



Plug-in hybrid electric vehicles and smart grids: Investigations based on a microsimulation



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ABSTRACT

The introduction of plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs), commonly referred to as plug-in electric vehicles (PEVs), could trigger a stepwise electrification of the whole transportation sector. However, the potential impact of PEV charging on the electric grid is not fully known, yet. This paper presents an iterative approach, which integrates a PEV electricity demand model and a power system simulation to reveal potential bottlenecks in the electric grid caused by PEV energy demand. An agent-based traffic demand model is used to model the electricity demand of each vehicle over the day. An approach based on interconnected multiple energy carrier systems is used as a model for a possible future energy system. Experiments demonstrate that the model is sensitive to policy changes, e.g., changes in electricity price result in modified charging patterns. By implementing an intelligent vehicle charging solution it is demonstrated how new charging schemes can be designed and tested using the proposed framework.

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1. Introduction

These days, fossil fuels are the most important primary energy source in most countries of the world. The transportation sector and individual transport in particular is highly dependent on fossil fuels. For several reasons, endeavors are undertaken to break this dependence. Reasons include concerns about the economic and political implications of the current unsustainable use of limited fossil resources or the impact of greenhouse gases on climate change. One solution to these problems could be the electrification of vehicles. It has been estimated that electrifying the whole transportation sector could shrink energy consumption to one fifth of current consumption (MacKay, 2009). Moreover, driving with electricity is currently far less expensive than driving with gasoline (IEEEUSA, 2007). In addition, electrifying the transport sector would promote sustainable ways of generating electricity, such as wind and solar energy (Short and Denholm, 2006). Also, there are advantages for the air quality and human health, such as reduction of particulate pollution and acid rain (Sovacool, 2010).

1.1. Plug-in hybrid electric vehicles

Although EVs have been around for quite some time, their limited range has hindered their widespread use. Plug-in hybrid electric vehicles (PHEVs) can run on both electricity and gasoline. The batteries of these vehicles can be charged at

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home or at other locations by means of an ordinary plug. As most people generally drive short distances during the week (BFS, 2006), the vehicles would mainly run on electricity. Only during longer trips would gasoline be used when the vehicles' batteries became depleted.

The introduction of PHEVs might also create the demand needed for companies to invest in electric fuel stations (Bradley and Frank, 2009). This would also foster the introduction of EVs, which vitally depend on such an infrastructure.

1.2. Smart grid

For electric power generation and distribution utilities, the ability to predict the demand for electricity during the day is vital, because this ability directly influences the operation of the system and hence revenues as well as the security of supply. A shift to electric vehicles would increase the demand for electricity. Furthermore, the demand for electricity from these cars would be dynamic in terms of time and location. This can lead to several challenges for the electricity system. An increase in peak load demand could cause the need to utilize more expensive generation units, if available. Furthermore, presuming the electricity generation capacities are sufficient, the electricity network's physical constraints could be violated by the additional PEV demand at the medium- and low-voltage levels (Peças Lopes et al., 2009). A possible solution to this problem could be offered by a future *smart grid* (National Energy Technology Laboratory, 2007).

The idea of a smart grid is to use advanced information and communication technologies in order to intelligently manage the provision of electrical energy to consumers. This means that by consolidating data from different sources (e.g., conventional generators, renewable energy producers, consumers, network operators and PEVs), the demand and supply are matched in a way to ensure network security and system sustainability. For instance, PEV owners and electric utilities could sign an agreement according to which vehicle charging could be stopped for a few minutes during demand peak times. In turn, the vehicle owners would receive compensation from the utility company or responsible entity. The general role of PEVs in such a future smart grid environment is elaborated in Galus et al. (2012a,b).

1.3. Vehicle-to-Grid technology

Through the use of a smart grid, the Vehicle-to-Grid (V2G) concept could become reality (Kempton and Tomic, 2005). A V2G implementation allows PEVs to act as resources to the grid. There are various potential applications for V2G technology (Kempton and Kubo, 2000; Galus et al., 2012a,b): If the demand for electricity in the grid exceeds the supply during peak hours, PEVs could supply peak power. There are also applications in which the vehicles are used to balance the power in feed prediction error of renewable energy generators (Kempton and Dhanju, 2006; Galus and Andersson, 2012), or where they provide ancillary services to the electric grid in order to stabilize the network (Galus et al., 2011).

Our paper presents the initial version of a framework, which helps to analyze the interaction of emerging technologies in connection with PEVs (e.g. smart grid). This framework is able to uncover limitations of existing electricity grids for potential future electricity demand of PEVs. The developed framework is able to analyze differing charging policies and their impact on transportation and electricity networks. Therefore, this framework can also be used to design charging policies for PEVs, which help balancing the electricity demand and planning of PEVs infrastructure (e.g. charging stations).

In the following section, related work is presented together with the two systems on which the framework is based. Then, the methodology and subsequently the experiments are described. Before presenting the conclusions, an outlook on possible future research is given.

2. Related work and background information

Several studies have been conducted regarding the energy consumption of PEVs and their influence on the electric grid. Some of the most recent and relevant work to the topic of this paper is summarized in the following.

Peças Lopes et al. (2009) demonstrate the impact of electric vehicle charging on medium voltage distribution grids. The results point to the appearance of various bottlenecks in the electrical network, such as excessively low voltage and transformer and line capacity violations. In their study, fixed durations (e.g., 4 h) are assumed for electric vehicle charging.

In Letendre et al. (2008) and Letendre and Watts (2009) an accumulated energy model is used to show that a large number of PEVs could be accommodated by the utility grid in Vermont, USA if PEVs are charged during the night. Furthermore, the potential number of cars which could be accommodated by a smart grid is estimated. For the experiments, the charging time of the PEVs is fixed to 6 h. The arrival times of the cars are uniformly distributed between 8 a.m. and 9 a.m. at work locations and between 6 p.m. and 8 p.m. at home locations.

The paper at hand also presents several PEV charging schemes. In contrast to the above-mentioned papers, the charging times and locations of the vehicles are based on an activity model of people. Therefore, the vehicles' energy consumption and charging durations are not constant. Furthermore, an electricity grid and a gas network are interconnected and model a possible future energy infrastructure that offers much flexibility and diversity. The electric networks incorporate physical constraints for the power flow. In the following two sections, both, the mobility model used for the transportation simulation and the energy system are described.

2.1. Multi-agent transport simulation (MATSim)

Traffic simulations can be performed at different levels of detail. On the one hand, traffic can be modeled as flows consisting of an aggregate number of cars; on the other hand, it can be modeled as individual vehicles. A simulation in which each car owner is an agent is called an “agent-based micro-simulation”; it allows vehicles to be tracked dynamically over time. MATSim (MATSim-T, 2008) is such an agent-based micro-simulation with focus on large scenarios. Simulations with more than seven million agents in a navigation network containing around one million links have already been implemented using MATSim (Charypar et al., 2007a; Waraich et al., 2009). Vehicle owners in MATSim are modeled as agents. Fig. 1 shows the MATSim simulation process: Each agent has a daily plan of trips and activities, such as going to work, to school or shopping. The agents' daily plans, the street network and the facilities are modeled in the *initial demand* (Balmer, 2007). The plans of all of the agents are executed by a *micro-simulation*, resulting in traffic on roads and perhaps traffic jams (Cetin, 2005; Charypar et al., 2007b).

The execution of each plan is *scored* and assigned a utility. For example, a person with a lower travel time has a higher utility than one whose travel time was longer because of a traffic jam. Furthermore, work (earning money) and other activities increase the utility. The goal is to maximize the utility of each agent's daily plan by *replanning* the day based on a co-evolutionary algorithm (Holland, 1992). Such an algorithm generally tries to find a maximum fitness function (here, the utility function) by using crossovers and mutations. In the MATSim context, the utility function has several degrees of freedom, such as the routes, working hours, travel mode chosen, locations visited, and so on. It can also be extended to include the energy consumption of the vehicles. The daily plans are evaluated, and *bad* daily plans (plans with a low performance or low utility) are deleted, which corresponds to the *survival of the fittest* function in co-evolutionary algorithms. New plans are then generated based on the results of the previous set of plans. The cycle of executing all plans, scoring and replanning them is called an iteration. The simulation is an iterative process which approaches a point of rest corresponding to a user equilibrium called *relaxed demand*. The relaxed demand can then be analyzed. More details about the conceptual framework and the optimization process of the MATSim toolkit can be found in MATSim-T (2008).

One of the reasons for using an agent-based approach instead of an aggregate one is that individual agent preferences (e.g. when or where to charge the PEV) can be modeled based on the utility function. Furthermore, simulating the constraints of the electric network requires detailed data regarding locations and times of electricity demand. In MATSim, high-resolution road networks, including individual buildings, can be simulated, which makes a mapping to the underlying electric grid infrastructure possible.

2.2. PEV management and power system simulation (PMPSS)

Fig. 2 depicts the power system used in the following. It contains multiple energy carriers. Each node in the power network is modeled by an energy hub. Energy hubs interconnect multiple energy carriers in order to optimize the supply of the consumers' demand. They are elaborated in Geidl and Andersson (2005), and their application in networks is described in Geidl and Andersson (2007) and del Real et al. (2009). Each hub should be understood to model an urban area, e.g., a residential, business or industrial area. Real electricity load curves are used to model the demand for the particular area. The hubs contain a furnace to meet the heat demand, a transformer to supply electricity and a small combined heat and power (CHP) turbine. The CHP interconnects the electricity and gas networks and can relieve the electricity networks.

The electrical power lines (Wollenberg and Wood, 1996) and gas lines (Menon, 2005) are modeled according to physical laws. The system can thus be understood to model a potential future energy system, because the share of distributed power generation is very high (Ackermann et al., 2001; Chicco and Mancarella, 2009). Furthermore, each area incorporates a PEV management device called PEV manager (Galus and Andersson, 2009b; Galus et al., 2012a,b). The managing entity signs the vehicles connected in its area into the scheme and performs optimizations in order to determine whether the power system is capable of supplying the additional load. Constraints on the total consumption of power by the PEVs are derived from the network state including the base load. Typically, the transformer and line capacities as well as the voltage levels in medium- and low-voltage networks limit the transmittable power at nodes, i.e., hubs. For simplicity, only the transformer and CHP capacities are considered as limiting factors. In the PEV manager optimization scheme, a benefit function and an individual utility are assigned to the PEVs based on the battery energy level and the charging activity (Galus et al., 2012a,b). The utility function depends on the relative state of charge (SOC), the desired SOC at departure, the departure time, and an exogenously given price signal. In congested networks, the PEV manager creates a control price signal which is derived from the optimization. The control price signal is directly correlated with the network state, the number of PEVs demanding power

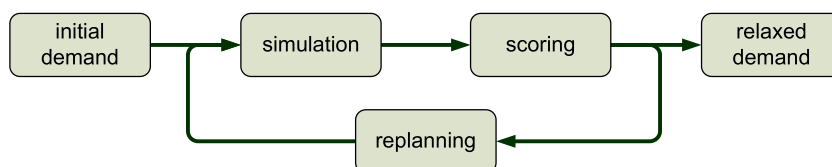


Fig. 1. Co-evolutionary simulation process of MATSim.

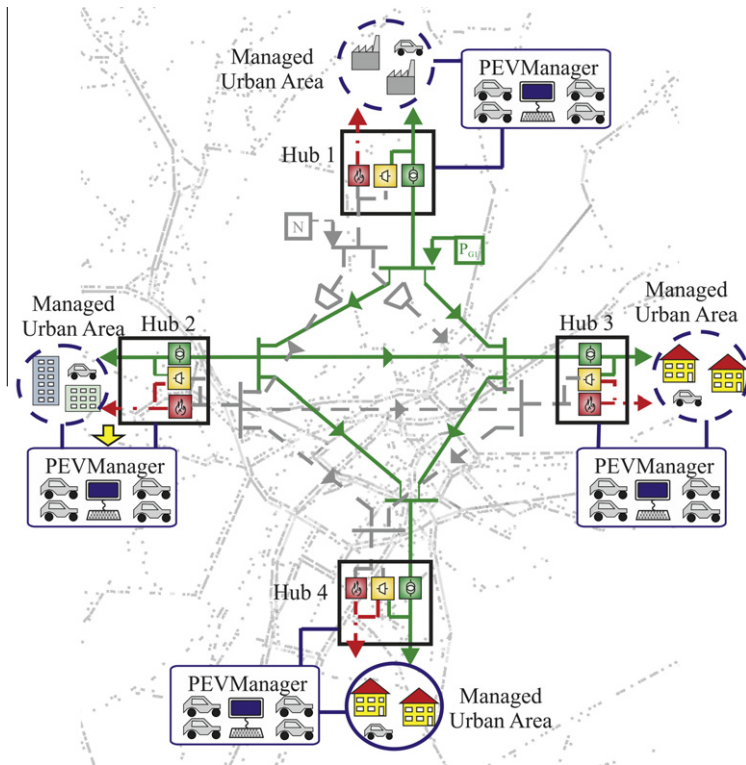


Fig. 2. Four-hub network including PHEV managers for urban areas.

and the urgency with which they demand it. This control price signal differs from system energy prices which are used to minimize overall energy carrier consumption costs.

3. Methodology and simulations

3.1. Overview

In order to investigate different charging strategies, MATSim and PMPSS are combined and a charging module is implemented (see Fig. 3). The charging module receives information about vehicle movement and vehicle parking times from the MATSim micro-simulation. Based on the charging scheme which is being investigated (e.g. smart charging), it derives the energy consumption of the vehicles, which is based on a simple PEV model simulating actual driving cycles in cities (Galus and Andersson, 2009a). For the scenarios which are investigated, standard (3.5 kW, 240 V, 16 A, single-phase) Swiss plugs are assumed. The charging module knows where each vehicle is parked, and for how long. For charging, three different strategies are implemented: *dumb charging*, *dual tariff charging* and *smart charging* (see Sections 3.2, 3.3 and 3.4; the strategy names follow Peças Lopes et al. (2009)). After assigning charging times to the cars, the charging module can assign scores to the agents (e.g., the cost of the electricity charged). Once the MATSim simulation process has reached a relaxed state, the charging times, locations and state of charge of the agents are sent to the PMPSS. The PMPSS determines whether the electricity demand based on these charging times together with the base load violates certain physical network conditions, as described in Section 2.2.

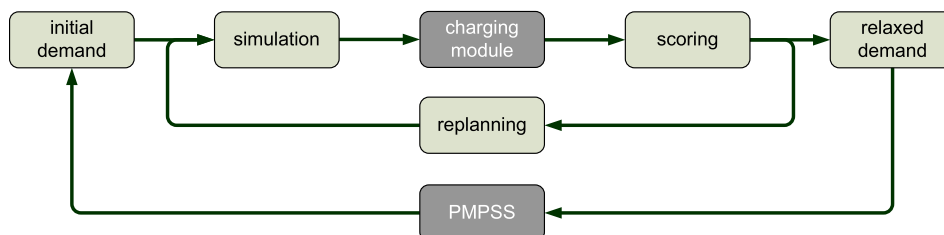


Fig. 3. Charging module with PMPSS added to the MATSim simulation process.

For some applications it could be enough to know, where overloads in the electricity grid occur, while for other applications (such as the one in Section 3.4), iterations between the transport simulation and the PMPSS are might be required to avoid network overload and to determine a favorable charging schedule for the vehicle fleet. In order to enable an information exchange between MATSim and PMPSS, a control price signal is sent back from PMPSS to MATSim after each iteration for the whole day. The higher the control price signal the more congested the network. If the PMPSS control price signal indicates congestion in the network, a new MATSim iteration is started. If no constraint violation occurs, the physical network can meet the PEVs' electricity demand and a viable charging pattern has been found. The initial price used by the charging module depends on the charging scenario to be simulated, e.g., dumb charging or dual tariff charging.

As MATSim simulates a 24-h day, it is assumed that the agents start in the morning with a full battery and try to fully charge it again before starting the next day.

In the following sections the different charging schemes are presented together with simulation results. Table 1 gives an overview on the scenarios.

3.2. Dumb charging scheme

“Dumb charging” means that agents start charging their cars as soon as they arrive somewhere, in the attempt to fully recharge the battery. The dumb charging scheme assumes that the costs of electricity are the same throughout the day, and therefore agents connect their PEVs to the energy system as soon as they arrive at a location.

For testing this charging scheme, a simplified Berlin scenario is used (Rieser et al., 2007), which is available to test new MATSim models. The city of Berlin, Germany is divided into four parts, and each part is assigned a hub. Each hub incorporates a base load curve that corresponds to a typical urban area (residential, industrial or business). The maximum power input, e.g., transformer capacity ratings for hubs 1–4 is defined as 9 MW, 4.4 MW, 8 MW and 8.2 MW, respectively. The maximum usable battery capacity of each PEV is assumed to 10 kWh.

In the test scenario, only car trips with home–work–home and home–education–home activity chains are considered. It contains a 1% population subsample of Berlin with 16,000 agent plans.

In Fig. 4, the energy consumption at the different hubs after applying dumb charging is shown (Scenario A). Hub 1 dominates in consumption, as it is assigned more transportation network links and hence activities. As expected, the energy consumption displays typical morning and evening traffic peaks. When the charging times of each agent are sent to the PMPSS, it produces price control signals for the hubs, as shown in Fig. 5. The price control signal is measured in [Rp./kWh], where one Swiss Franc contains 100 Rappen (Rp.). A price signal of 9.0 Rp./kWh indicates no congestions, whereas peaks above 9.0 Rp./kWh indicate violations of the maximum power capacity of the hubs. The height of the peaks correlates to the intensity of constraint violations in the energy system. Even though the peak load from the PEVs is lower in the evening than during the day, the PMPSS price signal is still higher, indicating a higher base load (e.g., household consumption of electricity) in the evening hours.

3.3. Dual tariff charging scheme

One approach which is used by many utilities today in order to shift load is a dual tariff strategy, also known as “time of use” (TOU) pricing. Electricity consumption is much lower at night than during the day. In order to give people an incentive to shift their consumption (use of washing machines, etc.) to later times, i.e., off-peak hours, the price of electricity is low during the night (e.g., from 9 p.m. to 5 a.m.) and high throughout the rest of the day.

To model such a scenario (Scenario B), the price for electricity is set to 9 Rp./kWh from 9 p.m. to 5 a.m. and to 18 Rp./kWh for the rest of the day. The agents are expected to charge their vehicles with just enough energy to get back home (during high tariff times) and fully charge their PEVs at night after the low tariff pricing starts. The resulting pattern, simulated with the implemented charging module, is depicted in Fig. 6. Agents who need energy to return home start charging their vehicles immediately upon arrival at work. The agents stop charging when a sufficient amount of energy is attained to reach their home location. At 9 p.m. all agents who are at home start to charge their vehicles. The peak generated in this charging scheme is almost twice as high as the one generated by dumb charging, as it contains both the morning and evening energy demand, previously observed in the dumb charging scheme. Since most agents arrive home before 9 p.m., the load peak

Table 1
Overview of Scenarios.

Scenario	Description	Figure
Scenario A	Dumb charging scheme, PHEV	4 and 5
Scenario B	Time of use charging scheme, PHEV, low price from 9 p.m. to 5 a.m.	6
Scenario C	Time of use charging scheme, PHEV, low price from 3 p.m. to 5 a.m.	7
Scenario D	Time of use charging scheme, only EV – low price from 9 p.m. to 3 a.m., else excessively high prices	8
Scenario E	Smart charging scheme, PHEV, initial price control signal based on base load curve	9a–d
Scenario F	Smart charging scheme, PHEV, bad initial price control signal	9e
Scenario G	Smart charging scheme, PHEV, maximum power at hub 1 decreased to 8.5 MW	9f

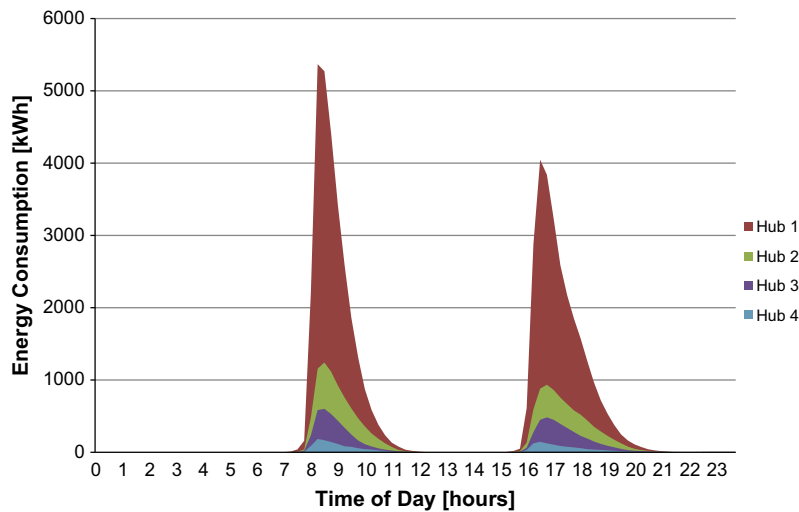


Fig. 4. Vehicle energy consumption with the dumb charging scheme.

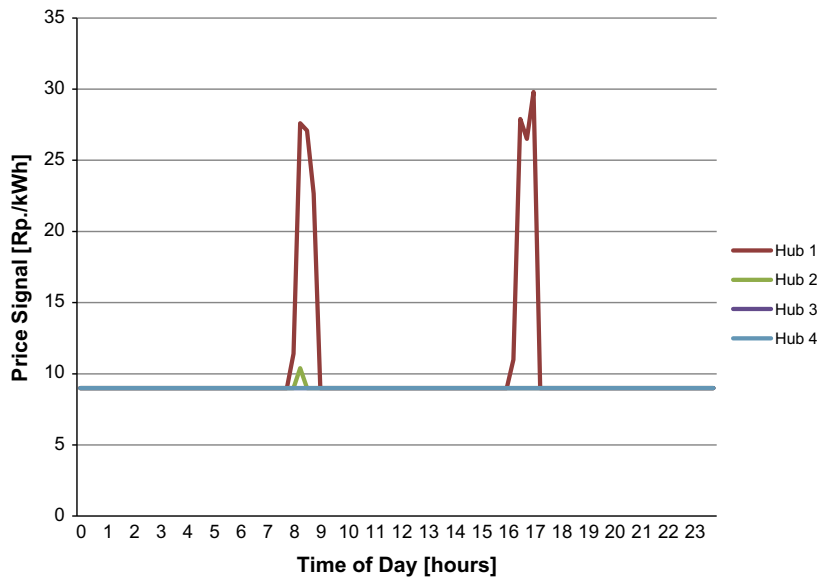


Fig. 5. PMPSS price signal for dumb charging.

perceptibly shifts to hours after 9 p.m. This leads to high energy system loads, resulting in high PMPSS control price peaks with maximum heights of 41.79 Rp./kWh for hub 1 and 41.93 Rp./kWh for hub 2.

It could be argued that the low tariff starting time is set late, and that starting the low tariff period earlier could reduce the intensity of the peak. In a “best-case scenario” (Scenario C), the start of the low tariff could be set to begin before 3 p.m., when people first begin to arrive home, as can be concluded from Fig. 4. Indeed, this approach would help to distribute the load better than in the previous scenario, but the load peak at 3 p.m. would still reach a similar height (see Fig. 7). In fact, it would increase a bit, because vehicle charging in the morning would decrease as agents who are still at work at 3 p.m. and need energy to return home would start charging at 3 p.m. instead of in the morning. In addition, the load peak would be shifted to times where the systems electric load is high already. Hence, such an extreme case would further aggravate the system stress, i.e., high loads, instead of resolving the problem.

Note that in these two dual tariff scenarios, the price of electricity is comparatively cheap to the achievable utility of performing activities, e.g. earning money. Therefore the price does not motivate agents much to change their travel behavior, e.g. their arrival and departure times for activities.

The next example shows that the travel behavior of agents can be changed by increasing the charging price strongly (see Fig. 8). Such an extreme scenario (Scenario D) is merely meant to demonstrate how the price of electricity, integrated in the

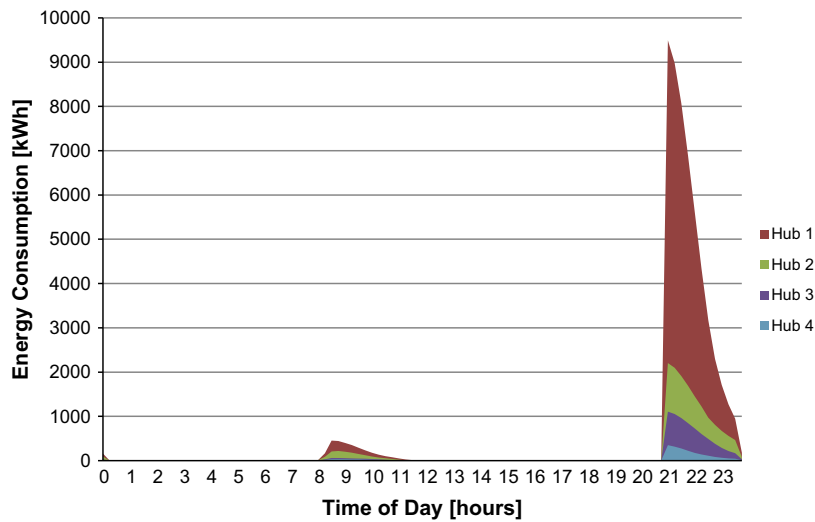


Fig. 6. Vehicle energy consumption with a dual tariff charging scheme (low tariff from 9 p.m. to 5 a.m.).

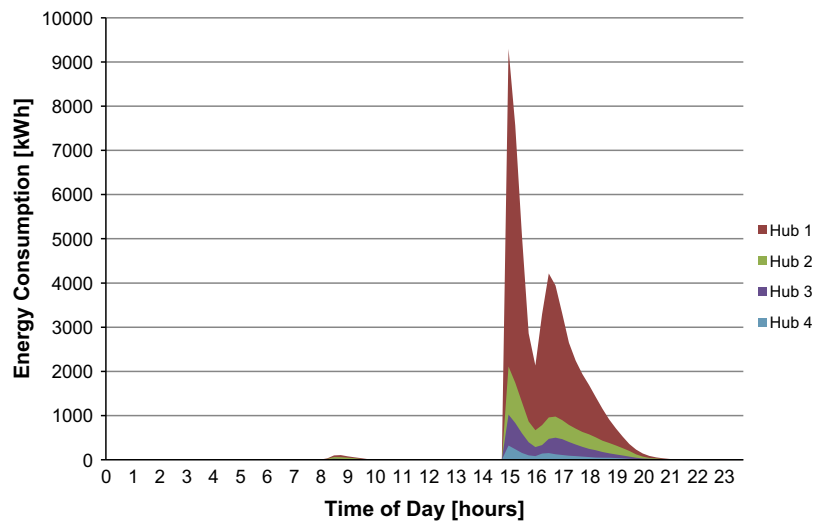


Fig. 7. Vehicle energy consumption with a dual tariff charging scheme (low tariff from 3 p.m. to 5 a.m.).

utility function of MATSim, influences agent travel behavior. For this experiment, agents, who can complete their trips using electricity only, are assigned EVs. Agents with longer trips between activities (who could not complete their travels using EVs), are assigned conventional vehicles and as such are not part of the analysis. As EVs are assigned to agents instead of PHEVs, the EV owners have not the option to switch to gasoline if the electricity price rises above the gasoline price level. Additionally in this scenario agents are not allowed to switch the transportation mode or vehicle type. For this experiment, the low tariff is set between 9 a.m. and 3 p.m. During the rest of the day, the price of electricity is set to a very high value (much higher than the agents can earn through working – corresponding to infinity). Hence, it is vital for the overall utility score of the agents that they charge their vehicles between 9 a.m. and 3 p.m. As the agents in the simulation are not allowed to drop any activities, they leave to work earlier in the morning and come back home immediately. By doing so, the agents can charge their cars for the next day taking advantage of the low electricity prices. The simulation result shown in Fig. 8 is derived from a still-evolving MATSim run; therefore, some agents still charge their vehicles after 3 p.m.

Based on Scenarios B and C, it seems obvious that a pricing scheme which is more granular than the dual tariff pricing scheme could be an alternative, e.g., with 1 h intervals. In such a case, manually connecting and disconnecting the PEVs seems impractical. Instead, an approach that utilizes ICT in both, the vehicles and the energy system, seems more appropriate in order to handle this problem. In the next section a solution is implemented which takes the electric load and network constraints into account and is active in 15-min time steps. The 15-min interval is used because it is the current measuring and accounting interval for electricity in power networks.

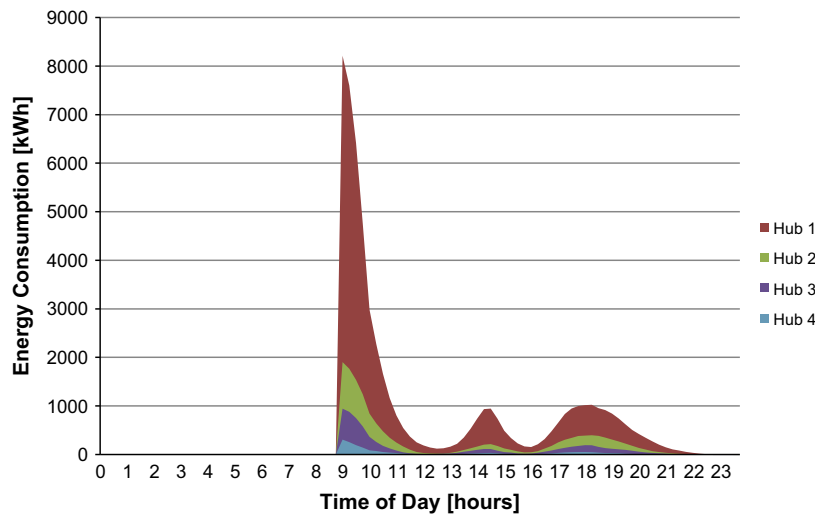


Fig. 8. Vehicle energy consumption with a dual tariff charging scheme (low tariff from 9 a.m. to 3 p.m.). Excessively high charging tariff during the rest of the day.

3.4. Smart charging scheme

There are many ways to implement smart charging. One way is to give more control to the utilities that own the electricity grid. The utilities could receive information from car owners, such as where and how long their vehicles will remain parked and their expected energy consumption for the rest of the day. Based on this information, a central utility controller could determine for the PEVs when and when not to charge. In a V2G scenario, the controller could also determine when to feed power back to the energy system. Appropriate electricity rates could be based on a contract between the utilities and PEV owners, whereby the owners of vehicles, which stay connected to the energy system for a previously announced duration would receive cheaper rates. Longer connection to the energy system could also result in lower electricity prices for the PEV owners, as the PEVs could be used as storage for buffering electricity. Such an approach in which a central entity possesses network, load and generation information and is able to decide when the PEVs are to be charged or discharged is hereafter referred to as *centralized smart charging*.

A second way to implement smart charging would be to publish a charging and discharging rate scale based on time and locality. Software in the PEVs could then decide when to charge or discharge electricity. An algorithm used to make such decisions would depend on data, similar to that needed in the previous case: parking duration and the location of the next activity. In this paper, the approach in which a PEV (and its owner) can decide when or when not to charge the battery is referred to as *decentralized smart charging*.

Whether one of these two general approaches or even a mixture of the two will become established depends on many factors, including legislation, utility policy, car manufacturing and smart grid evolution. It is unclear which approach would lead to a more robust grid infrastructure, an important goal of the smart grid initiative. In this paper the first approach will be presented. One possible application of the second approach has been implemented in PMPSS (Galus and Andersson, 2009a), but it may become necessary for it to be reimplemented in the charging module in order to meet the energy demand of agents' longer activity chains.

3.4.1. Centralized smart charging scheme

In the centralized smart charging model, which has been implemented and tested as part of the current work, a PEV's on-board computer tells the smart grid what trips are planned for the day together with the car's location and the expected duration of the activities throughout the whole day. Although it can be assumed that people are able to make rough estimations of their weekday activities, smaller variations in working times can still happen in real life (see Section 4.3 for further discussion and future work).

To give an example, an agent not only tells the smart grid that he or she will go shopping after work, but also that the agent will drive home directly from shopping. The current policy is set in such a way that the smart charging model ensures that all cars are fully charged by morning in time to start the next day. Providing the central smart entity information on the next trip, e.g. shopping, and on the subsequent trip (driving home) gives the smart charging algorithm a wide range of flexibility. The smart entity can decide when and when not to charge a PEV depending on the electric load while trying to fulfill the constraint that all PEVs should be provided with enough energy, so that they can drive home using electricity only (if possible). Such agent cooperation could be rewarded by the power utilities, e.g., by offering them a lower price per unit of electricity.

The MATSim–PMPSS iteration starts with the above-mentioned vehicle activity information and assumptions about the initial base load. If no initial base load information at a location is given, a constant base load is assumed. Then the smart charging is performed based on the vehicle's energy demand constraints. After each MATSim–PMPSS iteration, the smart charging algorithm determines whether the proposed charging scheme was successful, i.e., the feedback from the PMPSS does not reveal control price signal peaks. Should this not be the case the algorithm tries to reschedule charging times so that energy system constraint violations are avoided.

3.4.2. Simulations

In the first smart charging simulation (Scenario E), the price at the start of the smart charging scheme is based on a control signal directly proportional to the actual base load of each hub. Five combined MATSim–PMPSS iterations are needed before

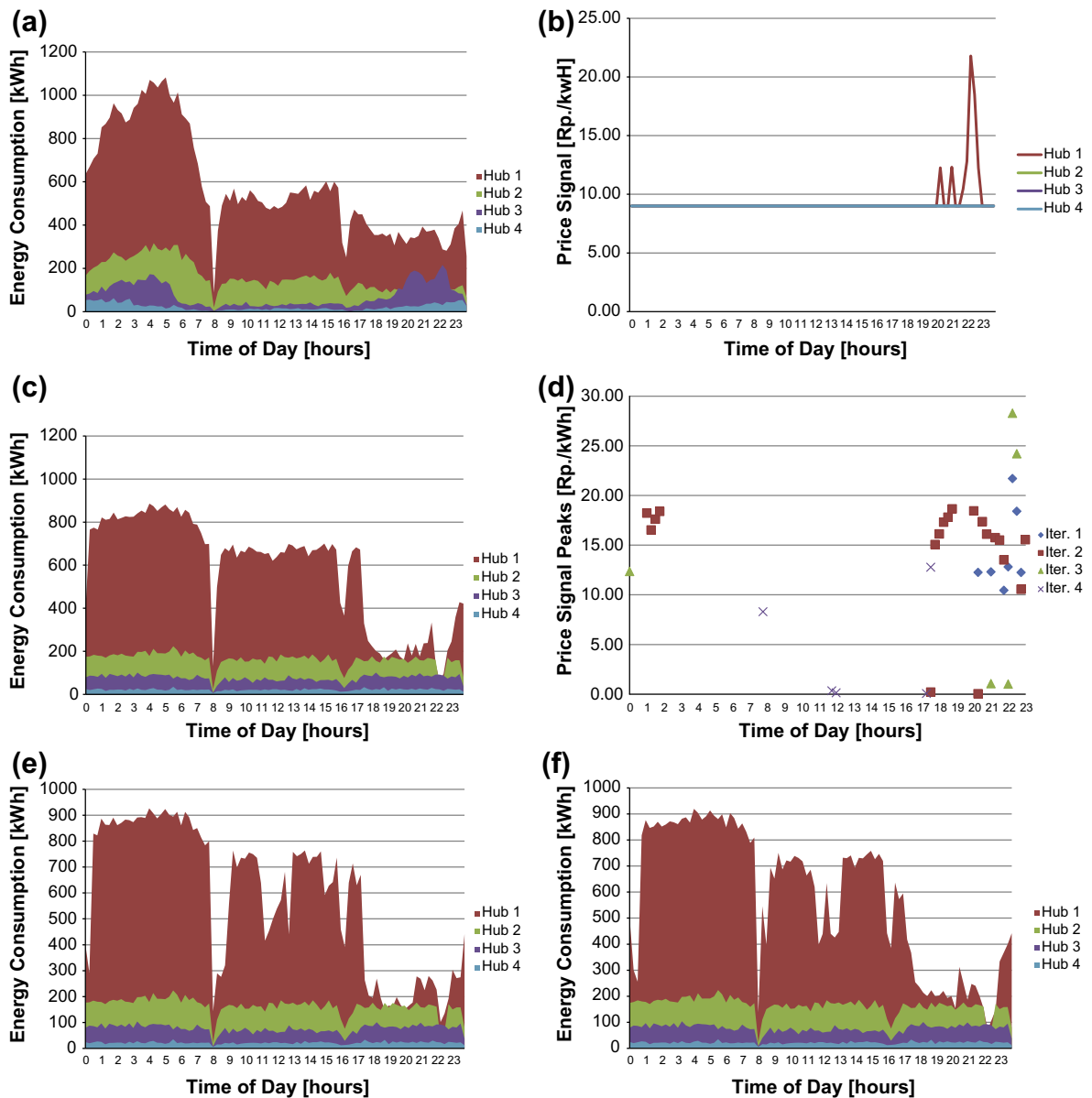


Fig. 9. Smart grid experiments. (a) The PEV electricity demand after the first MATSim–PMPSS iteration. Real base load information available to the charging module. (b) The PMPSS price signals based on the electricity demand in iteration 1. (c) Electricity demand by the PEVs in iteration 5 does not cause any peak price signals. (d) The PMPSS price signal peaks for the first four iterations at hub 1. (e) Experiment using a bad base load assumption. A charging pattern which does not result in any peak price signals is found after seven iterations. (f) The maximum input power of hub 1 is reduced by 0.5 MW compared to all previous experiments. It took three times as many iterations compared to the original experiment to find a charging configuration which did not cause any network violations.

a charging pattern, which does not cause constraint violations of the energy system is found. The vehicles' consumption of electricity in the first iteration of the experiment is shown in Fig. 9a. Even though the charging activity of vehicles is lowest in the evening for hub 1, several price signal peaks occur (see Fig. 9b). The vehicles' consumption of electricity after the fifth iteration (Fig. 9c) does not exhibit any price signal peaks. As expected, the smart charging scheme produces vehicle electricity consumption levels which are much lower than the ones observed for dumb charging or dual tariff charging. Fig. 9d shows the price signal peak intensities for the first four iterations at hub 1. The number of physical energy system constraint violations are lower in the third and fourth iteration than in the first two iterations, as expected.

In contrast to the first simulation (Scenario E), in which the price at the start of the charging scheme is based on the actual base load of each hub, a second experiment is performed (Scenario F) in which wrong information about the base load is given to the charging module to demonstrate that the smart charging scheme can find a solution independent of the initial load information. The initial control signal is set very low from 9 a.m. to 3 p.m. and high for the rest of the day for all hubs. The smart charging algorithm found a solution which does not cause any constraint violations after seven iterations. Fig. 9e shows the vehicles' electricity consumption after the final charging in the seventh iteration. The results are similar to the charging behavior found in Fig. 9c. Even though it takes two iterations more than the previous simulation which uses an initial control signal based on the actual base load, this experiment demonstrates that the smart charging algorithm is able to find a solution independent of the quality of the initial control signal (although it may require additional iterations). Thus it is robust.

Up to this point the maximum power input for hub 1 is 9 MW. When the maximum power of hub 1 is decreased to 8.5 MW (Scenario G), the smart charging scheme finds a solution after 15 iterations even under these tight energy system conditions (see Fig. 9f). This solution is similar to Fig. 9e as only minor electricity consumption peaks needed to be reduced in order to find a charging pattern which does not violate any energy system constraints. When the value is decreased further to 8 MW, the system does not relax, even after 25 iterations. This is because the capacity of the physical energy system is no longer able to accommodate all vehicles.

One point, which is observed in all smart charging scenarios, is that the electricity demand declines at around 8 a.m. and 4 p.m. This occurs, because around these times most agents in the simulation test scenario are traveling by car and hence they cannot charge.

3.4.3. How can the system relax?

The smart charging algorithm uses the PMPSS as a black box to receive information about energy system load for a certain charging pattern. The system could never relax if only the control signal from the PMPSS is considered by the smart charging algorithm. If the charging module produces a charging pattern which does not violate any constraints, the PMPSS just gives back a constant price signal of 9.0 Rp./kWh. If the charging module receives only such input, it is as if the PMPSS sent no information, and the system could again produce peaks.

Therefore to achieve system relaxation, the smart charging algorithm learns about system constraints over iterations. This is done by keeping an internal price signal in the charging module. This price signal is based on MATSim–PMPSS iterations. For example, if there is a constraint violation from 6:15 a.m. to 6:30 a.m., the charging module will remember its intensity. In

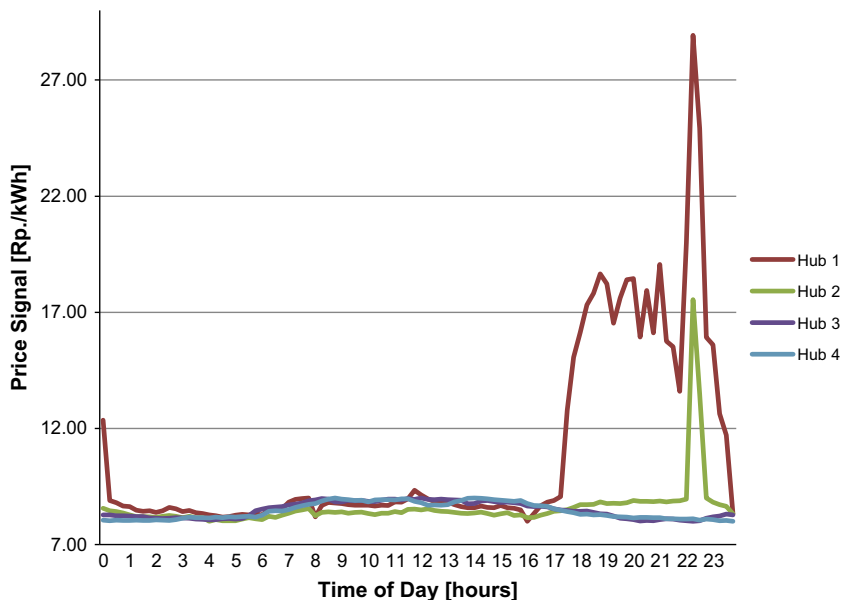


Fig. 10. The internal price signal of the charging module after the 5th iteration of the first smart grid experiment.

the next MATSim–PMPSS iteration the charging module will adapt the charging pattern, and fewer vehicles will charge between 6:15 a.m. and 6:30 a.m.

The internal price signal of the smart charging module from Scenario E just after the 5th iteration is shown in Fig. 10. At this stage the control signal received from the PMPSS does not show any peaks, as no energy system constraint violations appear. This internal price signal of the charging module contains information learned about the base load, the vehicles' energy consumption, and also at which PMPSS price signal level constraints violations could occur. Utilizing this information, the charging module achieved a relaxation of the system and load balancing.

4. Discussion and future work

4.1. Vehicle-To-Grid technology

Although the simulation system and output presented here can help to make rough estimates about the potential of V2G technology in case of power system emergencies, the presented smart charging module still lacks the ability to simulate discharging. Furthermore, a future energy system should be able to cope with distributed energy generation (National Energy Technology Laboratory, 2007). Whether energy is generated from a solar roof on top of a house or is excess energy from the solar roof of an EV, it should be possible to feed it back into the energy system. Whereas energy is traditionally transported by power lines, energy in a V2G-enabled smart grid could be charged in one area of the network, transported via PEVs and fed back at a different spot. For example, a person could charge his car from his solar panel and discharge some of the energy at a nearby shop with a parking lot equipped with electric dis/charging stations. In this case also battery limitations need to be considered. The MATSim–PMPSS framework presented here provides a solid basis for analyzing the dynamics of future smart grids in terms of time and space especially in connection with PEVs.

4.2. Designing the system

The charging module presented within the MATSim–PMPSS iterations can be used to investigate how electricity networks need to be designed in order to supply an additional PEV load. For example some city areas will not have the capacity to support PEV charging. Applying a smart charging algorithm could help: PEVs from such areas could be charged during the day at other locations, e.g., the workplace could become their primary charging place.

4.3. Unexpected demand

It seems reasonable that people with the ability to predict and adhere to their daily plans should be rewarded. To define a fair price for this ability, it is important to find out how much uncertainty the system could handle. Because this, amongst other factors, determines how many underutilized reserve power plants are required in the system. For example, can the smart charging algorithm handle situations in which people's plans change slightly by an order of 15–30 min at random? In a further example, if 5% of the car users departed from their original activity plan during the day, for instance to engage in sports instead of working, how would this impact the energy system, i.e., the electricity grid? How does the energy system behave when little data about people's activities is available (e.g., only information about the next activity of the day)?

The algorithms, which are used in the charging module for smart charging could also be applied to decentralized smart charging in the real world. At the moment, the smart charging module is not tuned towards handling unexpected demands for electricity. If the demand changes during the day, the smart charging algorithm can be run again to adapt to the change.

4.4. Simulating heterogeneous vehicle fleets

In this paper, only the energy consumption of PEVs is tracked. In future research this should change. At the moment, data about the energy consumption of a whole range of vehicle types is being prepared for Switzerland. The data produced will depend on maximum speed limits, average speeds driven and vehicle engine types. This will allow simulating both the energy consumption and the greenhouse gas emissions of the vehicle fleet in Switzerland much more precisely than with the model utilized here.

4.5. Utility of agents

In this paper MATSim runs are used to generate a relaxed traffic demand for the charging module. In Scenario D it is shown that excessively increasing the price of electricity could induce electric vehicle users to change their travel behavior and drive to work earlier. In the future, agents should have more alternatives, e.g. if an agent using an EV is unable to reach his or her destination because it runs out of electricity, the agent might change to a different vehicle type or transportation mode (if no electric fuelling stations are introduced). Conversely, when gasoline prices are high, people might want to switch to PEVs. This would require good estimations of the utility parameters, which could for example be obtained from a stated preference survey (see for example Jäggi and Axhausen, 2011; Erath and Axhausen, 2009).

If V2G technology is included in future versions of the smart charging schemes, the utility might influence travel behavior even more. For example with centralized smart charging, people could get paid according to how long they remain plugged to the energy system. With decentralized smart charging, people would pay and earn different prices for different parking times, locations and durations, so the effect on agent utility could be much greater: The costs of charging and discharging would directly influence the agents' activity times and durations.

4.6. Improving load balancing

At the moment, load balancing (spreading out the electricity load over the day) in the charging module is still quite rough. In the future, the charging module could be extended to include the actual base load as input and to utilize this input when assigning charging slots, instead of just using PMPSS price signal as input.

4.7. Comparing smart charging schemes

Estimates of the cost of modernizing the electricity grid to a smart grid range from hundreds of billions to trillions of USD for the United States alone (Gold, 2009). At the moment, it is unclear even for vehicle charging what type of smart grid algorithms should be incorporated into cars and the electricity system in order to reach optimal gains for all parties involved. Therefore, it seems quite reasonable to simulate and compare different types of charging strategies to see how they can handle different types of situations using the presented framework. One of the next steps therefore is to extend the framework presented here to simplify comparison between smart charging schemes (e.g. centralized vs. decentralized smart charging).

5. Conclusions

Previously, aggregated traffic models have been used to model PEV electricity demand. Such models are appropriate to uncover grid wide electricity demand peaks, but are unable to pinpoint bottlenecks in the electrical network at various voltage levels, as these require high resolution spatial information. To the best of the authors' knowledge, the presented approach is one of the first attempts to successfully use a micro-simulation to overcome this obstacle to model potential electricity demand by PEVs. It is demonstrated that with the presented framework a variety of PEV charging policies can be tested. It is found, that although dual tariff charging schemes are effective in changing user behavior, their application in a real-life PEV context might cause more harm than good to the electricity grid depending on the scenario, e.g. base load and maximum transformer output. Through experiments it is demonstrated, that such problems can be overcome by smarter charging schemes, where communication technology between vehicles and the grid is involved.

The presented approach allows utility owners to analyse electric grids in order to determine whether the network capacity is sufficient for a particular penetration of PEVs. Several research topics surrounding this paper are in progress: At the time of writing, the presented approach is being applied on a real-live scenario to the city of Zurich, Switzerland and its surroundings containing more than one million vehicles. Even though this paper already allows investigation of a variety of smart charging schemes, it also opens ways to new research: One question is how could decentralized smart charging work and if that is a viable solution. Furthermore, it is planned that the presented framework should be extended by adding the possibility of speed-charging stations, which allow fast charging of PEVs. This would help both to optimally plan such infrastructure and to investigate its impact on traffic demand and the electric grid.

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