of electricity required is 11.4 kWh per day. It is striking that the adapted commuter behavior with weekend charging ("WE-charging Commuter") uses the local battery capacities less than the scenario "w/o BEV" in most of the cases. Fig. 4 b & d shows the own-consumption for the cases presented before. In general, it can be seen that own-consumption increase because of the electrical demand due to charging the BEV. The highest own-consumption values is reached in the scenario "WE-charging Commuter". The charging of the BEV results in an additional electrical demand during the day, which is opposite to the load profile of the household "evening-centered". By charging on weekends during the day, the solar power generated can be directly used for charging the BEV and thus results in higher own-consumption.

In particular for the WE charging commuter, the slope of the own-consumption curve towards high battery capacities reduces strongly, which corresponds directly to the low number of full battery cycles from Fig. 4 a & c at high-energy content of the batteries.

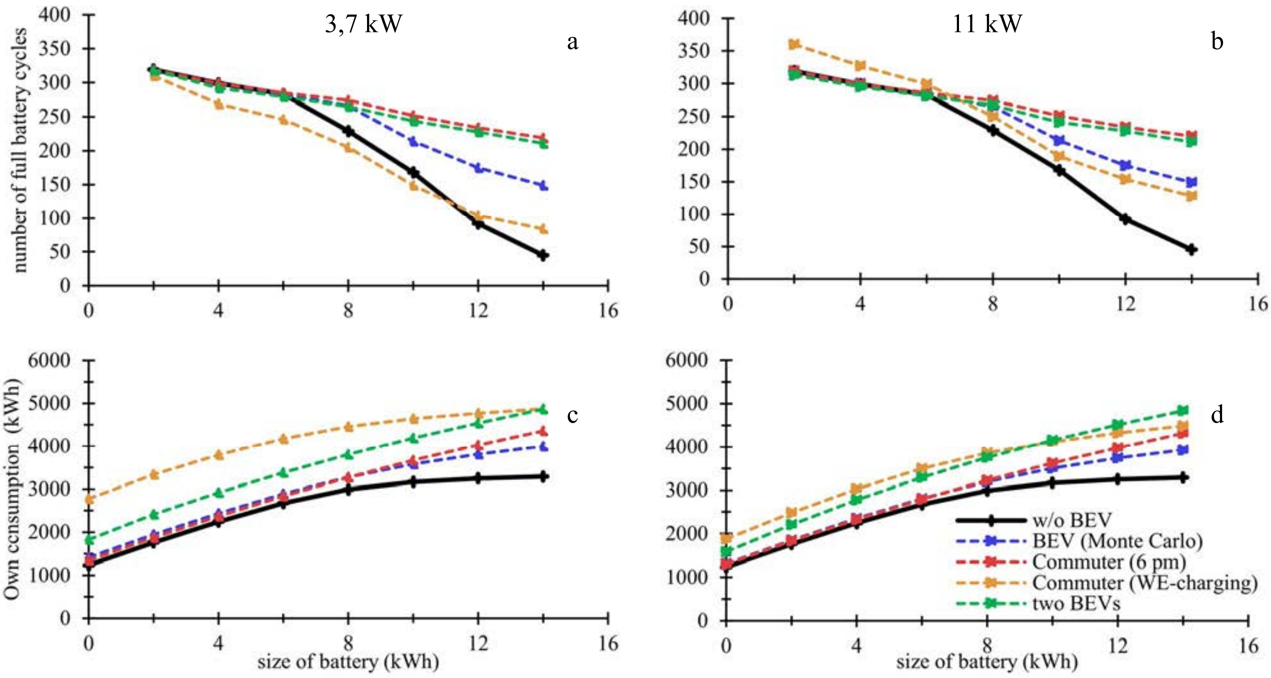

Figure 4. Number of full battery cycles (a & b) and own-consumption of PV(c & d) of the houshold “evening-centered”with a **10 kWp PV system**

The curves of own-consumption of the scenarios “BEV (Monte Carlo)”, “Commuter 6 pm” and “Two BEVs” reach about the same level at higher battery capacities but have a much steeper slope, which coincides with the larger number of cycles of the battery even at high battery capacities. Most important for a high utilization of the battery and for high own-consumption is however the presence of a large PV system.

If the BEV is charged with a charging power of 11 kW instead of 3.7 kW, only the results in scenario "WE-charging Commuter” clearly differ from those previously considered. Due to the significantly reduced charging time during the day at the weekend, the battery is cycled more frequently on weekends. As a result, the equivalent number of full battery cycles increases for all storage capacities.

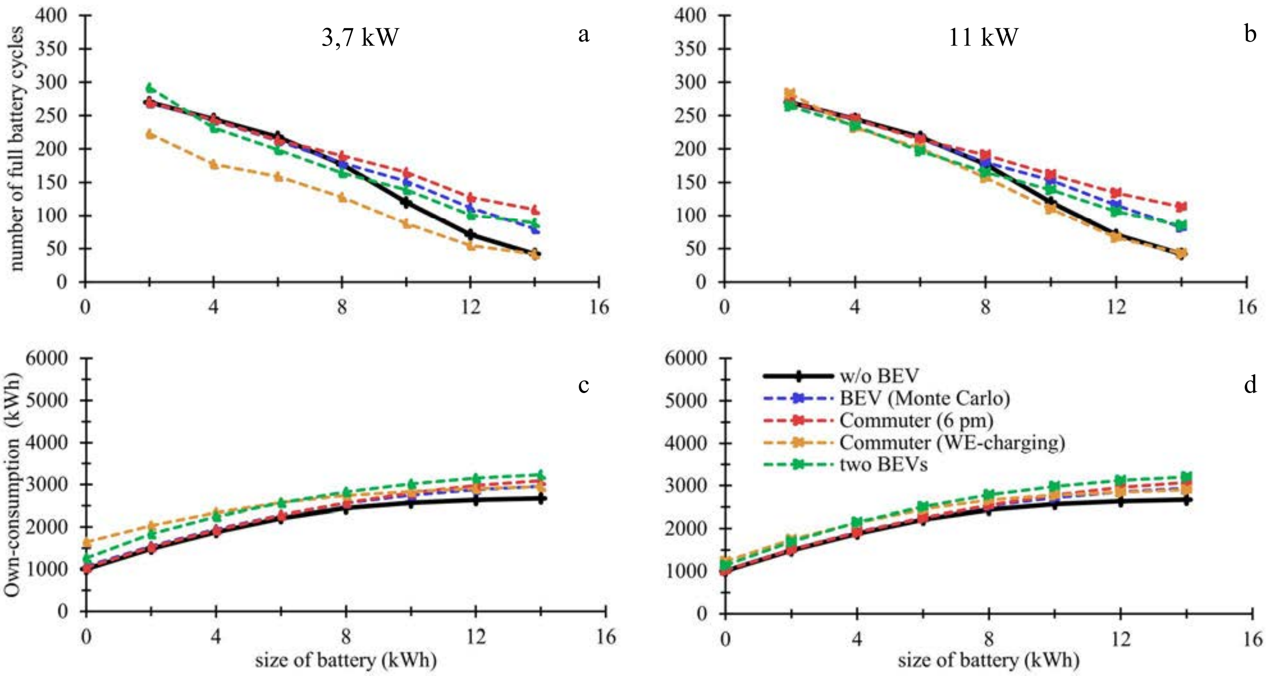

Figure 5. Number of full battery cycles (a & b) and the own-consumption (c & d) of the houshold “evening-centered”with a **4 kWp PV system**

However, since smaller storage units do not reach a charging power of 11 kW, more electricity is taken from the public grid to charge the BEV (Fig. 4 b & d). The PV system cannot supply the high power demand for the 11 kW charging process. This results in a decreasing own-consumption and an increasing amount of purchased electricity from the grid.

Comparing these results with those of a 4 kW_p (Fig. 5) instead of a 10 kW_p PV system, the advantage of the increased utilization of residential PV storage systems through locally charged BEVs is nearly negligible. The lower generation of solar power from PV leads to a decrease of the own-consumption (Fig. 5 b & d) of solar power for the charging of BEV and household. Furthermore, the number of full battery cycles decrease (Fig. 5 a & c).

For the household load "noon-centered", the equivalent number of full cycles for all scenarios (Fig. 6) are below those with the household load "evening-centered". The battery storage cycles less due to the high midday electrical demand.

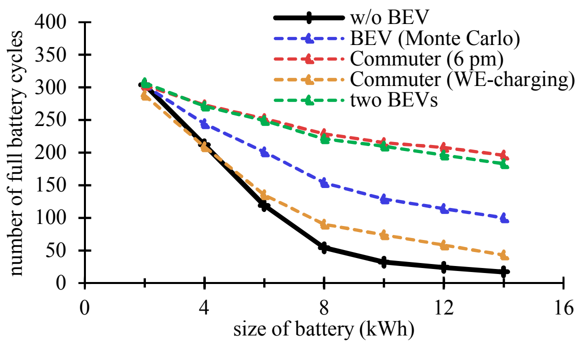

Figure 6. Number of full battery cycles of the houshold "noon-centered" with a 10 kW_p PV and a charging power of 3.7 kW

The own-consumption (Fig. 7) increases, if the charging load for the BEV moves into the evening hours like in the "Commuter" scenario. The low cycles by the batteries are also identifiable at the slope of the own-consumption curves. Charging during evening hours achieves a greater increase in own-consumption in particular for a larger PV system and for larger battery capacity.

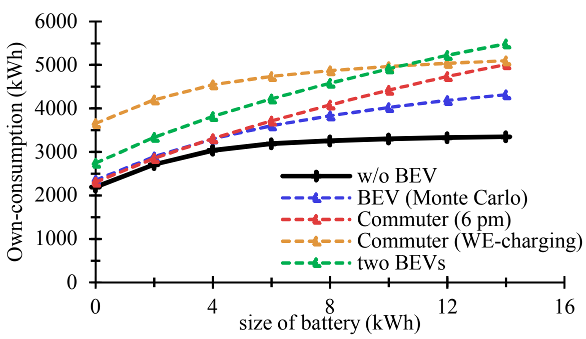

Figure 7. Own-consumption of the houshold "noon-centered" with a 10 kW_p PV system and a charging power of 3.7 kW

VI. Concusion

A large PV system is key to increasing the contribution of locally produced renewable energy towards the demand of electricity for household use and BEV.

A 10 kW_p PV system can deliver a 50% share of self-produced renewable energy (S.RE) in the energy mix of HH and BEV. If the HH profile is "noon centered" and the BEV is charged on weekends during the day, this share of 50% of S.RE can be reached without battery. However, if the HH-profile is less matched to the sunshine hours and the BEV is charged in the evening or at random (according to the distribution of arrival time at home of German vehicle owners), a battery of 10-14 kWh energy content is required to reach this share of 50%.

By adding favorable "sun-shine hour" charging events to the case of a large PV system and battery (10 kW_p and 12 kWh), the share of S.RE can reach 60 to 70% for the sum of HH and BEV. In the mentioned case, the share of S.RE for the BEV is 40 to 60%, respectively, depending on the household load profile.

In contrast a PV system of 4 kW_p, will lead with and without battery to less than 10% of S.RE in the energy mix of the BEV. A large battery does not improve the situation significantly and will have instead a very low utilization, shown by a low number of equivalent full cycles per year. With a larger PV system, the battery utilization will always improve.

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