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Charging strategies for a smart home connected battery electric vehicle

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Abstract

Amendments of the two German directives that define feed-in tariffs, the EEG and KWKG, guarantee a higher payment for self-consumption of locally produced electricity than feeding into the public grid. In the context of an emerging market of plug-in battery electric vehicles this legislation is a promising option for additional revenues: Batteries of Plug-In vehicles serving as energy storages in combination with smart charging schedules represent an opportunity to optimize the amount of local energy consumption. The approach used in this paper for evaluating this complex scenario is a model-based optimization using mixed integer linear programming (MILP) algorithms. Underlying data of the model based analysis are real load, PV and CHP generation data, realistic assumptions for driving patterns and a model for battery degradation of the plug-in vehicle. The simulation revealed a significant potential benefit for optimized local operation management. After that, different system control concepts for linking the charging times of electric vehicles with fluctuating local renewable energy production are studied. Finally, a prototype system has been developed which is being evaluated in a field trial. The system includes a home energy management and a mobile charging management. In this paper, the communication and system control concepts are being presented, followed by a first proof of principle.

Keywords: charging, infrastructure, smart grid, incentive, V2G (vehicle to grid)

1 Introduction

A widespread implementation of electric vehicles (EVs) offers great potential to minimize the CO_2-emissions of the transportation sector and reduce the dependency on fossil fuels. However, intelligent mechanisms of controlling the charging processes are necessary in order to reduce the EV's impact on the distribution grid and to enable them to even act beneficial to grid operations in times of a high share of fluctuating renewable energies.

The latter can be achieved by means of demand-side-management when charging uni-directionally or even by implementing vehicle-to-grid (V2G) mechanisms when bi-directional charging is available. The negative impact on grid operations can further be limited by linking charging processes to local energy production, which is referred to as self-consumption.

Another benefit of optimized charging processes is that battery ageing can be reduced if the respective information about the current state of the battery is taken into account by the charging management

and the user allows a slower charging with a lower power.
All these features of controlled charging strategies can be mapped to financial gains, thus they are likely to be more interesting than uncontrolled charging even from an economic point of view.

2 Profitability analysis

2.1 Regulations

In Germany the introduction of the EEG (renewable energy sources act) [1] and KWKG (combined heat and power act) [2] regulations in the year 2000 has triggered a massive increase in the share of renewable, distributed energy resources (DER). By prioritizing the feed-in of renewable energies and guaranteeing fixed feed-in rates for 20 years after construction, a high investment protection is reached.
A critical issue in the further development of DER is the limited grid capacity. Since grid expansions are expensive and take time, one aspect of the regulations is the dedicated support of self-consumption, thus reducing the grid load. Both German directives guarantee a higher compensation for electricity, which is used in immediate vicinity and at exactly the same time it is generated instead of fed into the public grid.

2.2 Smart home environment

The optimization potential of an electric vehicle operation connected to a smart home is assessed for different scenarios. In each case the smart home is equipped with a 5.5 kW_{el} micro-CHP plant in combination with a heat storage system and a 10 kW_p PV system (see fig. 1).

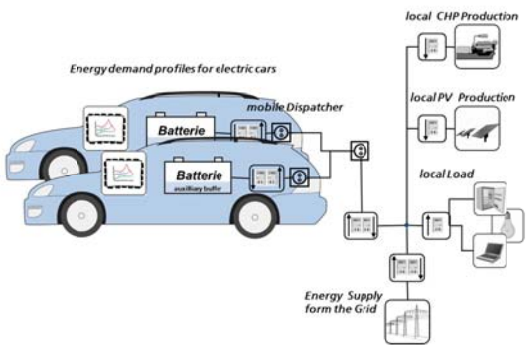

Figure 1: Relevant system components of the electric vehicles connected to a smart home

The electrical and thermal load profiles are measured data from terraced houses in Freiburg, southern Germany. The data set was taken from January to July 2008 at quarter-hourly intervals. The generation profiles of the PV system contains real data from an adjacent solar energy plant with 45 kW_p (DN 30° south) from the same period that has been scaled to match the scenario's 10 kW_p system.
The profile of the energy demand and availability of the electric vehicles has been created using data from the data set of the study "Mobilität in Deutschland" (MID, 2002) [3]. The study analyzed the mobility patterns of private households in different areas in Germany. A further benefit is expected for a bi-directional interconnection of the EV and the smart home (V2G), as this provides not only load shifting potential but buffering the locally generated electricity for a later usage. Since bi-directional chargers are not state-of-the-art, the simulation was carried out for both scenarios, uni- and bi-directional connection. In the latter case, the additional costs of battery degradation are considered in the model.

2.3 Modelling and optimization

Optimization goal is the maximization of the so-called contribution margin, which is defined as the sum of all revenues minus the sum of all variable operating costs.
The approach used in this paper for evaluating this complex scenario is a model-based optimization using mixed integer linear programming (MILP) algorithms. Besides the simulated components like CHP, low-temperature boiler, thermal and electrical storage streams of data are used for the modeling. This includes local requirements of mobility, generation data of the PV system, the current price per kWh, the different compensation tariffs as well as electrical and thermal load.
Exact rates and more details to the underlying technical constraints of the simulation can be found in [4].

2.4 Simulation results

Based on the models described above different scenarios were simulated to better understand the impact of the different compensation and marketing options.
The reference scenario considers a heat-operated CHP, while the generated electricity from PV and CHP is completely fed into the grid. The electric vehicles are being charged in an uncontrolled manner directly after arrival. The contribution margin in this first scenario was found to be -5039.- € (roughly -6700.- US$).

In a scenario, where both the CHP operation and the charging of the two EV is optimally controlled and synchronized, the contribution margin is reduced to -3016.- €, translating to a benefit compared to the reference scenario of 2023.- €.
If a bi-directional connection of the EV is available, an additional benefit of 95.- € is possible. Here, already the costs of battery degradation are considered. Selected results are summarized in table 1.

3 Vehicle to smart home concepts

3.1 Smart home's perspective

Full knowledge and control of each system component as well as reliable prognosis of load and generation are most desirable conditions for a home energy management. The consideration of an electric vehicle is difficult in many respects.

- Availability: The user behavior and thus the availability of the vehicle for energy management measures is difficult to predict.
- Importance of mobility: It is of vital importance to guarantee that the user's mobility is not affected by any energy management action in order to not compromise the user's acceptance of electric mobility. Hence the battery shall be charged at a given time, thus the utilization of the EV as an electricity buffer is limited.
- Technical properties like maximum power, uni-/bi-directional charging, usable capacity, charging behavior, state of charge, etc. must be known.
- For an economical optimization also the degradation and the costs per cycle, respectively, is needed.

3.2 EV's perspective

Since an EV is primarily used for mobility the battery should be charged at all times. The battery is the most valuable and at the same time most crucial part in a BEV. Battery parameters and especially charging behavior are well protected by OEMs. The availability of these parameters for an external usage is therefore not guaranteed. However, EV-specific information should be incorporated into smart charging strategies in order to achieve an optimal solution. This paper proposes to locate the smart charging engine in the EV and provide a means of asserting indirect control through variable tariffs. In the end, the EV and the battery management system resp. is the only instance controlling the charging. Lastly, in order to fully exploit its numerous advantages smart charging should be possible everywhere and not only at compatible smart homes.

3.3 Incentive system

To overcome these different requirements a control mechanism based on incentives has been developed at Fraunhofer ISE.
The core of the system is a mobile charging management system, fully integrated within the EV's control systems. This allows full knowledge about battery parameters and user preferences without sharing this information with the external world.
External input parameter is a variable tariff for electricity in both directions. These prices are computed by the smart home's energy management. They represent the availability of locally generated renewables and are supposed to trigger a predefined charging behavior of the vehicle. In return, the EV provides a charging schedule after the internal optimization. This

Table 1: Main simulation results of the optimized local operation and EV charging for the exemplary smart home test site in Freiburg / Germany.

Results of the local optimized operation and PHEV charging (two electric vehicles in an exemplary smart home with local PV system (10 kWp) and CHP system (5 kWel))		Simulation period January till July in **2010**	**2015**	**2020**
Contribution margin benefits through optimized operating & charging strategies, instead of feeding the locally produced energy into the grid	in €	2023	2939	4550
Additional contribution margin benefits with the V2G option	in €	95	286	620
Energy supply from the grid	in kWh	3518	2351	1966
PV energy used and stored in both EV	in kWh	142	728	1117
CHP energy used and stored in both EV	in kWh	2467	3144	3355
V2G feeding from both EV	in kWh	1284	2505	3051
Battery degradation costs by using the V2G option	in €	95	140	123

schedule is an important input parameter for the following iterations of the home energy management system or – in case of a public charging spot – for the grid operator.

4 Implementation and evaluation

4.1 The concept of decentralized optimization

The main reason not to implement a central control within the Smart Home but the EV itself was that the optimization should take place where most of the input data actually arises, i.e. the degrees of freedom that the current state of the battery and charger of the EV offer and the user input. To enable the EV to decide on an optimized charging strategy the following functions have to be implemented in the EV itself: bi-directional metering of energy flows, communication with control units within the EV as well as external communication, a fast optimization algorithm to determine a charging schedule at optimal cost and a software framework to monitor the charging process and update the underlying charging schedule if necessary.

All these functions have been implemented within a control unit called the mobile Smart Meter (mSM). As shown in fig. 2 the mSM takes the current status from the battery management system, the user input and the electrical characteristics as well as the variable tariff signal from the charging infrastructure to create an optimal charging schedule. The algorithm used to create this schedule is introduced in section 4.2. The charging schedule then is communicated to the battery management system which in turn controls the charger. Since the mSM is enabled to monitor the energy flows in and out of the vehicle the compliance of the actual charging behavior with the optimal schedule can be evaluated. An updated schedule is created if certain battery parameters prevent the original schedule from being followed through.

Since the current charging schedule is also communicated to any upper level system, e.g. a smart home, it is ensured that the charging behavior of the EV is known in advance but no vehicle-specific data or implementation details have to be made available.

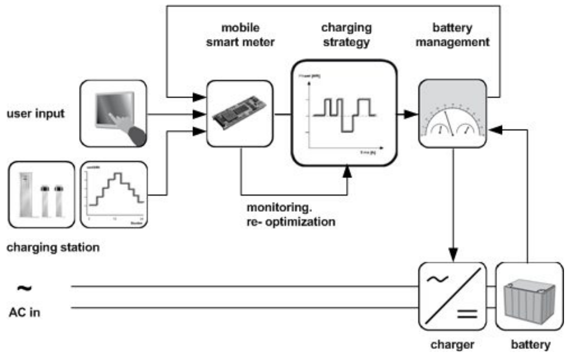

Figure 2: The mobile Smart Meter (mSM) Control of the charging process with the mobile Smart Meter (mSM)

Thus the sphere of the upper level energy management system and the EV implementation are not interlaced but communicate only via the variable tariff signal as the main reference value to exert control over the EV's charging behavior and the charging schedule that contains all the necessary information to predict the EV's charging behavior.

4.2 The optimization algorithm used

The input values for the optimization algorithm stem from the battery management system (current and maximum battery capacity as well as maximum charge and discharge rate), the user input (time and length of the next trip, where the latter results in a target battery capacity) and the charging infrastructure (maximum available charge and discharge rate and the tariff signal).

The variable tariff signal communicates the availability of energy from renewable sources as well as the situation in the local grid. It may be updated on short notice in order to trigger a response from the EV that is beneficial for the grid operation, i.e. that implements demand-side-management or vehicle-to-grid (V2G) options.

Important for the V2G option of feeding energy back to the grid are the battery degradation costs. Therefore highly simplified battery cost degradation models are used, e.g. a monotone decreasing function based on the depth of discharge (DoD). To allow for fast processing speed of the optimizer a graph search algorithm is used.

If assumed that the battery only charges and discharges exactly 1 unit of energy, the system can only be in M+1 different states at every time step where M is the max. capacity of the battery. If there are tmax time steps, a graph of (M+1)*(tmax) nodes can be created, where each node represents a state and a time. Then edges are introduced which represent possible state transitions. Each edge can be assigned certain costs/gains which occur through this transition, e.g. costs for charging, gains for discharging. Finding an optimal plan can then be solved by finding the best path from an initial node at time 0 to a node at time tmax. This method is also used for similar optimisationoptimization problems of energy systems with different components such as smart homes combining heat and power (CHP) plants, thermal storage and a heating system.

Fig. 3 shows a screen shot of a Java visualization for an exemplary charging schedule. The upper diagram shows the assumed variable electricity cost (red) and feed-in tariff (green), in the example both curves are related to the German reference load profile (SPL H0Winter-Workday).

Figure 3: Visualization of the optimized charging strategy as created by the graph search algorithm

Further assumptions in the example are the shaded input parameters at the bottom of the visualization. In the example, the EV arrives with a SoC of 10 kWh and approx. 26 hours later it has to be fully charged (20 kWh). A common German single phase grid connection point (max. ~3.5 kW) and the cost and cycle life of Li-Ion batteries given by the USABC goals are used.

The optimized charging schedule is illustrated in the lower two diagrams of the Java visualization applet. The black line in the central diagram shows the SoC. The green and red bars illustrate the amount of energy charged and discharged for each time step. At times when the tariffs for drawn energy are low, e.g. in the morning between 2 and 5 o'clock, the battery is charged fully. Furthermore the battery is charged at times when the energy prices are below the peak of the feed-in tariff so that energy may be fed into the grid at times of high feed-in tariffs, i.e. around noon or 8 pm. Energy is only fed back if the spread between electricity costs and feed-in tariffs is higher than the battery degradation costs. In the lower diagram the energy cost and benefit for each time step are illustrated. The total amount of the green and yellow bars stands for the money which could be earned by feeding energy back. The yellow part illustrates the battery degradation costs which are based on the simplified battery cost degradation models mentioned earlier. The green bar illustrates the profit and the red bar the cost for the consumed energy.

4.3 Results

A small batch of prototypes of the mobile Smart Meter is being used in a German field test to gather hands-on experience with the charging strategy outlined in this paper. Fig. 4 shows a screenshot taken from the related project's user web portal, showing two charging processes that took place on February 28, 2012.

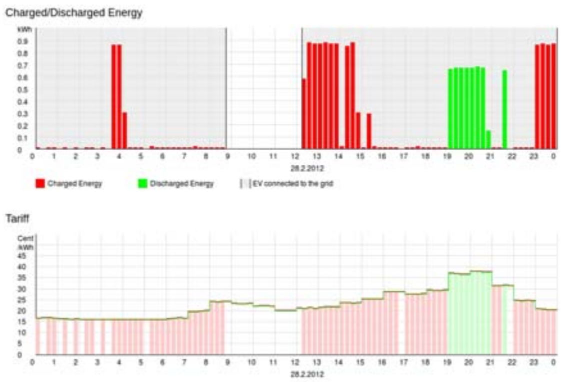

Figure 4: Screenshot showing the energy transfer (upper diagram) and the tariff used (lower diagram)

The upper diagram in fig. 4 shows the energy that has been transferred to (red) and from (green) the vehicle. The lower diagram shows the tariff signal of the respective day. The timeslots with energy transfers have been highlighted to allow for a quick visual connection of tariff value and energy transfer.

The charging process that took place during the second half of the day shows that the system works according to the concept outlined in this paper. Early in the charging process when the price of electricity was still low the battery has been fully charged. From 7 pm to 9 pm there was a timeslot where electricity was rather expensive, thus the EV fed electricity into the grid that was subsequently re-charged after 11 pm during another time of low prices.

This example shows that the charging process can be controlled using a variable tariff signal. This approach offers benefits not only for the user of the EV, who is enabled to optimize his charging budget, but also for further stakeholders like grid operators or utility companies who can indirectly control the charging behavior of an EV fleet.

5 Conclusion

In this paper the potential economic benefits of a controlled charging in a smart home environment is presented. The simulation of different control operation scenarios identified a significant optimization potential. Furthermore a reference implementation has been designed that acts as a proof of concept, showing that it is possible to locate the smart charging engine in the EV and control the charging processes by the means of variable tariff signals. The first results that have been gathered during a small-scale field test show that the charging behavior of the EVs can be controlled according to the needs of an upper-level system.

To integrate an EV with decentral decision making into a smart home environment the energy management of the smart home therefore only has to create a tariff signal to influence the EV's decision making. Since the charging schedule is communicated to the smart home the system can check the EV's reaction to the tariff signal and apply corrections to the tariff, if needed.

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