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Plug-in electric vehicles automated charging control

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Abstract

This paper examines how plug-in electric vehicles can be managed to balance the fluctuation of renewable electricity sources. In this context, different control strategies are introduced. To investigate indirect control via electricity tariffs, an electricity market analysis is conducted of a system with a high share of generation from renewable electricity sources. The analysis uses driving data collected from battery electric and plug-in hybrid vehicles in a research project which means that real charging and driving behavior can be considered. The results show that it is difficult to implement smart charging based on economic arguments because the incentives from day-ahead electricity markets are relatively small. In addition, a novel, autonomous control approach is discussed for plug-in electric vehicles. While measuring the voltage at the grid connection point, plug-in electric vehicles are able to fully independently generate operation schedules that can avoid load peaks and integrate fluctuating power outputs from distributed renewable generation sources. The results reveal that combining indirect, price-based control to consider the system level with autonomous voltage-based control to consider the situation in distribution grids is a very promising control approach that allows electric vehicles to benefit from sustainable renewable generation and avoids load peaks due to simultaneous charging.

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1   Introduction

This section provides the background to the research objective of studying the role of electric vehicles in a modern electricity system and introduces the research project in which large parts of this work were conducted.

1.1   Background

Plug-in electric vehicles (PEVs) are a promising option to increase efficiency in the transport sector, if these vehicles are powered with electricity generated by renewable energy sources (RES). In theory, using RES to power vehicles is a win-win situation. PEVs are ideal RES consumers because of their high electricity-to-wheel efficiency compared to fuel cell vehicles or those based on liquefying RES. RES installations benefit from PEV demand that could boost RES expansion. In practice, this interaction is more complex because the most promising RES – photovoltaic and wind energy – are fluctuating sources. The value that needs to be considered when combining renewable generation and PEVs is not the amount of energy available (in kWh) but rather the amount of power available (in kW) .

The far-reaching changes fluctuating generation will bring to modern electricity systems are illustrated in Figure 1.
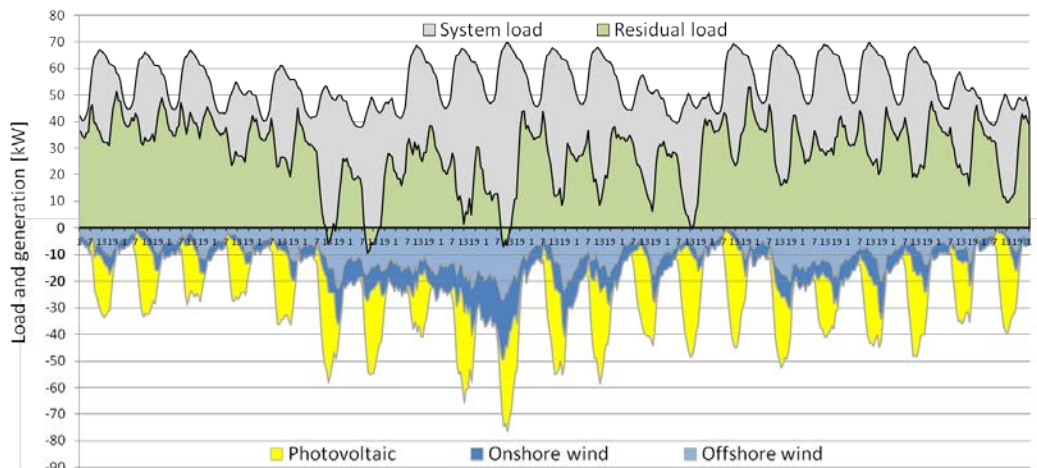

Figure 1: Example of the possible residual load situation for 3 weeks in summer, Germany, 2030

The diagram shows the fluctuating generation, the system load and the resulting residual load for an example scenario reflecting a likely situation in Germany in 2030. The residual load fluctuation for these three weeks in sum-

mer is mainly caused by the high installed photovoltaic capacity. Compared to the system load, huge ramp rates can be observed and, for some hours, the generation from fluctuating sources even surpasses the system load demand (negative residual load).

PEVs are able to balance the increasing fluctuation of the residual load by providing flexible charging loads and vehicle-to-grid services (V2G). This makes it possible to integrate RES into the energy system. To achieve this win-win situation, it is necessary to develop flexible control strategies that are able to manage the rapid changes in electricity systems with high RES shares.

1.2   The iZEUS Project

The Project intelligent Zero Emission Urban System – iZEUS was funded by the German Federal Minister for Economic Affairs and Energy. iZEUS is part of the funding program "Information and Communication Technologies for Electric Mobility II – Smart Car – Smart Grid – Smart Traffic". The project partners are ads-tec, Daimler, EnBW (coordinator), the Fraunhofer ISI and ISE, KIT, Opel, PTV, SAP, and TWT. Toyota and bridgingIT supported the project as associate partners. The main aim of the involved Fraunhofer institutes, the Fraunhofer Institute for Systems and Innovation Research ISI and the Fraunhofer Institute for Solar Energy Systems ISE, was to investigate to which extent controlled charging and discharging of PEVs can support the grid integration of fluctuating renewable generation. Large parts of the work presented here were conducted within the iZEUS Project.

1.3   Objective and procedure

The objective of this study is to investigate different control strategies for PEVs. The main intention of the control strategies is to combine PEVs and fluctuating renewable generation. This requires more flexibility than other common control methods such as time-of-use pricing or load shifting to nighttime hours. The paper is structured as follows. First, possible control methods are introduced and discussed (Section 2). Second, real PEV driving data from the iZEUS field trial are presented and analyzed because PEV-drivers' behavior determines the potential to balance the system. The applied simulation methods and results are then presented and the main conclusions discussed.

2   Charging control methods

Different control methods are discussed to avoid load peaks due to charging PEVs and to make full use of their demand response potential for balancing the electricity system. Three main methods can be distinguished to control distributed generation units and flexible loads: direct control, indirect control and autonomous distributed control. The three methods are described in the following section.

2.1   Direct control

Direct control is a common method applied in conventional power systems consisting of large power plants and transmission grids. Power plants or large pumped-storage hydro plants are controlled to meet demand from a centralized objective. Exact operation schedules are defined by a utility and implemented by the controlled generation units. Where PEVs are concerned, this means the operating schedule is defined by a third party outside the vehicle (e.g. a system service provider or the utility). This implies the necessity to communicate to this third party specific information about the battery such as the state-of-charge, capacity and battery health requirements as well as information about consumer preferences such as the electric range buffer, next expected trip and willingness to participate in smart charging programs. The information from several PEVs is collected and a charging schedule is generated for each unit and returned to the vehicle. This method enables almost perfect control of PEVs while considering the operation of other PEVs and power plants.

To explain the possible disadvantages of direct control in the case of small units connected to distribution grids, it is necessary to look at the general changes taking place in the electricity system and the characteristics of more distributed energy systems. Recently, the share of distributed generation units has risen sharply. In particular, massive price drops and subsidies for photovoltaic systems have boosted the shares of small-scale generation units. In contrast to conventional power plants, these units are often connected to the distribution network and not to the transmission grid. Further, generation fluctuates according to weather conditions as in the case of photovoltaic systems and wind turbines. The situation in conventional, load-based distribution grids is predictable with a very high degree of certainty. Adding distributed generation and flexible loads to the distribution grid makes the situation much more complex.

To realize direct control of PEVs that are connected to the distribution grid, it is necessary to have not only information on a system level (transmission grid/ day-ahead market) but also information on the local situation (distribution grid). This information can be provided for a small closed system such as a smart home (KIT, 2014), but collecting all the information for larger areas with many loads and generation units requires a significantly greater effort. In the past, collecting such data was too expensive and also of limited interest because very few controllable devices were available in distribution grids. However, due to the progress made in developing advanced information and communication technologies, this topic is again becoming of interest within the topic of smart grids, but it is still unclear which applications are economically feasible.

With regard to the very limited information available on the distribution grid level and the small scale of PEVs, applying a direct control approach to PEVs will be more complex than, e.g. controlling a pumped-storage plant connected to the transmission grid. Further, the main purpose of PEVs is to provide mobility. This results in restrictions on the power storage availability and state-of-charge reductions (energy use for driving) that need to be communicated to an external control instance. The communication of vehicle-internal and consumer data is a big issue. The big car companies accept neither the communication of battery data nor charging schedules set by a third party. It is also doubtful whether consumers will agree to communicate their driving habits. The communication of sensitive data therefore represents a major obstacle to direct control of PEVs.

Disconnecting loads is a simplified direct control approach that does not necessarily require bidirectional communication. It is common to disconnect grid areas in case of significant breakdowns in order to stabilize the system. Disconnecting all PEVs could be a possible control approach to avoid the breakdown of a larger grid area.

2.2   Indirect control

Indirect control is realized using incentives and is already being applied to control PEVs in California (Pacific Gas and Electric, 2014). Incentives can be provided as time-of-use (TOU) or other electricity tariff designs such as critical peak or dynamic tariffs. The tariff reflects the power system's status. In contrast to direct control methods, here, the consumer or a device programmed by the consumer can decide whether to react to the incentive or not. Hence, the operating schedule is set by a local controller within the vehicle, where information on the vehicle battery and the driver's preferences are available without the need

for vehicle-external communication. For this reason, the car companies' acceptance of indirect control is generally higher. The final control decision, however, remains in the hands of the drivers, which probably increases acceptance but also requires their active participation.

The main challenge associated with such indirect control is how to create the right kind of tariff. For successful control of PEVs, the tariff should reflect the situation on a system level as well as the local grid. The system level's status is represented by day-ahead or intra-day electricity market prices. No information is available for the local situation. Tariffs that represent the specific situation of local grids are rare. In addition, any widespread simultaneous reaction to a tariff could also result in peaks if only one tariff is used to control many PEVs (for further information, please refer to Schey et al., 2012 and Dallinger et al., 2013). Therefore, one challenge from using indirect control is being able to predict PEVs' reaction to the control signal. The possibility of forecast errors reduces the reliability of indirect control compared to direct control, but the fact that it does not require bidirectional communication[1] (no communication of the vehicle to the backend system) is an advantage.

In the context of integrating fluctuating renewable generation, tariffs based on day-ahead or intra-day markets are best able to reflect the supply of renewable generation units on a system level. Due to their very low marginal generation costs (Sensfuss, 2008), a high share of fluctuating renewable generation results in a reduction of the electricity prices (due to the merit-order effect). Hence, the market mechanism of today's electricity markets already provides incentives to charge PEVs when the supply of renewable energy sources is high.

2.3 Autonomous distributed control

The main characteristic of autonomous control is the lack of an external control signal; vehicles only use internal sensors. In the case of smart charging, this is mainly realized by measuring the voltage and the frequency. Negative frequency and voltage deviations indicate the need for more power generation or less consumption. Vice versa, positive frequency and voltage derivations indicate the need for less power generation or more consumption. Hence, both

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[1] If onboard metering is available, the vehicle could support the billing process and send information once a week or month (not real-time).

frequency and voltage indicate the current status of the electricity system and can be used as control signals.

The concept of autonomous control is already widely realized. Big power plants adapt their generation to stabilize the frequency on a system level (primary control markets). The net frequency is the same for all nodes in the network and all grid levels (transmission grid and distribution grid). Consequently, frequency is an indicator for the entire network. A frequency-based control approach to PEVs was introduced by (Yang et al., 2013).

On a distributed grid level, generation units such as photovoltaic systems adapt their generation or disconnect at certain voltage or frequency levels. Furthermore, in many microgrids, the autonomous control of generation and storage units is a common approach. The voltage in distribution grids is sensitive to local changes in generation and load and is affected by the patterns of fluctuating generation units as well as local consumers. As a result, measuring grid voltage provides information about the local situation that can be used by PEVs to optimize their charging behavior in terms of integrating renewable generation and avoiding peaks caused by simultaneous charging.

2.4   Discussion

It is not yet clear which control strategy will prevail for PEVs. In practice, it is likely that different control strategies will be combined to realize the control goals for different applications and operating conditions. The main advantages and disadvantages of the different control strategies are summarized in Figure 2.

The authors believe that the question, "Who defines the charging schedule?" is crucial. Both car companies and utilities demand to control the vehicles' operation. Ultimately, we think that car companies or vehicle owners will make the final decision about the charging schedule. This is because utilities cannot determine the vehicles' design or communication protocols. Even the charging infrastructure at the most important charging location – at PEV users' homes – cannot be directly influenced by the utilities. From a market perspective, it is also clear that the supply side and the demand side should be separated (unbundling). Hence, flexible loads act as competitors to utility-owned generation units. From this point of view, direct control by utilities or a third party can only be an option as the last resort to avoid a power blackout. In addition, the local generation of operating schedules implies they are controlled in the vehicle

or by another device owned by the consumer (e.g. a smart phone or computer). From a technical point of view, this means that charging infrastructure can be kept simple. Controllers, grid monitoring technology and communication units could be directly implemented in the vehicles. For these reasons, in the iZEUS project, the Fraunhofer Institutes ISE and ISI focused on autonomous (considering the local situation) and indirect control (considering the system level) as the most promising options to intelligently connect PEVs to the grid.

Strategy	Utility	OEM	Consumer	Advantages	Dis-advantages
Direct control	Defines the charging schedule	Provides vehicle and battery data	Provides information on the expected driving behavior	Perfect control	Acceptance of users and OEMs is questionable
Indirect control	Competitors	Provides control signal (Tariff)	Defines the charging schedule	Less communication effort	Load estimation, with the possibility of forecasted errors necessary
Autonomous	-	Grid monitoring	Defines the charging schedule	Simple charging infrastructure	Additional hardware to measure the voltage is needed

Figure 2: Overview of control strategies[2]

3 Driving and charging behavior

How vehicle batteries are used is an important factor for PEVs' total costs of ownership as well as their ability to provide grid services. Many regular trips with a high share of electric driving increase the fuel savings compared to a conventional vehicle and help to recoup the higher investment costs of PEVs. From an energy management perspective, higher electricity use results in a higher amount of energy available for load management. Large amounts of energy make load management more attractive but also reduce the degree of freedom, because longer charging times are required that reduce the period during which the vehicle can provide grid services. Hence, driving behavior is the major factor that determines the operation and possible profits of PEVs on

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[2] OEM: Original Equipment Manufacturer

energy markets. In the following section, the specific driving behavior of the vehicles involved in the iZEUS test fleet is analyzed.

3.1   iZEUS test fleet

The iZEUS test fleet consists of purely electric and plug-in hybrid vehicles. Overall, more than 60 vehicles were involved, provided by Daimler AG, Opel AG and the Toyota Motor Corporation. The incentive to participate in the research project was a reduced battery leasing rate and a navigation applet provided with a Tablet computer. In the following analysis, real driving data were used from 28 Daimler Smart Fortwo electric drive and 3 Toyota Prius PHVs. For both vehicle types, logging data are analyzed from the time period October 1st, 2013 to June 30th, 2014using vehicle internal systems provided by the Toyota Motor Corporation and Daimler AG. The vehicle data are summarized in Table 1.

Table 1:   Overview of iZEUS vehicle fleet

Parameters	Smart fortwo electric drive	Toyota Prius PHEV [2]
Battery	17.6 kWh	5.2 kWh
Efficiency[1]	0.148 kWh/km	0.139 kWh/km
Number of vehicles	28	3
Electric range/ longest trip	119 km/ 93 km	18 km/ 240 km
Ø trip duration/range	0:11/ 6.9 km	0:16/ 12.7 km
Test period	1 Oct. − 30 June	1 Oct. − 30 June

[1]Own calculation   [2] Pre-series vehicle

The Smart Fortwo is a purely electric two-seater with a usable battery capacity of 17.6 kWh. The electric range is about 119 km at a driving efficiency of 0.15 kWh per km. The Smart BEV's driving efficiency strongly depends on the usage of auxiliary equipment such as air conditioning and heating[3]. The maximum single trip range realized within the investigation period was 93 km. The smart vehicles were located in the areas surrounding Stuttgart and owned by companies and private users. Exact information on the charging infrastructure of individual users is not available.

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3   Driving efficiency quantile = 9.9 kWh/100km (alpha =0.2) and

    quantile = 19.3 kWh/100km (alpha =0.9)

The Toyota Prius PHV is a pre-series, mid-size vehicle based on the third Prius generation. The battery capacity is 5.2 kWh. The purely electric range is about 18 km and the efficiency is 0.14 kWh/km. The vehicles were lent for 6 weeks mainly to full-time employees from the Karlsruhe Institute of Technology as well as the Fraunhofer ISI and Fraunhofer ISE, who included administration and research workers. The Prius vehicles were located in the areas surrounding Karlsruhe and Freiburg. Charging infrastructure was available at the workplace. Exact information on the availability of charging infrastructure at employees' homes is not available. It is assumed that more than 50 % of the employees who used the vehicles were able to charge at home. Other public infrastructure provided by the utility EnBW AG was available (EnBW, 2014).

3.2 Driving data evaluation

Data are evaluated separately for the Prius PHV and Smart Fortwo. This could provide some first indications of whether BEVs and PHEVs are used differently. Given the limited data available, the difference in vehicle type (mid sedan versus small vehicle) as well as the different users and use cases, the evaluation can only indicate preliminary conclusions when comparing BEVs and PHEVs. Nevertheless, the data do reflect real PEV driving behavior and are therefore of high research interest.

The 28 Smart vehicles involved in the evaluation conducted 19,415 trips with an overall range of 134,715 km and an average trip range of 6.9 km. The average estimated yearly driving distance is 6,286 km per year (minimum 1,566 km/a; maximum 16,861 km/a). The 3 Prius PHVs realized 1,090 trips with an overall range of 13,854 km. The average range per trip is 12.7 km and the average estimated yearly driving distance is 9,554 km per year (minimum 8,465 km/a; maximum 11,286 km/a). The average yearly driving distance in Germany is between 12,000 and 14,000 km per year.

The trip range is an indicator for how vehicles are used. The accumulated frequency of different trip classes is illustrated in Figure 3 for both the Smart and Prius vehicles in iZEUS, as is the German average taken from the survey Mobility in Germany (MID, 2008). The German average and the Prius PHV driving behavior are similar for many trip classes. Only for trips shorter than 10 km do the Prius data have slightly higher frequencies than the German average. The reasons for this are unclear. It could be because of the specific user segment, the novelty of vehicles that results in short test drives, or a type of rebound effect. A reduction in the number of trips by bicycle or on foot in favor of

trips using PEVs might be motivated due to participating in a research project, the environmental benefits of PEVs or again simply by the novelty of the vehicles.

There are a higher number of trips between 2 and 20 km observed for the Smart BEVs. This could be because of the vehicle's characteristics (small size, two-seater), the specific user segment and/or the limited electric range of 119 km. Again, it is not possible to offer conclusive reasons for the differences in behavior.
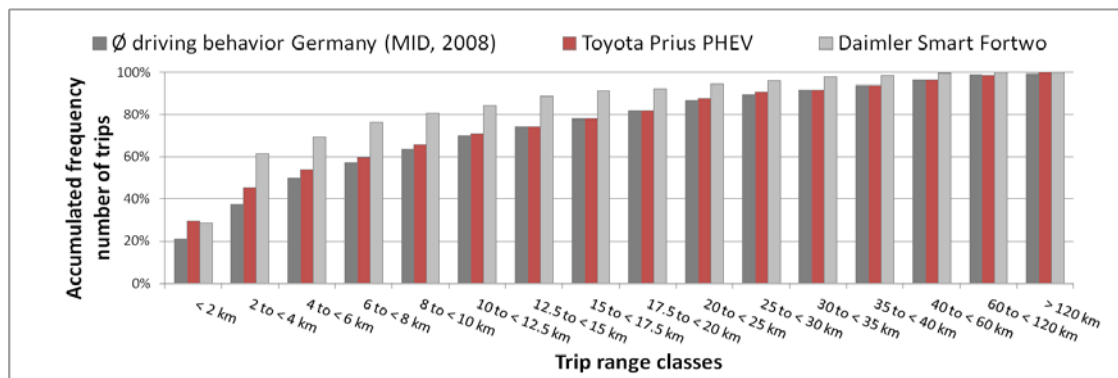

Figure 3:   Accumulated frequency of trip range in iZEUS versus German average

Figure 4 illustrates the total mileage share of different trip range categories and clearly shows which trip classes contribute most to the total mileage driven by the vehicles. In case of the Smart vehicles, trips with a range below 30 km make up nearly 80 % of the total kilometers driven. These vehicles do not fully use their total potential electric driving range of 119 km. It is not clear whether the Daimler Smart users also had access to an additional vehicle and consequently only used the Smart to realize short trips. To further investigate this issue, Figure 4 also includes the driving behavior of a single Smart BEV that has one of the highest utilizations in the fleet trial. For the single Smart BEV, the trip class 30 to < 35 km contributes a high share to the total mileage. This is a strong indication for a regular/daily trip in this range class (e.g. to the workplace or to the workplace and home again). For the Prius PHV, trips below 30 km only represent about 50 % of the total mileage. About 20 % of the Prius' total mileage comes from trips longer than 100 km.
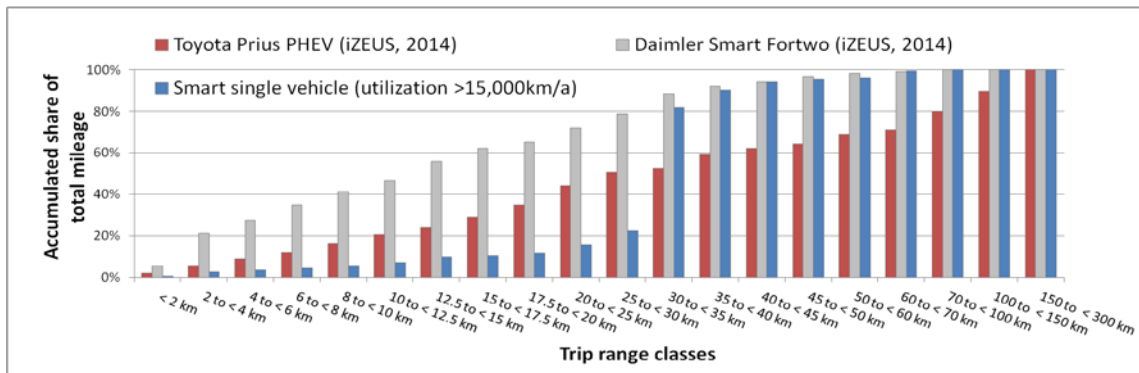
Figure 4:   Accumulated share of total mileage for different trip range classes

The relatively low utilization of the Smart vehicle battery is also demonstrated in Figure 5.
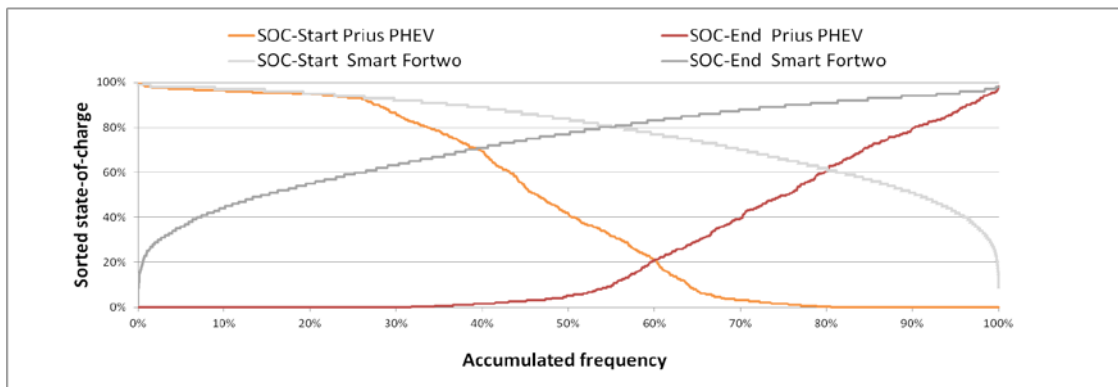

Figure 5:   State-of charge before starting a trip and when ending a trip.

Figure 5 shows the state-of-charge when starting[4] a trip and ending[5] a trip for the Smart and Prius vehicles. For both vehicle types, the battery is fully charged (SOC > 95%) before a trip in about 20 % of all cases. The Prius starts 30 % of trips with a fully discharged battery, whereas the Smart ends less than 10 % of trips with a battery discharged more than 40 %. In other words, 40 % of the Smart BEV's battery is not or only rarely used.

3.3 Charging behavior

Charging and driving behavior are closely related. From an economic point of view, frequent charging results in fuel savings for PHEVs and a higher daily

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4 SOC-Start: Sorted in descending order

5 SOC-End: Sorted in ascending order

driving range for BEVs. Therefore, unlike conventional vehicles, regular daily charging is expected for PEVs. Here, especially the basis location of the vehicles (at home for private users and at the company/workplace in case of business/private users) plays an important role. In iZEUS, the charging location was not logged for all vehicles.

Furthermore, the availability of infrastructure is not entirely clear. For the Prius vehicles, infrastructure at the user's workplace was available in all cases and additional infrastructure at home in many cases.

Charging behavior is captured by changes in the state-of-charge (SOC). The following analysis shows the charging results for the iZEUS fleet. Figure 6 illustrates the accumulated trip frequency and the driving range before charging. This again shows a much more restrictive use of the battery for the Daimler Smart. In 80 % of all trips, the battery is charged after a range of less than 20 km. This frequent charging implies that only a low amount of energy (about 3 kWh for 20 km) is charged and therefore charging times are mostly shorter than one hour.
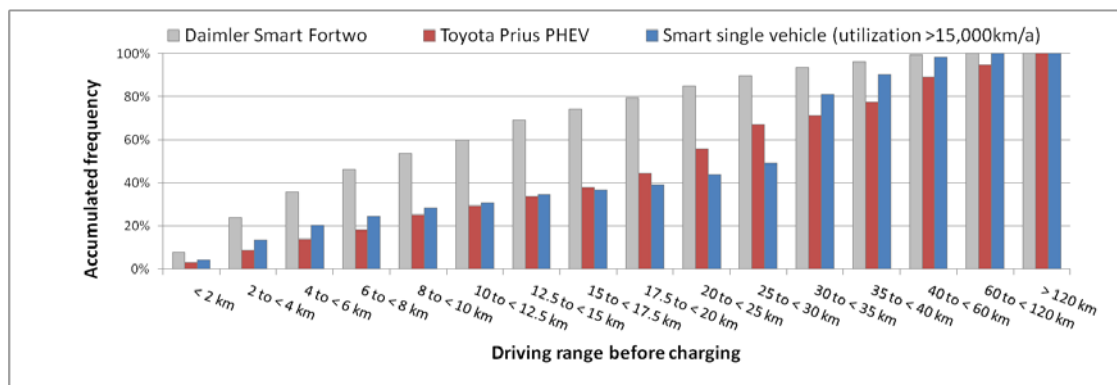

Figure 6:   Frequency of driving range before charging

Prius PHV users do not charge as frequently after short and medium mileages as the Smart users. One reason is the general tendency of Smart BEVs to make short trips. Further, it seems that Smart BEV users are very keen to avoid a restricted driving range due to a discharged battery. Reanalyzing the high utilization of the single Smart BEV for short trips shows that the behavior is similar to the Prius users. This user seems to be much more confident about the vehicle's electric range. The steep rise in frequency in the range class 30 to <35 km again indicates that the user makes a regular trip in this range class. Further, it seems the user has the opportunity to charge after this trip.

The observed average charging behavior on weekdays is given in Figure 7. Three different load curves are shown assuming a charging power of 4 kW per PEV. The German average is represented by the black line and simulated using average driving behavior (MID, 2012) as well as "last trip charging" strategy (Dallinger, et al., 2012).
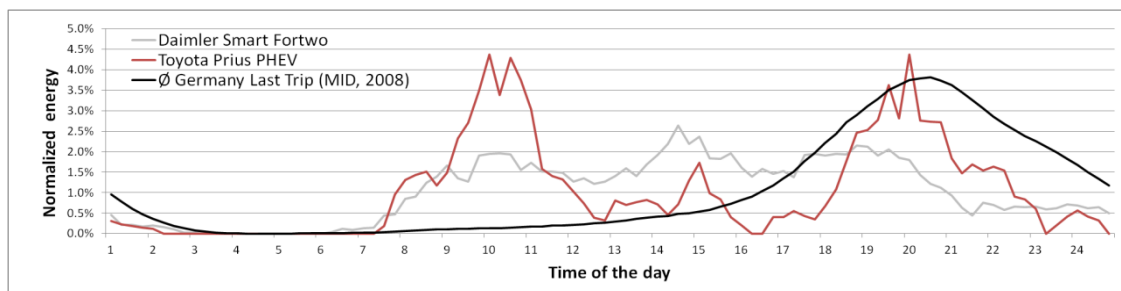

Figure 7:   Load curve for an average working day of different PEVs with 4 kW
            charging power

The peak in the early evening is typical for last trip charging. The load curve of the Prius PHVs' users shows two main peaks. The expected load peak during the evening/after arriving at home and a second load peak after arriving at work. The morning work peak is as high as the evening home peak and could represent a second serious challenge to uncontrolled charging in case of a significant market diffusion of PEVs. Especially in the case of PEVs equipped with small batteries,[6] it is likely that PHEVs' users will increase their electric driving share due to a second charge at work. This causes strong simultaneous charging behavior when employees arrive at the workplace. In the iZEUS fleet trial with Prius users, the work arrival peak is enhanced by the availability of infrastructure at work, the user group of mainly full-time employees and the possibility to charge for free. Nevertheless, a work arrival peak is a likely future scenario that needs to be considered. The load curve of the Daimler Smart users does not show significant peaks and fluctuates only slightly from the morning hours to the early evening with a small peak at 3 o'clock in the afternoon. The Daimler Smart user group consists of private and business users. The flat load curve could be explained by business users charging during working hours as well as the high frequency of short trips that result in short charging times.

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6   The pre-production Toyota Prius PHV used in iZEUS has an electric range of 14 – 18 km
     with a usable battery size of about 2.5 kWh.

3.4   Discussion

Evaluating the real driving data collected in the iZEUS project allows the following conclusions to be drawn.

Representativeness of the data: It is not clear how representative the collected data are to describe the future driving behavior of PEVs. The Smart BEVs were purchased[7] by private and company fleet test participants. The relatively low average mileage indicates that most vehicles are not being used economically. Hence, other reasons seem to dominate the decision to buy during this early phase of BEVs' market diffusion. For companies and tech-savvy users, this might be their high-end technology image. The data are therefore probably only representative for early adopters of a new technology and not for future markets with higher volumes.

The Prius PHVs are lent to users with free charging at work and, as a result, only the additional operating costs are covered by the users. Consequently, each user stood to benefit from utilizing the Prius PHV instead of their normal vehicle. This fact and the evaluation results comparing the Toyota Prius data with average German driving data (see Figure 3) are indicative for a usage similar to conventional vehicles. Whether this would also apply to the usage of self-owned PHEVs cannot be determined.

State-of-charge utilization: The Daimler Smart's battery is utilized in a completely different way to that of the Toyota Prius. This is obviously due to the different battery size, but also to driver behavior. It seems that BEVs are charged more frequently to a SOC of 100 % and are only rarely discharged below 40 %. This provides very important information for the design of the usable battery capacity. For BEVs, the upper boundary of the usable SOC is more important. Here, a bigger buffer is necessary to reduce the calendar life aging that can result from fully charged batteries. At least for the behavior observed in the trials, deeper cycles that reduce battery cycle life are not a big issue for the batteries of the participating BEVs. For the participating Toyota Prius PHVs, the SOC is fully charged and discharged in equal proportions (about 30 %) at the start of a trip (see Figure 5). Here, both usable SOC boundaries seem to be equally important.

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[7] The battery could be leased.

Range anxiety: It cannot be determined whether Smart BEVs' users are worried about the vehicle's limited range. Nevertheless, their frequent charging compared to the Toyota PHEVs with a similar availability of infrastructure indicates that a fully charged battery is of greater interest to BEVs' users. This could be because BEVs' users plan trips with higher accuracy to guarantee a charging opportunity at the point of arrival, or because they want to ensure as large a driving range as possible. The specific charging behavior could also affect the smart charging capabilities of BEVs. The differences in charging behavior between BEVs and PHEVs are not yet part of the scientific discussion, but are of great interest for further research.

Load curve shape: The shape of the load curve is important to quantify the effects of PEVs on the grid and whether additional power plant capacities are needed to meet PEVs' demand. The observed charging behavior is different to previous assumptions made about charging PEVs. The Smart BEVs' load curve rises between 8 and 9 o'clock in the morning and remains level during the day before falling between 8 and 9 o'clock in the evening. The shape is similar to instant charging behavior. The impact here is much smaller than for simulated German average last trip charging and the Prius PHVs' charging behavior. The Prius PHVs' load curve is characterized by the typical evening peak and a work arrival peak. This can be explained by the specific design of the fleet test and the availability of charging infrastructure. Nevertheless, these results are very important because they show how sensitive charging behavior can be and that it is necessary to consider uncertainties in the shape of the load curve.

4 Simulation of charging control

The following sections present the simulation methods and scenarios.

4.1 Method

The PowerACE model and a grid simulation tool are used to model how PEVs affect the overall electricity system and local grids. PowerACE is an electricity market model that can be applied to investigate how fluctuating renewable electricity generation affects electricity spot market prices. The incentive-based indirect control strategy uses prices as control signals (see Section 4.1.1).

The grid tool is used to investigate autonomous distributed control. Because electricity spot market prices only represent the overall situation within the

electricity system, an additional local control component becomes a possible control option. The basic idea is to monitor the situation in the local grid and to use this information to decide how to charge or discharge the PEVs' batteries. This method is introduced in Section 4.1.2. In practice and also in the PowerACE simulation environment, it is possible to combine both control strategies. In the following, the control strategies are discussed separately. The indirect control method focuses on the incentives for PEVs' users in a 2030 scenario. The section on autonomous charging focuses on the basic principle of autonomous control for PEVs.

4.1.1   Indirect control

PowerACE is an electricity market simulation model that includes an agent-based indirect control mechanism for PEVs (Dallinger et al., 2012). The modeled electricity prices represent the basis to control PEVs via dynamic pricing and are used to calculate the savings due to smart charging and V2G.

Electricity prices for a scenario with a high share of RES generation are calculated using the agent-based simulation model PowerACE (Sensfuss, 2007). This model provides a detailed representation of the German electricity sector and simulates the electricity spot market. Spot market prices are calculated on an hourly level for an entire year. The merit-order follows the marginal electricity generation costs of power plants, which are mainly comprised of fuel and CO_2 prices as well as start-up costs. For intermittent renewable energy generation, the variable costs are assumed to be zero. Hence, prices are low in hours with high renewable power supply or a low residual load. This merit-order effect (Sensfuss et al., 2008; Nicolosi et al. 2009) of intermittent renewable energy generation in a uniform price auction is one possible reason for higher price spreads and price fluctuation in energy systems with a high share of renewable generation.

Vehicles are modeled as agents receiving a control signal that consists of a price forecast of the electricity auction (Dallinger et al., 2012). A graph search optimization algorithm is used to find the charging spots with the lowest price (Dallinger et al., 2014). The optimization time period is given by the driving behavior, which is taken from the Daimler Smart BEVs and Toyota PHEVs participating in the iZEUS project. In terms of charging strategies, two cases are distinguished. In the first case, real PEVs' charging behavior is used from the PEVs participating in the iZEUS project. In the second case, smart charging is applied based on the price signal provided by the PowerACE market simulation.

The introduced simulation model makes it possible to examine the possible savings and control incentives of PEVs. The method is used to investigate a 2030 scenario and captures the effects of fluctuating generation on electricity prices as well as the real driving behavior of PEVs' users collected during the iZEUS field test.

4.1.2   Autonomous distributed control

The principle idea behind autonomous control is to monitor the grid and use this information to manage charging and V2G operation. Especially in distribution grids with a high share of fluctuating renewable generation, local monitoring could be advantageous because it becomes more complex to predict the situation. Possible monitoring measurements are the frequency and the voltage at the PEVs' grid connection point. In the following, the voltage is used as an indicator because it represents the local grid situation to which the vehicle is connected.

Autonomous voltage-based control could be applied as a stand-alone control or to supplement other control methods. The stand-alone option allows grid-conform charging to be realized without any third party intervention. Specific hardware or communication on the grid side is not required. A relatively simple autonomous control system implemented only in the PEVs undermines the argument of network operators that too many PEVs harm the grid. As an extension of already implemented charging control methods such as time-of-use (TOU) or other price-based indirect control methods, autonomous control can compensate possible disadvantages. The most obvious is to even out the simultaneous reaction of PEVs to time-of-use prices that is already being observed in California (Schey et al., 2012) and investigated using simulation approaches (Dallinger et al. 2013, pp. 676).

The voltage in the grid is affected whenever one or several vehicles charge or discharge their batteries. Charging results in a drop of the voltage, whereas discharging causes the voltage to rise. This also applies to other consumers and distributed generation such as photovoltaic systems. Voltage in the low voltage network should be kept in the range of plus/minus 3 % of the nominal voltage.

Possible options (O) to stabilize the grid using PEVs are given as follows:

O1: Reduce the active charging power. No reactive power is provided (cos phi =1). The reduction of charging power results in a lower voltage drop due to

charging but also causes a charging delay because of the reduced charging power. In many cases, especially for charging at home and work, increasing the charging time is not an issue for the consumers because the PEV standing time is more than sufficient to charge the vehicle even at reduced power.

O2: Provide V2G and feed power back into the grid. No reactive power is provided (cos phi =1). The battery is discharged and the voltage in the grid is increased. V2G is not common in today's PEVs. Therefore, this option is less likely. Further V2G results in additional losses due to discharging the battery and to additional battery wear out. Hence, energy-based billing or other compensatory payments are needed to provide V2G.

O1.1: Providing inductive reactive charging power. Inductive power results in a voltage drop. Hence, inductive charging enhances the drop in voltage effect due to charging. The application of this charging strategy is therefore limited to situations with high distributed generation or overvoltage.

O1.2: Providing capacitive reactive charging power. Capacitive power results in a voltage rise. This charging strategy helps to reduce the voltage drop due to charging. Hence, in a situation with too much demand in the grid, capacitive reactive charging enables a higher power to be used without violating the low voltage boundary.

O2.1: Providing inductive reactive V2G power. Feeding power back causes a rise in voltage. Inductive V2G power reduces the rise in voltage. Hence, in situations with high supply from V2G and/ or distributed generation, inductive reactive power enables more power to be fed back.

O2.2: Providing capacitive reactive V2G power. Capacitive V2G power enhances the voltage-increasing effect of feeding power into the grid. The application of this V2G strategy is therefore limited to situations with high demand and low voltage.

O3 and O4: Providing inductive (O3) or capacitive (O4) reactive power. Besides providing both real power and reactive power at the same time (O1.1, O1.2, O2.1 and O2.2) as well as only real power (O1 and O2), another possible strategy is to only provide reactive power (O3 and O4). If PEVs are connected to the grid, they can help to stabilize it by providing inductive reactive power, which reduces the voltage, or by providing capacitive reactive power, which raises the voltage. The effects are rather small but the strategy can be beneficial in some situations or specific grids. Further, providing reactive power

is associated with losses due to the power electronics but does not result in battery wear out (Ehsani et al., 2012).

Grid simulation based on a non-linear equation system and an iterative approach is used to examine the described autonomous control strategies. The grid simulation is done quarter hourly and based on the Gauss-Seidel method (Schwab 2009, pp. 968).

The voltage level in each time step is calculated in a first grid simulation without PEVs. The resulting voltage values then form the basis for the autonomous control strategy. A second grid simulation includes the charging or V2G operation of the PEVs. The share of real and reactive power is adjusted according to a linear function of the voltage (see Figure 8). To provide an example the function for actual capacitive reactive charging power is given in the following Equation.[8] The actual capacitive reactive charging power (operation O1.2) share $Q_{cap,y}$ is calculated according to Equation 1.

$$Q_{cap,y} = (1 - V_x) * \frac{Q_{max}}{(1 - V_{min})} \quad \text{For voltage } V_x > V_{min} \text{ and } V_x < 1 \text{ [p.u.]} \qquad \text{Eq. 1}$$

Where V_x is the actual measured voltage, Q_{max} is the maximum reactive power that can be provided and V_{min} is the lower voltage boundary. V is given in the per unit system (p.u.). For voltage values lower than V_{min}, Q is constant and is set to Q_{max}.
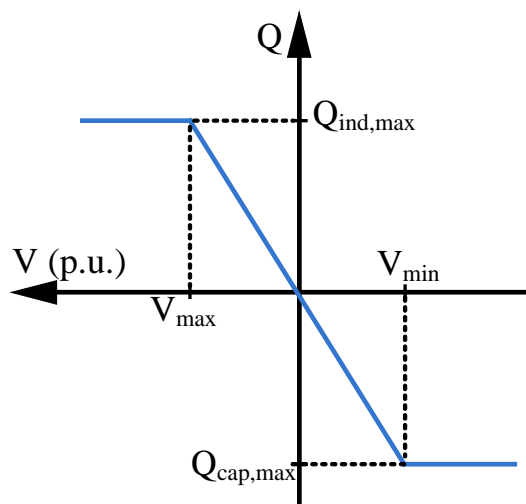

Figure 8:   Reactive power provided by PEVs based on node voltage level

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[8]   For inductive charging and V2G cases, a simple adaptation of the equations is necessary.

The results of the second grid simulation with adapted charging and discharging are used to quantify how autonomous charging can contribute to stabilizing the grid.

If the autonomous control strategy is used in combination with optimized price-based operating schedules (indirect control), it is necessary to compensate the energy used for the autonomous control services. For example, if capacitive reactive charging power is provided, it would be necessary to extend the charging period, because the real charging power is reduced by providing reactive power. In this case, additional charging time slots in the price-based optimization are needed to guarantee that the battery is fully charged within the charging schedule.

In the iZEUS project, an autonomous control system was realized using a three-phase voltage measurement chip and a smart charging controller. Upon receipt of the voltage measurement and a price signal provided according to ISO 15118, the controller calculates a specific charging or V2G operating strategy. Additionally, a 22 kW bidirectional four quadrants onboard charger was developed that manages charging and V2G operation (see Section 5.2 and Dallmer-Zerbe et al., 2014). This demonstrates the feasibility of the autonomous control approach even if the currently available PEVs so far do not feature chargers with active power electronics.
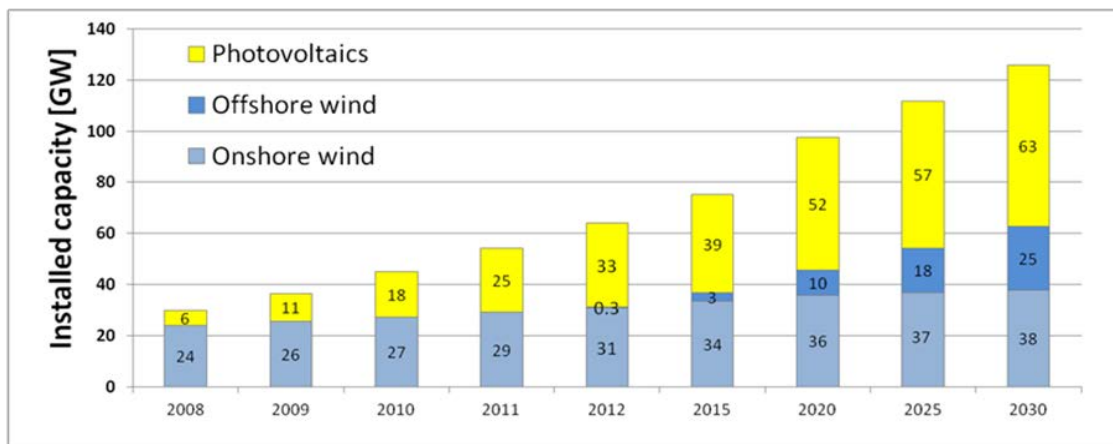
4.2   Scenario

To analyze PEVs' control strategies, scenarios are defined for the electricity system (indirect control) and the grid simulation (autonomous control). The scenario[9] for the electricity system defines the input parameters of the PowerACE model. The PowerACE model is used to investigate the incentives for indirect control due to participation on the day-ahead spot market for electricity. Here, assumptions about fuel prices as well as the amount of generation from fluctuating renewable sources are very important because they affect the day-ahead spot market prices and PEVs' incentives. A simple grid is defined for the grid simulation. Further, a function is introduced for the relation between voltage and the provided reactive power. Vehicle parameters for both simulations are taken from the iZEUS field trial.

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[9] The scenario is the same as in (Dallinger et al., 2013).

4.2.1   Electricity system

In order to investigate the incentives for PEVs to integrate renewable energy generation into the grid, a scenario is defined based on surveys available in the literature. This scenario assumes very high generation shares from renewable energy sources (necessary to reach the German government's CO_2 reduction target). The main scenario used here, which is called "GER 2030", refers to the "Lead Scenario 2010, which was part of a survey investigating high generation shares from renewable energy sources in Germany conducted on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Nitsch et al., 2010).

The installed capacity of fluctuating renewable generation is shown in Figure 9. Values until 2012 represent real installations in Germany. The future assumptions are based on (Nitsch et al., 2010). The total installed capacity from fluctuating generation in 2030 is 125.8 GW, which equals 162 % of the 77.8 GW peak-load. The generation share of intermittent RES is 47.6 %, with 87 TWh, 95 TWh and 57 TWh coming from wind onshore, wind offshore and photovoltaics, respectively. Total electricity demand is 502.1 TWh per year. The hourly characteristics of RES generation and the load curve are taken from [EEX, 2011 and ENTSO-E, 2011] with 2008 as the reference year. Electricity imports and exports as well as storage technologies such as hydro-pumped storage are not taken into account because the focus is on how V2G can contribute to balancing RES-E.


Source: [3] and Lead Scenario 2010 [14]

Figure 9:   Installed capacity of fluctuating generation in Germany

he assumed power plant park includes power plants >10 MW from (Platts, 2010) that are still available in 2030. New installations are added that assume

an optimal power plant mix to serve the residual load curve for the assumed load and RES-E scenario (Dallinger, 2013). The installed capacities are 749 MW from oil power plants, 32,461 MW from gas turbines, 13,942 MW from combined cycle gas turbines, 14,375 MW from coal power plants, 9,119 MW from lignite power plants and 820 MW from waste power plants. The assumed fuel prices and the resulting merit-order curve of the fossil power plant park are given in Figure 10.
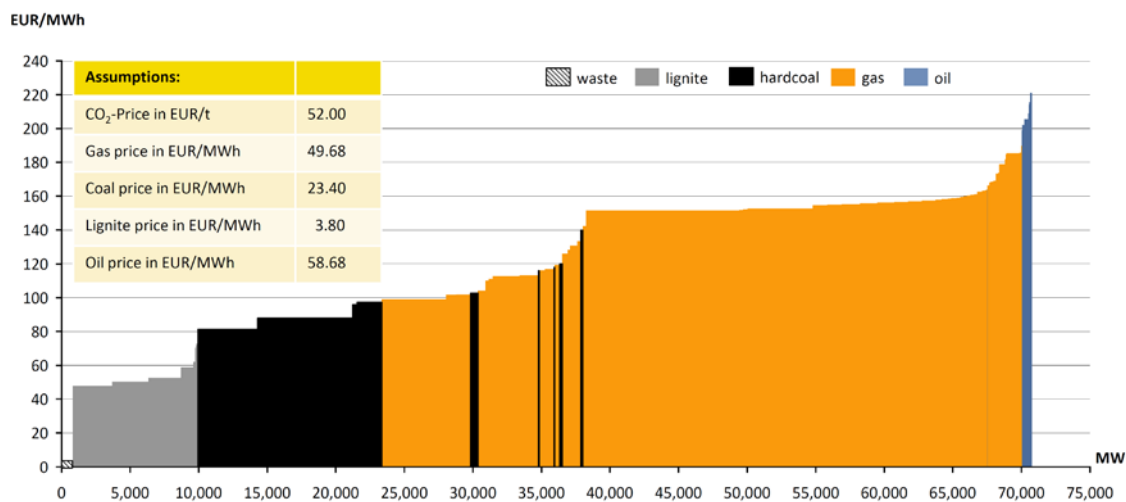
Source: Own assumptions based on (Platts, 2010 and Dallinger, 2013]; CO2 and fuel prices (Nitsch et al., 2010); figure created by David Biere

Figure 10: Merit-order curve of the power plant park in Germany in 2030

4.2.2   Grid simulation

The local distribution grid is modeled as a single-branch 0.4 kV[10] network, which consists of two nodes. The cable which connects the nodes is between 150 m and 6 km long and of type NAYY-J 4x95.[11] The first node represents the slack bus, which is connected to the next higher voltage level. The second node is the grid connection point of one PEV and a household. A typical profile with a fixed real power factor of 0.95 and maximum power of 3 kVA is applied to the household. The PEV can charge or discharge with a maximum power of 4 kVA. The energy needed and the time of arrival at the grid equals the typical home arrival behavior observed in the iZEUS project. The minimum power factor

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[10] Line-to-line voltage: usual low voltage level in Germany.

[11] Details are available at (Faber Kabel, 2014)

(cos(phi)) is set to 0.5. Hence, the modeled car is capable of providing a maximum reactive power of 3.46 kVAr.
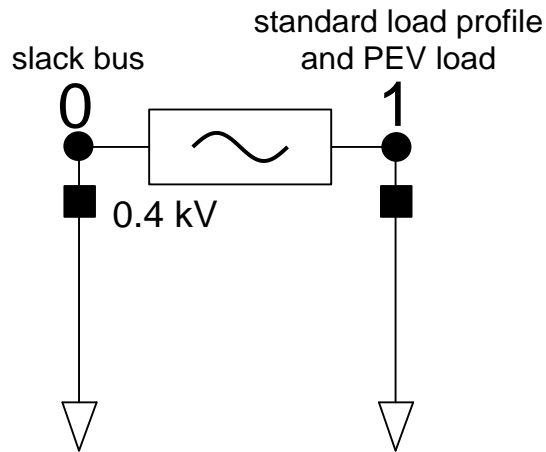

Figure 11: Low-voltage test feeder (4 nodes)

5   Results

The results section starts with a consumer survey of tariff designs to control PEVs conducted during the iZEUS project. Next, the results of the energy system analysis, prototype development and grid impact analysis are presented.

5.1   Indirect price-based control – a consumer survey

Technology acceptance is crucial for the dissemination of innovative technology. Any technology like the electric vehicles' automated charging control will only be successful on the market if the target group is willing to accept it. Technology acceptance is usually high if a personally perceived benefit exists which is big enough to justify any necessary efforts taken (Rogers, 2010). It does not matter whether the benefit originates from the technology itself, or if it is artificially created (e.g. financial benefits through subsidies).

To exploit the full potential of integrating energy from renewable sources into the grid, electric vehicles' automated charging control obliges the owners of electric cars to enter variable electricity supply tariff contracts. Currently, such variable tariffs that offer smart and flexible charging opportunities for electric cars to meet the fluctuating demand and supply patterns of the electricity grids are only very rarely available in Germany. Thus, it is not surprising that, so far, no research has been done concerning their general acceptance and preferred

configuration. Research of this topic is essential in order to learn about the acceptance of charging tariffs in general and about the preferred configuration of specific features in order to minimize the effort involved in introducing the respective tariffs, discover the preferences of future users and increase the acceptance of such tariffs.

We therefore studied consumer preferences for systems (tariffs) of demand-side management for electric vehicles by applying a scenario-based survey design. The main part of the questionnaire consisted of five short texts, each describing a possible scenario offering an electricity tariff for electric vehicles, which are summarized here:

- **Manual (MC):** Charging is operated entirely manually, several rate periods, possible reward up to 150 Euro p.a. (depending on charging behavior)

- **Automated Charging (AC):** Automated charging control, mobility buffer of 40 km, origin of energy used is the standard German mix, reward 100 Euro p.a.

- **Automated Charging – Comfort (AC-COM):** Automated charging control, mobility buffer at 70 km, origin of energy used is the standard German mix, reward 85 Euro p.a.

- **Automated Charging – ECO (AC-ECO):** Automated charging control, mobility buffer at 40 km, origin of energy is solely renewable sources, reward 85 Euro p.a.

- **Automated Charging – V2G (AC-V2G):** Automated charging control including feedback when the supply of renewables is low, mobility buffer at 40 km, origin of energy used is the standard German mix, reward 130 Euro p.a.

- **No Tariff:** This alternative includes the option not to select a new tariff for charging the electric vehicle, but to charge it with the currently used standard home tariff.

The scenarios differed with regard to a) whether charging management is operated automatically or manually, b) whether a vehicle-to-grid option is included, c) the minimum range guaranteed by the system (mobility buffer stated in km), and d) the generation sources of the electricity used. Additionally, each scenario provided explicit information about the sustainability, possible financial savings and necessary efforts by the consumer to operate the system. The participating sample of 1027 individuals is representative for the German population with regard to socio-demographic criteria.
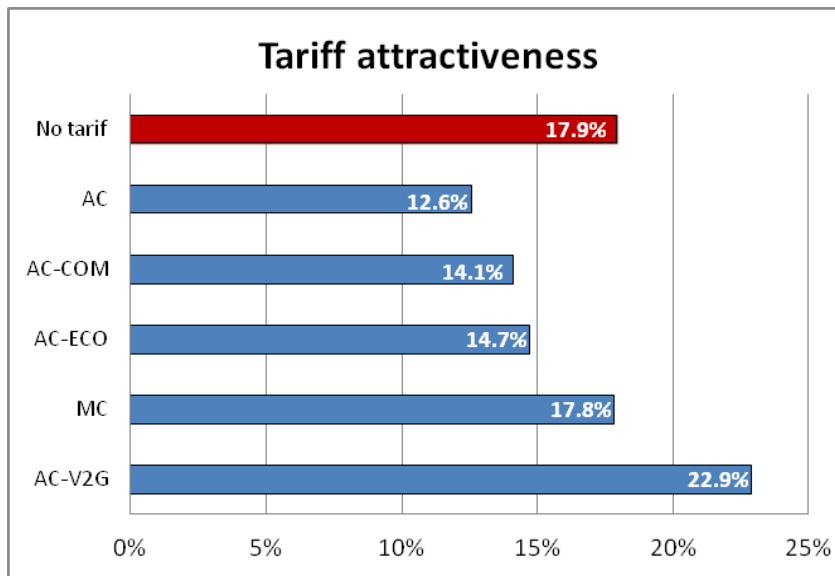
Figure 12: Consumer survey results

Analyzing the results (see Figure 12) reveals that the automated vehicle-to-grid tariff is the most preferred option with almost 22.9 % of the total votes. This is followed by the manual charging tariff (MC) with 17.8 %, the automated charging version with eco touch (AC-ECO) with 14.1 %, the automated charging tariff in the comfort version (AC-COM) with 14.1 % and the standard automated charging tariff (AC) with 12.6 %. Remarkably, almost 18 % of the test persons did not favor any of the tariffs, and chose the "No tariff" option.

The main conclusion is that, despite varying preferences within the offered tariffs, more than 80 % of the persons interviewed are generally open-minded to one of the tariffs offered and are thus willing to contribute to demand-side management in the mobility sector. In addition, further analyses of the data showed that the indicated scenario preference is usually in line with the motives for their choice, e.g. sustainability or simplicity.

5.2   Energy system analysis

The energy system analysis is based on work by (Dallinger, 2013) using travel survey driving data. The results presented here show possible smart charging and V2G revenues using real PEVs' driving data. The analysis is based on the energy system scenario introduced in Section 4. The simulation is conducted with the PowerACE model. Section 5.2.1 presents the results on smart charging only. Section 5.2.2 shows the results for smart charging and V2G.

5.2.1   Smart charging savings

In the following, the savings obtained due to controlled or smart charging are presented compared to uncontrolled charging for an electricity system scenario in 2030. The uncontrolled charging behavior is the same as the charging behavior observed during the iZEUS field trial. Controlled charging uses the same mobility behavior, but shifts the charging process during the observed parking time. The control signal is the electricity price simulated by the PowerACE model for a 2030 scenario. Hence, charging is realized at minimum electricity prices within the constraints of the observed parking times and energy demand for driving. The differences in yearly electricity costs between uncontrolled and controlled charging are given in Figure 13. Figure 13

For the Toyota Prius PHVs, the observed driving behavior is randomly assigned to 50 simulated vehicles on a weekly basis. Further, the battery size in the simulation is varied between 2.5 and 20 kWh. For the Daimler Smart BEVs, the observed driving behavior is directly assigned to a simulated BEV.
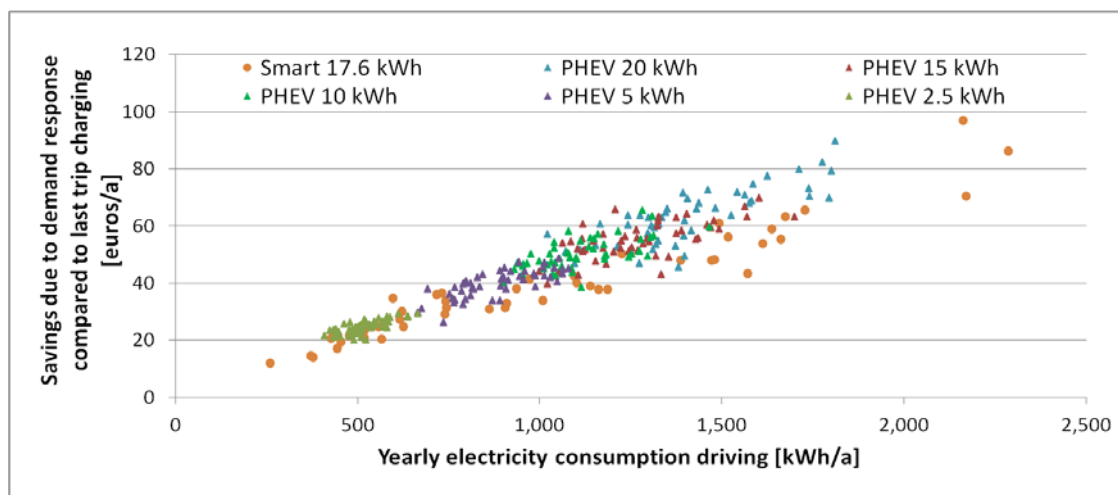

Figure 13: Savings for controlled charging compared to uncontrolled charging

The results show that the yearly electricity costs are mainly a linear function of the electricity demand. Savings are between 10 and 100 euros per year. In case of smart charging, a larger battery enables a longer grid management time and therefore the opportunity for additional savings. However, comparing Daimler Smart BEVs with a usable battery size of 17.6 kWh and Toyota Prius PHVs with a usable battery size of only 2.5 kWh indicates that bigger batteries do not result in additional savings (see Figure 13 for electricity consumption between 400 and 700 kWh).

If the same driving behavior is assumed with a bigger battery, as simulated for the Toyota Prius PHVs, higher electric driving shares result in an increase of the yearly electricity demand and savings. For higher consumption values, a higher variability of the savings obtained is also observed (for example, see the three Smart BEVs with a demand over 2000 kWh/a). Here, due to the higher utilization of the vehicles (reduced parking times), the periods when vehicles are connected to the grid become more relevant. A high installed capacity of photovoltaic systems is assumed in the applied 2030 scenario. Due to the photovoltaic peaks, low prices during the day are more likely (see Figure 1). The fluctuation of renewable generation deviates from the conventional picture of low prices during the night and higher prices during the day. Therefore, it becomes more important that PEVs are available during the day to realize savings due to low smart charging prices.

5.2.2   Vehicle-to-grid savings

Smart charging is extended by the ability to feed power back into the system in order to simulate vehicle-to-grid savings. The V2G efficiency is 94 % and battery aging is assumed according to (Dallinger, 2013).

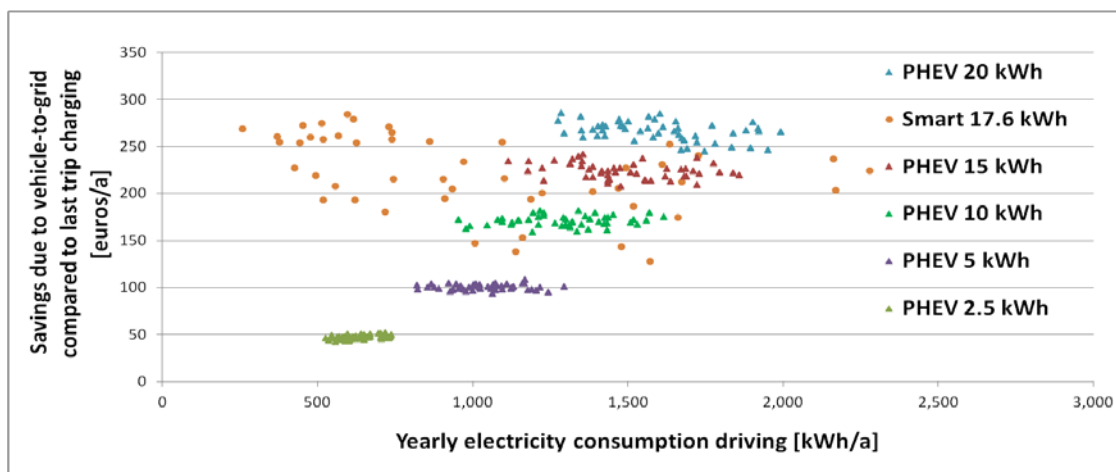The simulation results are given in Figure 14.

Figure 14: Vehicle-to-grid saving#s compared to uncontrolled charging

Savings compared to uncontrolled charging are between 50 and 300 euros per year. Savings follow a step function when simulating PHEVs applying the Toyota Prius driving behavior observed in the iZEUS project. Each simulated battery size results in a different magnitude of savings. Battery size strongly affects the possible savings for V2G in contrast to the results for load shifting. The results

are not as clear for the simulation of the Daimler Smart BEVs. Here, BEVs with low utilization are able to reach the highest savings. Vehicles with higher yearly electricity consumption show slightly lower savings.

Overall, possible incentives from day-ahead electricity markets will not significantly reduce the PEV total costs of ownership. Savings are low even with a high share of fluctuating renewable generation that increases the market price spreads due to the merit-order-effect. With respect to the conducted consumer survey on the acceptance of price-based control, smart charging still seems a promising way to realize an electricity system with a higher share of renewable generation.

5.3   Prototype development and demonstration

The control strategy outlined in Section 4.1.2 was implemented in an on-board control device referred to as the grid controller. Its block diagram is shown in Figure 15.
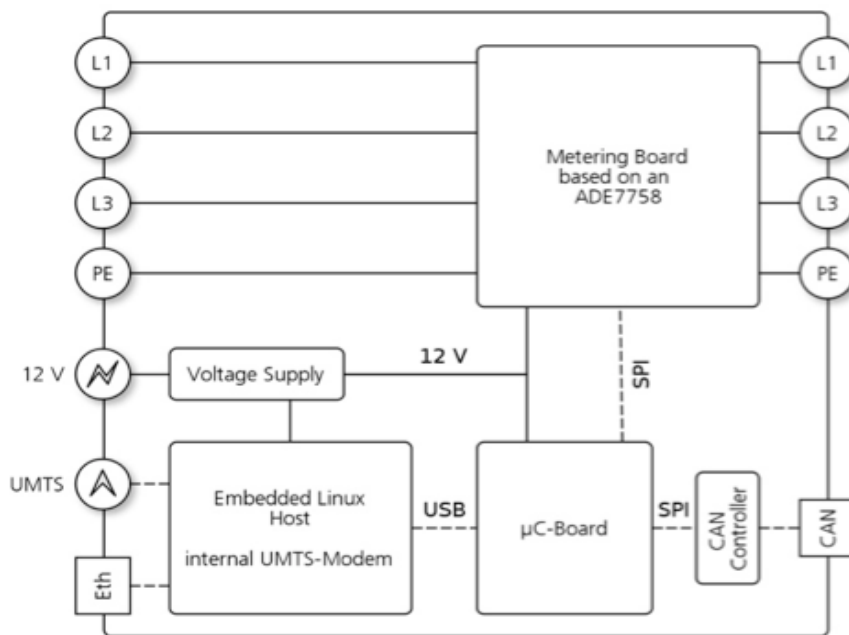

Figure 15: Block diagram of the grid controller for integration in a PEV

A metering board was developed based on an Analog Devices ADE7758 metering chip. This enables the grid controller to measure the root mean square (RMS) value of the voltage per phase, as described in 5.3.1. The µC-board

handles all tasks with hard real-time constraints such as the voltage controller and the on-board communication via the controller area network (CAN). An additional host controller running an OpenMUC[12]-based energy management system takes care of the intelligent charging strategies, representing the control level above the voltage controller itself. Both systems are described in 5.3.2. Ancillary components integrate the controller into the vehicle's system architecture as shown in 5.3.3.

In addition to the grid controller, a bidirectional, highly-efficient 20 kW charger was developed at the Fraunhofer ISE, which is capable of adjusting the power factor upon request. Charger, grid controller and additional vehicle control devices are interconnected via the on-board CAN bus. A similar setup is presented in (Reichert, 2010)

5.3.1   Metering Board

The key component of the metering board is an Analog Devices ADE7758 IC. This three-phase electrical energy measurement IC provides all the signal processing required to perform active, reactive, and apparent energy measurement and RMS calculations. The metering board utilizes the acquisition of the three phases voltage RMS values as input for the voltage controller. Other available metering values are the RMS values of the current, the maximum values of voltages and currents and the present values of voltages and currents using the integrated waveform-sampling mode. The integrated temperature sensor allows monitoring the grid controller's status during operation. High accuracy of the metering system can be achieved using the IC's system calibration features for each phase, allowing RMS offset correction, phase calibration and power calibration.

The metering board provides the circuitry for the current transducers, allowing measurements for a current range of ± 55 A with an accuracy of ± 0.25%. Voltage sampling is done using a resistive voltage divider (1 MΩ:1 kΩ) providing a voltage range of ±500 V with an accuracy of ± 0.5%. Additional protection circuitry has been engineered in order to separate the power and the control circuits. Communication with the µC-board as part of the control circuit is done via a serial interface.

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12   OpenMUC is an open source energy monitoring and control software framework developed at Fraunhofer ISE. See www.openmuc.org.

5.3.2   Controller Architecture

The grid controller was developed to demonstrate the feasibility of the proposed autonomous reactive power control. Therefore, a specially designed component was developed. The final design would also integrate the different tasks into existing components of the PEV, i.e. metering tasks into the charger, higher-level communication and control tasks into control devices.

The grid controller prototype comes with two control devices: a µC-board based on an Atmel AT90USB646 and a piA-AM3505 embedded Linux system from the German electronics and software company pironex GmbH. This setup allows operating modes such as an intelligent upper-layer demand response algorithm, e.g. according to price signals, and the lower-level voltage controller to stabilize the grid during charging.

The µC-board handles the acquisition and processing of the meter data. It runs the real-time voltage controller, which is fed with the voltage RMS values and the reference charging power from the upper-layer charging algorithm. The EV-internal communication via CAN is also handled by the µC-board, which effectively allows the embedded Linux system to only process the upper-layer control algorithms. Using an embedded Linux system enables control algorithms to be developed based on the OpenMUC software framework.

5.3.3   Automotive Integration

Various design decisions were made regarding the integration of the grid controller prototype into a PEV. Only components with an extended temperature range of -25 to +85 °C were used. The voltage supply circuitry was engineered to withstand various events where the supply may deviate from the 12 V voltage rating. The control algorithms of the embedded system realize a seamless integration into the charging process as defined in ISO/IEC 15118 by interacting with the respective in-vehicle control devices via CAN.

5.3.4   Demonstration

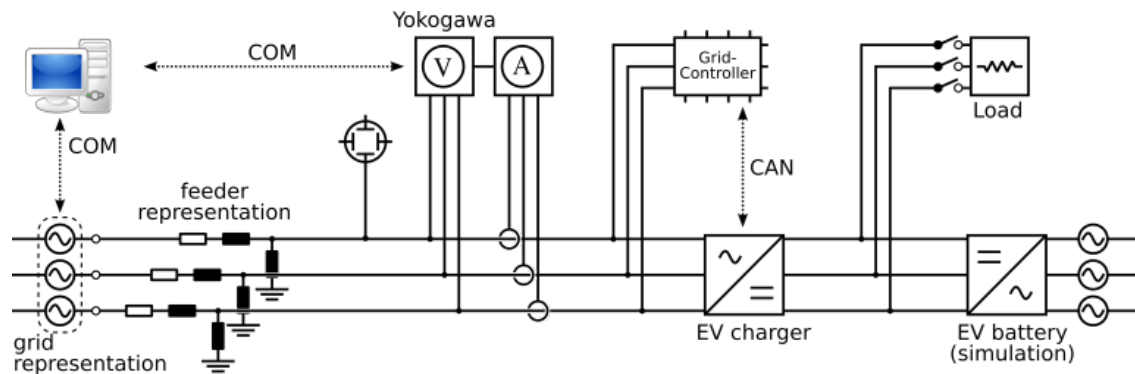The grid controller prototype and 20 kW charger were included in a test bed as shown in Figure 16.

Figure 16: Block diagram of the grid controller for integration in a PEV

The grid is simulated by a three-phase AC source and subsequent feeder representation. The grid representation is controlled via COM. The EV battery is simulated by a bidirectional three-phase converter and an optional resistive load. The grid controller requests a desired reactive and active current of the EV charger via CAN. The test bench is observed and documented using an oscilloscope and high-precision measurement equipment (Yokogawa). The feeder representation is adjustable to illustrate usual feeder characteristics via condensed elements. The tests with different feeder representations are still ongoing and therefore not included in this publication.

The following droops were measured to validate the controller at a charging power of 9kW (3kW per phase): The grid representation voltage was increased in 0.5 V steps and held for 10 seconds. The grid controller includes a PT1 characteristic with τ of 5 s to increase stability and hinder flicker production. Hence, a damped voltage signal is used to set the reactive power.

The biggest sources of uncertainty in the test bench are the grid representation, grid controller and EV charger. Within the grid representation, the voltage deviation between 3 phases can be up to 2 V. Since the grid controller is not a high-precision measurement device like the Yokogawa, this leads to differences between CAN and Yokogawa due to deviations in the voltage measurement per phase of up to 1.2 V. Additionally, the PT1 characteristic leads to damped control signals. The deviation between the de facto reactive current provided by the EV charger and the desired values sent by the grid controller sum up to 0.2 A. Plotting the reactive power provided against the voltage eliminates the uncertainties due to the grid representation because each voltage level is reached at different times in the different phases. Figure 17 shows the reactive power provided against the current voltage from CAN.
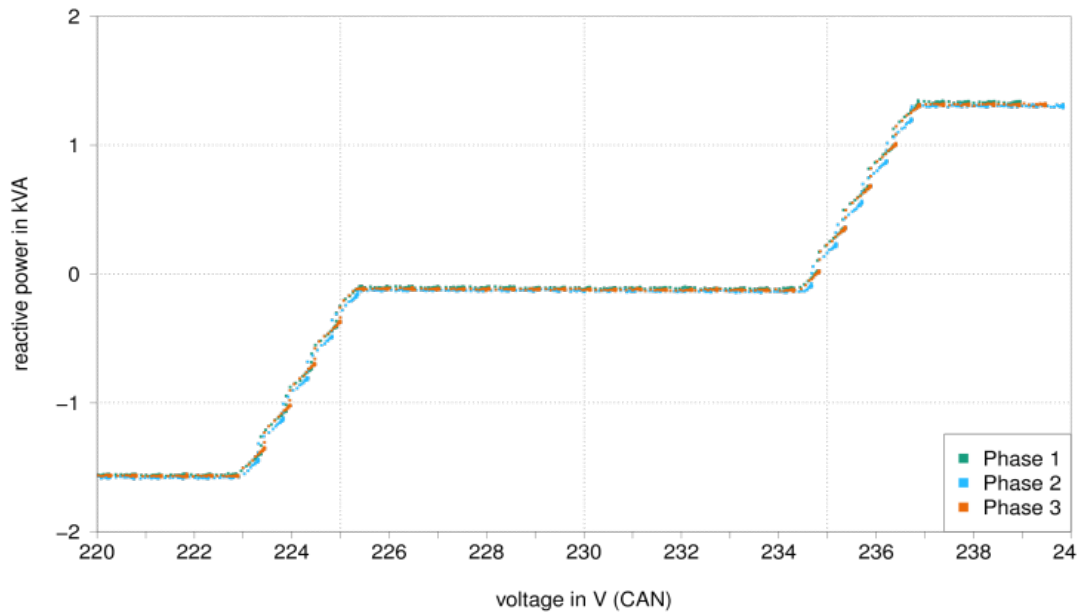
Figure 17: Measured voltage droop at 9kW charging with current voltage from CAN and reactive power measured by Yokogawa

This reveals the uncertainties due to EV charger and grid representation leading to a small offset of the droop and deviations within the slopes. Due to the PT1 characteristics of the controller an almost continuous adoption of the reactive power is realized. This contradicts the reality of the step-wise voltage changes in the grid representation.

Figure 18 shows the reactive power provision against the voltage measured by Yokogawa. This additionally reveals the uncertainties in the measurements of the grid controller metering board. Grid representation uncertainties show in the slopes. Nevertheless, the desired droop is controlled with sufficient accuracy since the slopes are only applied to avoid discrete steps and therefore increase the stability of the control system, especially with multiple EVs. An interesting effect is the uncoupling of the droops per phase due to the comparatively cheap grid controller's limited accuracy in measuring the voltage . This effect adds additional stability to the system since multiple PEVs lead to less synchrony of the reactive power provision and therefore a limited uncoupling of the decentralized controllers.
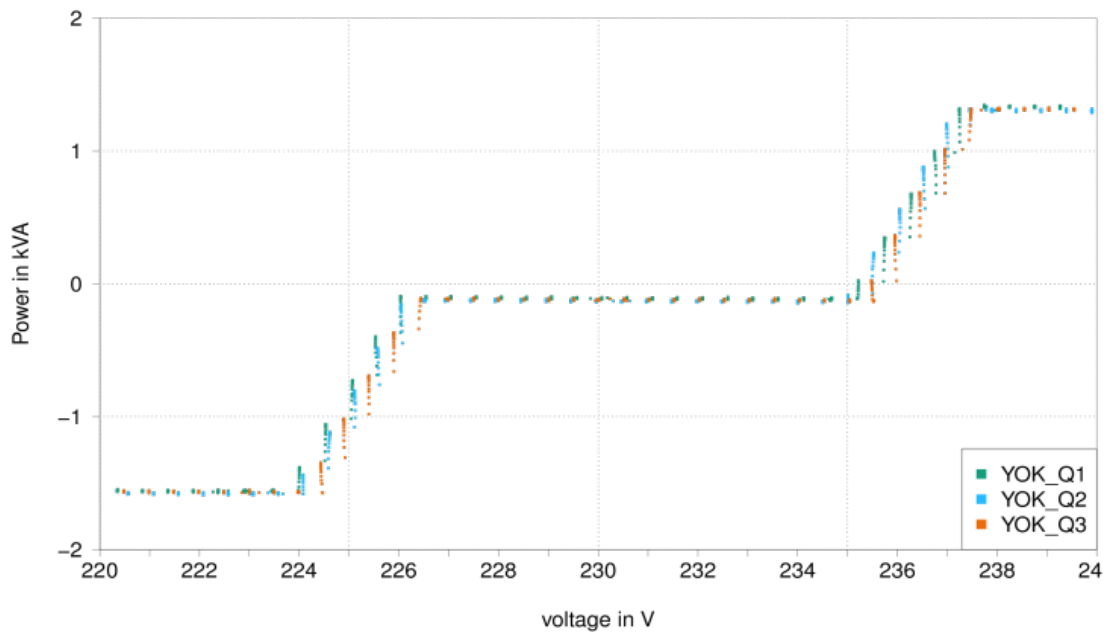
Figure 18: Measured voltage drop at 9kW charging with current voltage from
and reactive power measured by Yokogawa

5.4   Grid impact analysis

This chapter discusses the principal benefits of the autonomous control strategies introduced in Section 4.1.2. The presented results are based on a grid that consists of two nodes connected with a cable that varies in length between 150 m and 6 km. A setup with long cables increases the sensitivity towards voltage deviations in the grid and therefore enables illustrating possible benefits of smart charging. In practice, most grids are less sensitive and consequently the smart charging benefits in terms of voltage-control are smaller.

The voltage resulting from a grid simulation of one day is shown in Figure 19. Input parameters affecting voltage are the household load profile and the PEVs' charging profile. Even without PEV charging, the voltage drops close to the V_{min} boundary at noon and in the early evening for the 6 km cable. PEV charging at 6 pm with 3.6 kW power results in a massive voltage drop that violates V_{min} (6 km and 3 km cable length). For cable lengths below 3 km, the voltage is less sensitive to charging.
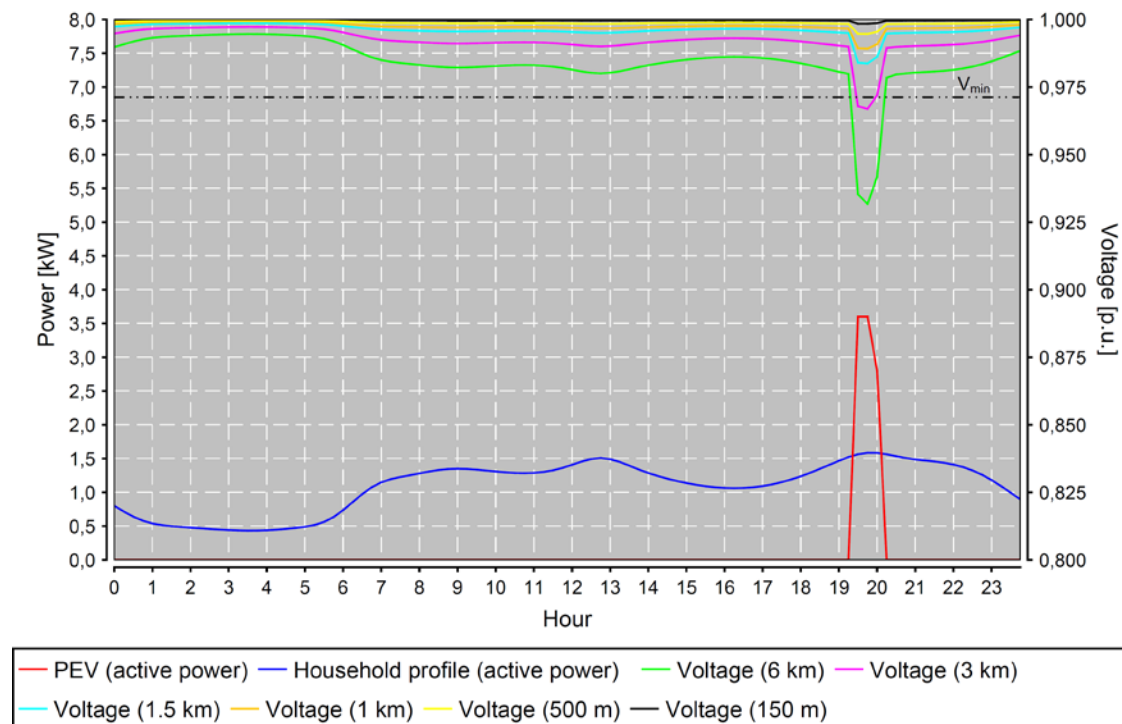
Figure 19: Power and voltage profiles at node 1

The voltage drop for the 6 km cable can also be observed in Figure 20 when P_{charge} is assumed to be 3.6 kW. Further, Figure 20 shows all charging and V2G options of a PEV equipped with a four quadrant 4 kW power inverter. To avoid violation of V_{min}, P_{charge} must be strongly reduced. A PEV equipped with a voltage monitoring system that allows autonomous control is able to detect the available real power before violating V_{min}. In the example presented here, the power would have to be reduced from 3.6 kW to below 0.5 kW. This would de-lay the charging process. Hence, if instant charging is needed and V_{min} should not be violated, the charging strategy O_{12} is valuable. Here, the vehicle uses capacitive charging to lift the voltage while consuming a higher real power of 3.3 kW (Q_y = 1.4 kVAr and S_y = 3.6 kVA).

In the example presented, the PEV is able to strongly lift and reduce the voltage thereby stabilizing the grid. Furthermore, providing reactive power in specific situations (when V_y is close to the voltage limits V_{min} and V_{max}) allows real charging or V2G power to be increased. In terms of renewable and especially distributed photovoltaic generation that lifts the voltage when available, the vio-lation of V_{max} is an issue. Here, the PEV can reduce the voltage due to charging (O_1), charging while providing inductive reactive power ($O_{1.1}$), or if no real charging power is needed, just by providing inductive reactive power (O_4).
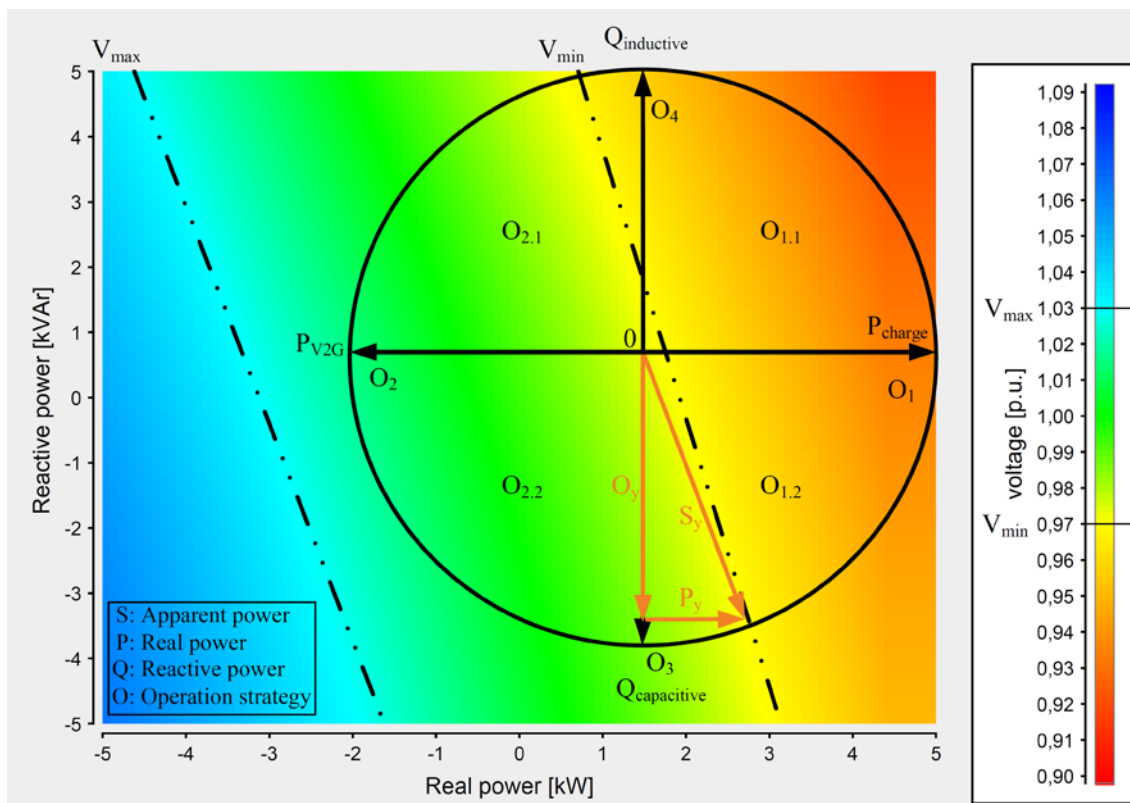
Figure 20: V2G and charging control options for the PEV

Even if the effects on voltage are lower in most grids, the presented results show that PEVs have a great potential to stabilize the grid and integrate fluctuating renewable generation. Autonomous control based on monitoring the voltage at the grid connection point will therefore be of great value in future smart grids. Further, it is possible to include PEVs in the existing infrastructure without complex charging control systems.

6   Conclusions

Using renewable energy generation to power electric vehicles makes it possible to decarbonize large parts of the passenger transport sector. Sustainable energy generation from renewable sources and electric vehicles' high efficiency in transforming this energy seem to be a match made in heaven. Nevertheless, the fluctuation of photovoltaic and wind generation is an issue that complicates the interaction of renewable generation and plug-in electric vehicles because a control mechanism is required to match demand and supply.

Analyzing possible control strategies reveals that indirect tariff-based control that permits the operating schedule to be finalized within the vehicle provides

many advantages such as reduced communication effort, high data security and users being able to adapt the operating schedule to suit their personal needs. Further, market-based electricity prices are able to reflect the supply of fluctuating renewable generation on a system level and therefore provide incentives to consume and balance renewable generation. The incentives for smart charging that could be provided to consumers were analyzed using the electricity market simulation model PowerACE as well as PEVs' driving and charging data gathered within the iZEUS field trial. The results show that smart charging and V2G revenues are only in a range between 10 and 300 euros per year even assuming a high share of fluctuating generation sources that reduce electricity prices and high fuel prices for conventional generation that lead to higher peak prices. Hence, even in electricity systems with high price spreads due to fluctuating generation from renewable energy sources, it remains challenging to realize successful smart charging business cases. Nevertheless, the conducted consumer survey demonstrates that over 80 % of the respondents are open to using specific tariffs for smart charging of plug-in electric vehicles even if the potential rewards are lower than 150 euros per year. This indicates that smart charging based on incentives from day-ahead electricity markets could still be an option to control PEVs.

A general issue of controlling flexible demand and generation units connected to the distribution grid is that current electricity markets mainly reflect the overall system level. The local situation in low-voltage distribution grids is not mirrored by electricity prices and in many cases information on the local situation is missing. Hence, on a distribution grid level, the issue is how to organize the interaction of generation units (e.g. photovoltaic) as well as the flexible demand and storage capabilities of plug-in electric vehicles. Here, a promising approach is autonomous distributed control based on the system voltage. The voltage in distributed grids reflects the actual demand and supply situation. Plug-in electric vehicles that monitor the voltage at the grid connection point can collect information that generates operating schedules able to avoid local load peaks and balance distributed generation from renewable sources without an external control signal. With regard to autonomous control through voltage measurement, our simulation results show that plug-in electric vehicles can provide benefits and stabilize the voltage in distribution grids. The actual benefits provided depend strongly on the grid to which the vehicles are connected. A reduction of the charging power and exclusively providing reactive power represent the most promising options to stabilize grids with many electric vehicles or with a high share of volatile power from renewable energy sources.

Both of the control strategies investigated, indirect price-based control and autonomous control, offer advantages for specific applications. Indirect price-based control allows the consideration of renewable generation at an overall system level, whereas autonomous control takes local renewable generation into account and avoids simultaneous charging. Therefore, if a general control mechanism is needed for PEVs, combining both strategies seems to be a promising option to help balance electricity systems.

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Karlsruhe 2015