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Plug-in Hybrid Electric Vehicles and Smart Grid: Investigations Based on a Micro-Simulation

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Abstract Introduction of Plug-in Hybrid Electric Vehicles (PHEVs) could potentially trigger a stepwise electrification of the whole transportation sector. But the impact on the electric grid by electrical vehicle charging is still not fully known. This paper investigates several PHEV charging schemes, including smart charging, using a novel iterative approach. An agent based traffic demand model is used for modeling the electrical demand of PHEVs over the day. For modeling the different parts of the electric grid, an approach based on interconnected multiple energy carrier systems is used. For a given charging scheme the power system simulation gives back a price signal indicating whether grid constraints, such as maximum power output at hub transformers, have been violated. This leads to a corrective step in the iterative process, until a charging pattern is found, which does not violate grid constraints. The proposed system allows to investigate existing electric grids, whether they are capable of meeting increased electricity demand by certain future PHEV penetration. Furthermore, in the future, different types of smart charging schemes can be added into the system for comparison.

1 Introduction

These days fossil fuels are the most important primary energy source in most countries of the world. The transportation sector and especially the individual transport is highly dependent on them. For several reasons, people want to break this dependence. Some people are concerned about the current unsustainable use of the limited fossil resources and its economical and political implications. Others fear the impact of green house gases on climate change. One solution to this problem proposed by many is the electrification of vehicles. It is estimated, that electrification of the

whole transportation sector could shrink energy consumption to one fifth of current consumptions (MacKay, 2009). Therefore the price for driving on electricity is factors cheaper than for gasoline (IEEEUSA, 2007). Furthermore electrification of the transport sector helps to promote sustainable ways of generating electric energy, such as wind and solar energy (Short and Denholm, 2006).

1.1 Plug-in Hybrid Electric Vehicles

Although electric vehicles (EVs) have been around for quite some time, among other factors their limited range has hindered a widespread penetration of these vehicles. Plug-in Hybrid Electric Vehicles (PHEVs) can run using both electricity and gasoline. The batteries of these vehicles can be charged at home or other locations using a usual plug. As most people in general only drive short distances during the week (BFS, 2006), the vehicles will mostly use only electricity. Only during longer trips, gasoline will be used, as the vehicle batteries are depleted.

The introduction of PHEV might also create the demand needed for companies to invest in electrical refueling stations (Bradley and Frank, 2009). This will 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 electric demand during the day is vital, because this ability directly influences the operation of the system and hence revenues and security of supply. A shift to electrical vehicles, will increase the demand for electricity. Furthermore the electric demand coming from these cars is dynamic with respect to time and location. This might lead to increased electric peak loads for which electricity producers would need to utilize more expensive generation units. Furthermore even if the power generators are producing enough power, the network on the medium and low voltage level might be unable to deliver the demand in some network areas (Pecas Lopes *et al.*, 2009). A possible solution to this problem might be provided by a *smart grid* (National Energy Technology Laboratory, 2007).

The idea of a smart grid is to use digital technology in order to introduce more intelligence in control for delivering electric energy from suppliers to consumers. This means, by consolidating data from different sources (e.g. generators, renewable energy production, consumers and network operators and PHEVs) demand and supply are matched favorably for network security and sustainability. One application might be, that PHEV owners and electric utilities sign an agreement, according to which during peak times of demand a vehicle charging will be stopped for a few minutes. In

turn the vehicle owner might be compensated by the utility company or the responsible entity.

1.3 Vehicle-To-Grid (V2G)

Through the deployment of a smart grid the Vehicle-to-Grid (V2G) concept could become reality (Kempton and Tomić, 2005). A V2G implementation would allow PHEVs to also act as suppliers to the grid. There are various potential applications of V2G (Kempton and Kubo, 2000): If the demand for electricity in the grid exceeds the supply during peak hours, the PHEVs could supply peak power. Furthermore, when there is a breakdown of a power system, the cars can supply the grid for a short time and replace expensive, redundant power plants. There are also other applications in the renewable energy sector. Production from renewable energy sources such as wind power is intermittent. For an optimal utilization of it, an energy storage would be needed, e.g. a pumped storage system, but is often not available or limited. If wind power production is too high during low load time intervals, surplus power is often wasted as to system security shall not be compromised. With V2G technology in place, the surplus energy can simply be stored and later supplied back to the grid as needed (Kempton and Dhanju, 2006).

In the next section related work is presented together with the systems on which the current work is based. Thereafter the methodology used and the experiments are described. Before the conclusions, a discussion on the methodology used in the paper together with possible future work is outlined.

2 Related Work and Background

Several studies related to the energy consumption of PHEVs and its influence on the electric grid have been conducted. Just some of the most recent ones are summarized here, which are most relevant to the topic of this paper.

In Pecas Lopes *et al.* (2009) the impact of electrical vehicle charging on the grid has been demonstrated. Especially they looked at bottlenecks in the electrical network, such as voltage drops or line capacity violations. For the study fixed durations of vehicle electrical charging were assumed (e.g. four hours). The vehicle charging places are based on an assumption of 1.5 vehicles per household.

In Plan *et al.* (2009); Letendre (2008), an accumulated energy model has been used to show that by charging PHEVs during the night many more vehicles can be accommodated by the utility grid in Vermont, USA. Furthermore the potential number of cars, which could be accommodated by a smart grid have been estimated. For the experiments the charging time of

the PHEVs is fixed as six hours. The arrival times of cars at work and home have been uniformly distributed between 8am and 9am resp. 6pm and 8pm.

This paper also presents several PHEV charging schemes. In contrast to the previous papers, the charging time and location of the vehicles is based on a model of people performing activities. Therefore the vehicle energy consumptions and charging durations are not constant. The electricity as well as a gas network are spatially and realistically modeled. Hence, they account for actual physical power flow constraints. In the following two sections both the mobility model used for the simulation and the electric grid model are presented (MATSim and PMPSS).

2.1 Multi-Agent Transport Simulation (MATSim)

Traffic simulations can be performed at different levels of detail. On the one hand side, traffic can be modeled as flows consisting of accumulated number of cars; on the other hand it can be modeled as individual vehicles. Simulating each car owner as an agent is called agent based micro simulation and allows tracking of vehicles dynamically in time. This can become very powerful, as the activities an agent performs can be evaluated and assigned a utility. This allows individual decision modeling, such as choosing the path to drive or choosing location for refilling gasoline.

MATSim (MATSim-T, 2008) is a travel demand simulation framework with focus on large scenarios. Simulations with more than seven million agents on a navigation network with around one million links have already been achieved using MATSim (Charypar *et al.*, 2007a; Waraich *et al.*, 2009). Vehicle owners in MATSim are modeled as agents. Figure 1 shows the MATSim simulation process: Each agent has a daily plan of trips and activities, such as going to work, school or shopping. The daily plans, street network and facilities are modeled in the *initial demand* (Balmer, 2007). The plans of all 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 all plans is *scored* and assigned a utility. For example a person with lower travel time has a higher utility than one, which has a longer travel time because of a traffic jam. Furthermore working (earning money) and other activities increase the utility. The goal of each agent is to maximize the utility of its daily plan by *replanning* its day, which is based on a co-evolutionary algorithm (Holland, 1992). Such an algorithm generally tries to find the maximum of a fitness function (in our case the utility function) using crossovers and mutations. In the MATSim context, the utility function has several degrees of freedom, such as the routes, working time, car types chosen, locations visited, and so on. And it can be extended, such that the energy consumption of the vehicle is also part of the utility function. The daily plans are evaluated, and *bad* daily plans (plans

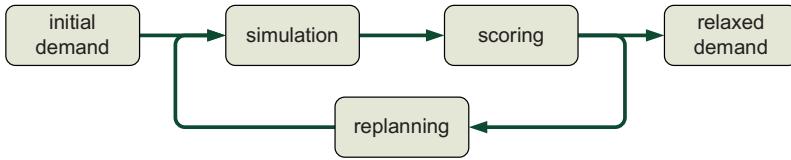


Figure 1: Co-evolutionary simulation process of MATSim

with low performance, respectively low utility) are deleted, which corresponds to *survival of the fittest* in co-evolutionary algorithms. Thereafter new plans are generated based on the previous set of plans. The execution of all plans, its scoring and replanning is called an iteration. The simulation is an iterative process, which approaches a point of rest corresponding to an 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 accumulated one, is that individual agent preferences can be modeled based on a utility function. Furthermore, for simulating constraints of the electric network, detailed location and time data on electricity demand is required. In MATSim high resolution road networks, including individual buildings, can be simulated, so that a mapping to the underlying grid infrastructure is possible.

2.2 PHEV Management and Power System Simulation (PMPSS)

Figure 2 visualizes the power system. It includes multiple energy carriers. Each node in the power network is modeled by an energy hub. Energy hubs are entities interconnecting multiple energy carriers in order to optimize the supply of the given consumer demand. They are elaborated in Geidl and Andersson (2005) while Geidl and Andersson (2007) and del Real *et al.* (2009) describe their application in networks. Each hub can be understood to model an urban area (e.g. residential, business or industry) since real electricity load curves are used to model the demand. The hubs incorporate a furnace in order to meet heat load, a transformer in order to supply electric loads and a combined heat and power (CHP) turbine in order to interconnect and relieve the energy networks.

Furthermore, the electricity- (Wood and Wollenberg, 1996) and gas lines are modeled according to their physical laws, respectively. The power system at hand can hence be understood to model a possible fu-

ture architecture because the share of distributed generation is very high (Ackermann *et al.*, 2001; Chicco and Mancarella, 2009). Furthermore, each area incorporates a PHEV management device called PHEV manager. It is introduced and elaborated in Galus and Andersson (2008) while Galus and Andersson (2009a) deploys it in a network. The managing entity signs the vehicles connected in its area into the scheme and performs optimizations in order to investigate whether the power system is capable of supplying this additional load. The constraints for total PHEV power consumption are derived through the network state including the base load. Typically, transformer- and line capacities as well as voltage levels in medium- and low voltage networks limit the transmittable power at nodes (e.g. hubs). For simplicity, only the transformer and the CHP capacities were introduced here as limiting factors. For the PHEV Manager optimization scheme, a benefit function and an individual utility are determined (Galus and Andersson, 2008). The functions depend on individual state of charge (SOC), demanded SOC at departure and departure time. In congested network cases the PHEV manager creates a price signal, derived from the optimization, that is directly correlated with the network state, the number of PHEVs demanding resources and the urgency with which they demand it. This price signal is different from system energy prices, which are used to minimize overall energy carrier consumption costs.

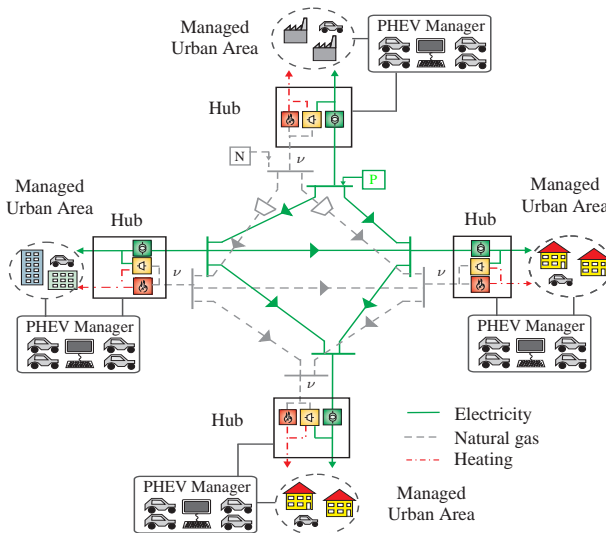


Figure 2: 4 Hub network including PHEV Managers for urban areas

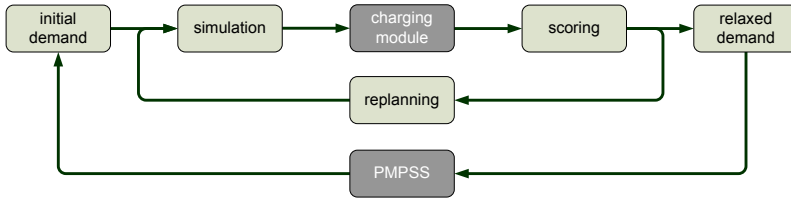


Figure 3: Charging module and PMPSS added into to the MATSim simulation process

3 Methodology and Simulations

3.1 Overview

In order to investigate different charging strategies, MATSim and PMPSS have been combined and a charging module has been implemented (see Figure 3). The charging module gets information about vehicle movement and vehicle parking times from the MATSim micro-simulation. From this information it derives the energy consumption of the vehicles, which are based on a simple PHEV model simulating actual driving cycles in cities (Galus and Andersson, 2009b). For the scenarios, which have been investigated, standard plugs with 3.5kW (240V, 16A, single phase, standard in Switzerland) power have been assumed. The charging module knows where which vehicle has been parked for how long. Three different charging strategies are implemented: *Dumb Charging*, *Dual Tariff Charging* and *Smart Charging* (see sections 3.2, 3.3 and 3.4, naming follows Pecas Lopes *et al.* (2009)). After assigning charging times to the cars, the charging module can assign scores to agents (e.g. price for the electricity charged). After relaxation of the MATSim simulation process, the charging times, locations and state of charge of the agents are sent to the PMPSS. The PMPSS determines, whether the electric demand based on these charging times together with the base load violates certain physical network conditions, as described in the PMPSS section. Based on constraint violation and the PHEV Manager optimization of the PMPSS a price signal is given back to the charging module. If the PMPSS price signal indicates a congestion in the network, a new MATSim iteration is started. If no constraint violation occurs, the physical network can meet the electric demand by the PHEVs and a charging pattern has been found which fulfills it. The initial price that the charging module uses depends on the charging scenario to be simulated, e.g. dumb charging or dual tariff charging.

As MATSim simulates a 24 hour day it is assumed, that the agents start in the morning with a full battery and charge it fully until the next morning, so that they have a full battery again, when starting the next day.

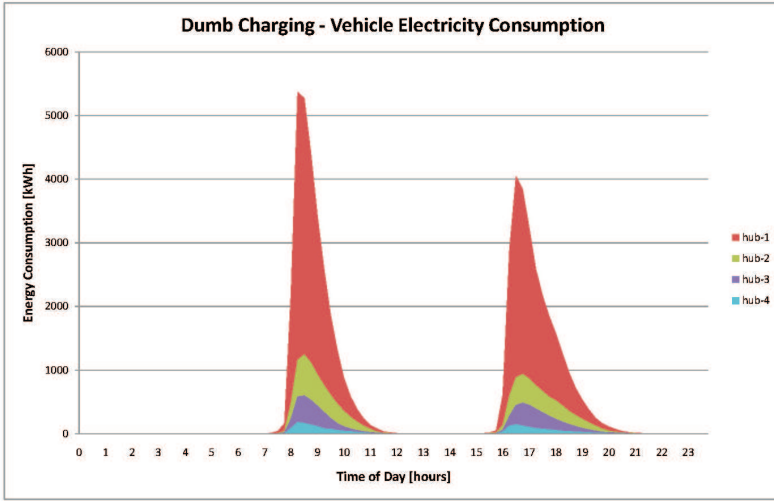


Figure 4: Vehicle energy consumption with the dumb charging scheme

3.2 Dumb Charging

Dumb Charging means, that a car starts charging immediately when it arrives somewhere, trying to fully recharge its battery. The dumb charging scheme assumes, that electricity costs are the same during the whole day and therefore people just connect their PHEV to the grid, when they arrive at some location.

An experiment with around 16 thousand PHEVs has been performed with this charging scheme. The city of Berlin has been divided in four parts and each of them has been assigned to a hub. Each hub has a base load curve, corresponding to a typical area in a city (residential, industrial and business). The maximum input powers (e.g. transformer ratings) for the different hubs 1 to 4 are 9MVA, 4.4MVA, 8MVA and 8.2MVA. The maximum usable battery capacity of each PHEV is 10kWh.

The daily activity plans of the PHEV owners and their activity locations are based on a Berlin scenario (Rieser *et al.*, 2007), from which a simplified test scenario is derived in MATSim. In this scenario, only car trips are considered with activity chains of the form home-work-home and home-education-home. A 1% population subsample of Berlin is used, resulting in 16 thousand agent plans.

In Figure 4 one can see the energy consumption at the different hubs. Hub 1 dominates in consumption as it has been assigned more network links. As expected the energy consumption follows the typical morning

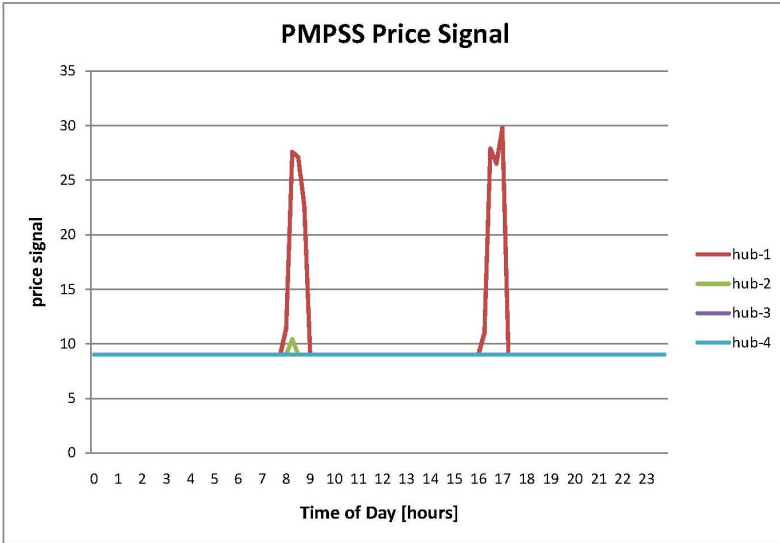


Figure 5: PMPSS price signal for dumb charging

and evening traffic peaks. When the charging times of each agent are given to the PMPSS, it produces price signals for the hubs, which are shown in Figure 5. A price signal of 9.0 indicates no congestions whereas peaks above 9.0 indicate violations of maximum power capacity of the hubs. The height of the peaks correlates to the intensity of constraint violations in the grid. Even though the peak load from PHEVs is lower in the evening than during the day, still the PMPSS Price signal is higher, indicating a higher base load (e.g. household electricity consumption) in the evening hours.

3.3 Dual Tariff Charging

One approach to shift load, which is used by many utilities nowadays is dual tariff pricing (i.e. time of use pricing (TOU)). Understandingly, during night there is much less electricity consumption than during the day. In order to give an incentive to people to shift their consumption (washing machines etc.) to later evening hours, i.e. off-peak hours, the price during the night is low (e.g. from 9pm to 5am) and high throughout the rest of the day.

In order to simulate such a scenario, the price for electricity has been set to 0.09 CHF/kWh (Swiss Francs per kWh) from 9pm to 5am and to 0.18 CHF/kWh during the rest of the day. The agents in this case would just charge enough energy for getting back home during high tariff times and

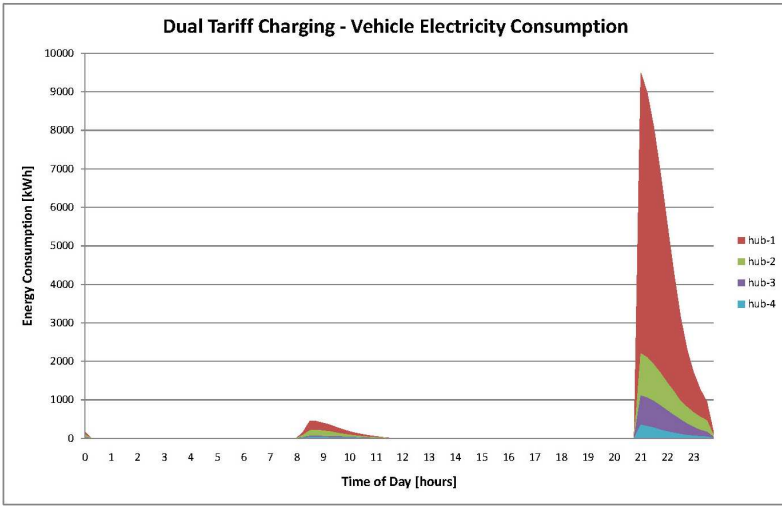


Figure 6: Vehicle energy consumption with a dual tariff charging scheme (low tariff from 9pm to 5am)

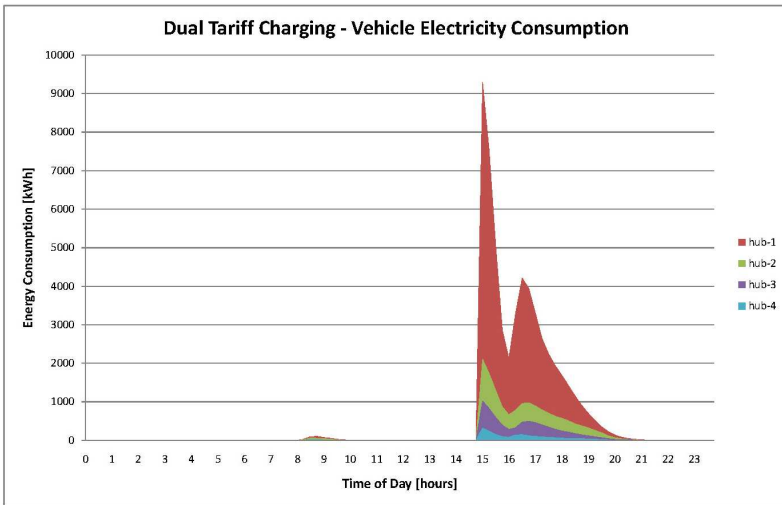


Figure 7: Vehicle energy consumption with a dual tariff charging scheme (low tariff from 3pm to 5am)

charge at night when low tariff pricing starts. The charging module, implements this. The resulting pattern is shown in Figure 6. One can see, that

agents which need energy for getting back home, immediately start charging upon arrival at work and disconnect, when they have enough energy to get back home. At 9pm all agents start charging their vehicles, which are then already at home. The peak generated by this scheme is almost double as high as the one for dumb charging, because it contains the load of both the morning peak and the evening peak observed in the dumb charging scheme. Especially as most agents have already arrived home before 9pm, the charging peak is shifted to hours after 9pm. This results in grid constraint violations, resulting in PMPSS peaks with maximum height of 41.79 and 41.93 for hub 1 and hub 2 respectively.

One might argue, that in this example the low tariff time is set too late and starting the low tariff time earlier could reduce the intensity of the peak. In the best case, the low tariff starting time could be set to before 3pm, where the first people start arriving at home as can be concluded from Figure 4. Indeed this approach helps to distribute the load more than in the previous case, but still the peak at 3pm shows around the same height as previously (see Figure 7). In fact, it increases a bit, as the charging in the morning has decreased. The reason for this decrease is that some agents, which are still at work at 3pm and which need energy for getting home, start charging at 3pm instead of in the morning.

In the two dual tariff scenarios just presented, the charging price is comparatively low. It will not motivate people to change their travel behavior (e.g. arrival and departure times for activities).

In the next example, it is shown that by increasing the charging price excessively, the travel behavior of agents could be changed (see Figure 8). This is just meant to demonstrate, that the charging price is part of the utility function of MATSim. For this experiment all PHEVs have been configured to run on electricity only. This constraint towards vehicles running only on electricity is required for this experiment, as PHEVs would just stop charging if the electricity price is above the gasoline price and would just drive using gasoline, when running out of electricity. Furthermore only those vehicles are considered, which can perform the whole day on all electric drive, meaning that the distance between two activity locations, such as home and work is not longer than the maximum battery capacity. For this experiment, the low tariff has been set between 9am and 3pm. During the rest of the day, the charging price is set to an excessively high value (corresponding to infinity). It is vital to the utility score of the agents to charge between 9am and 3pm. As the agents are not allowed in the simulation to drop any activities, they go to work earlier in the morning and come back home immediately. By doing so, the agents can recharge their car for the next day cheaply. The simulation result shown is derived from a still evolving MATSim run, therefore some agents still charge after 3pm.

Although under such high pricing, as demonstrated in the previous experiment, people would react to the price level and leave for home earlier,

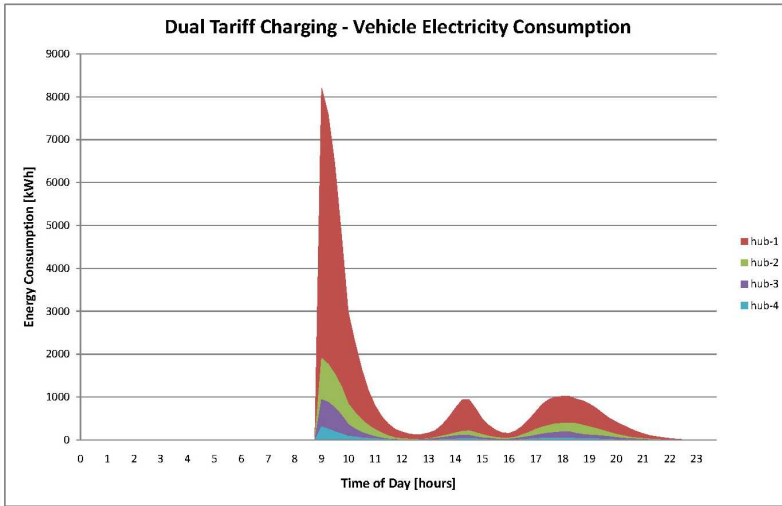


Figure 8: Vehicle energy consumption with a dual tariff charging scheme (low tariff from 9am to 3pm). Excessively high charging tariff during the rest of the day.

in reality it seems unreasonable that people would react to actual energy prices this way. It is clear, that a pricing scheme is needed, which is more granular than the dual tariff pricing scheme e.g. one hour intervals. But in this case manually connecting and disconnecting the PHEVs seems impractical. Instead an approach where digital technology is used in vehicles and the electric grid to handle this problem, seems more appropriate. In the next section a solution implemented in the context of a smart grid is proposed, which takes the grid load and constraints in 15 minute steps into account. The 15 minute interval is used, as it is the maximum resolution the PMPSS offers at the moment.

3.4 Smart Charging

There are many ways to perform smart charging. One way to do it would be to give more control to the utilities, owning the grid. The utilities would receive information from car owners, such as how long they will remain parked somewhere and information regarding their energy consumption for the rest of the day. Based on this, the grid could send signals to the PHEVs when to charge and when not. In case of V2G, the grid will also tell the PHEVs when to discharge. The electricity rates could be based on a contract between utilities and PHEV owners, which delivers cheaper energy to PHEV owners which can adhere to the planned duration for staying connected to the grid. Also staying longer connected to the grid could result

in lower electricity prices for PHEV owners, as the PHEVs could be used as a storage for buffering electricity. This approach where a central entity, possessing network-, load- and generation information, is able to decide charging and discharging is called *centralized smart charging* from hereon.

A second way to implement smart charging would be, that the utility owners publish prices for charging and discharging, based on time and location. Software in the PHEVs could then decide whether to charge or discharge. An algorithm used for making such decisions would depend on similar data, as needed in the first case: The duration the car will remain parked and the location of the next activity. This approach, where the PHEV owner can decide, when to charge and when not, is called *decentralized smart charging* in this paper.

Which of these two general approaches will be used or even a mixture of the two, depends on many factors such as legislation, utility policy, car manufacturing and smart grid evolution. It is unclear which of these approaches would lead to a more robust grid infrastructure, which is one of the important goals of the smart grid initiative. In this paper the first approach is presented. One possible implementation of the second approach is already implemented in the PMPSS (Galus, 2008; Galus and Andersson, 2009a), but a reimplementaion of it could be necessary within the charging module in order to account for the energy demand of longer activity chains of agents.

3.4.1 Centralized Smart Charging

In the first smart charging model, which is implemented, the PHEV on board computer tells the smart grid what activities are planned for the day together with location and duration for the whole day. Although it can be assumed, that people would be able to do rough estimations of their week day activities, still smaller variations in working times could happen in real life. At the moment this is not handled in the charging module, but it might be modeled in future (see section on future work).

To give an example, the agent not only tells the grid, that it will go shopping after work, but also that the agent will drive from shopping directly home. The current policy set is that the smart charging must assure that all cars are fully charged until the next morning for starting the next day. By giving information to the central smart entity, not only about the next trip (e.g. shopping), but also information about the consequent trip (driving home), the smart charging algorithm has a much wider range of flexibility. The smart entity can decide when to charge a PHEV and when not depending on the grid load while trying to fulfill the constraint, that PHEVs should be provided enough energy to get back home. Such cooperative behavior of agents could be rewarded by power utilities, e.g. by offering them a lower electricity price per unit.

The MATSim-PMPSS iteration starts with information just mentioned and assumptions about the initial base load. If no initial base load information is given, a constant base load is assumed. Then the smart charging is done, based on the vehicle energy demand constraints. The goal of the smart charging algorithm is, that all people must get home only using electric energy if possible. After each MATSim-PMPSS iteration the smart charging algorithm determines, based on the feedback from the PMPSS, if the proposed charging scheme was successful and it tries to reschedule chargings, so that grid constraint violations can be avoided.

3.4.2 Simulations

In the first simulation the price at the start of the smart charging scheme is based on a signal directly proportional to the actual base load of each hub. Five combined MATSim - PMPSS iterations are needed until a charging pattern is found, which does not cause any violations in the electric grid. The vehicle electricity consumption for iteration one of the experiment is shown in Figure 9a. Even though, the energy charging activity of vehicles is lowest in the evening for hub one, still several price signal peaks occur (see Figure 9b). The vehicle electricity consumption after the fifth iteration (see Figure 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. In Figure 9d, for the first four iterations the price signal peak intensities are shown. The number of grid violations in the third and fourth iteration are clearly lower then for the first two iterations, as expected.

In the previous simulation, the price at the start of the charging scheme was based on the actual base load of each hub. In order to demonstrate that the smart charging scheme finds a solution independently from the initial price, an experiment with a different initial price was done, by giving totally wrong information about the base load to the charging module. The initial price was set very low from 9am to 3pm for all hubs and high for the rest of the day. The smart charging algorithm found a solution after 7 iterations, which did not cause any constraint violations. In Figure 9e the final charging electricity consumption after iteration 7 is shown. The results are similar to the charging behavior found in Figure 9c. Even though it took two iterations more than using an initial price based on the base load, it demonstrates that the smart charging algorithm is able to find a solution independently from the quality of the initial price.

In the next simulations several different levels of maximum input power for hub 1 have been analyzed. Till now the maximum power input for hub 1 was 9MVA. Decreasing the value to 8MVA the system does not relax even after 25 iterations. This is due to the fact, that the capacity of the physical energy system is not capable any more to accomodate all vehicles. By

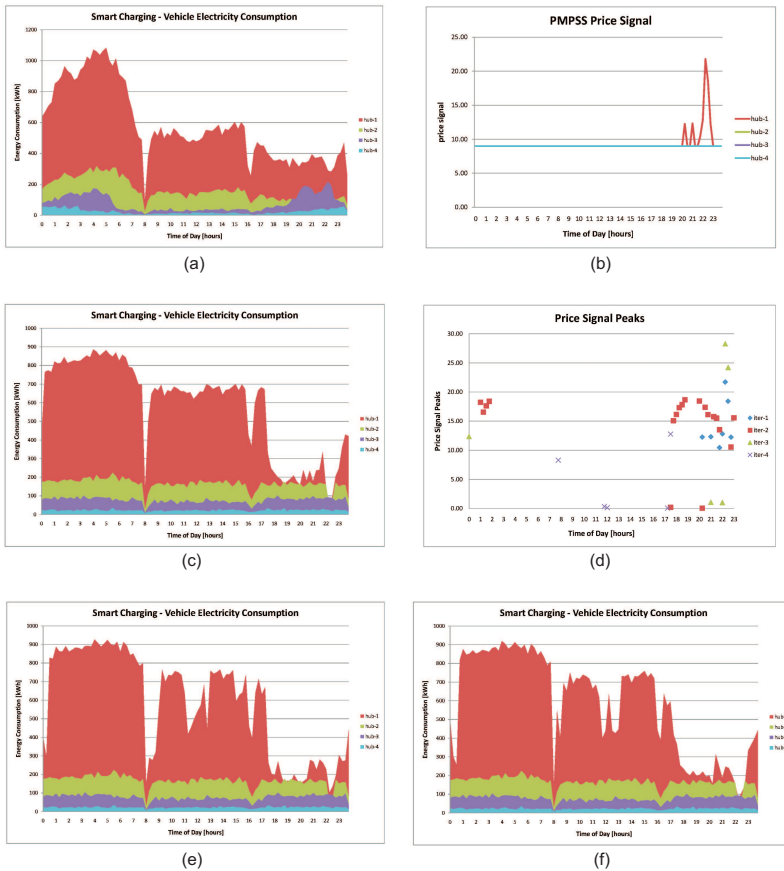


Figure 9: Smart Grid Experiments. **(a)** The PHEV electricity demand after the first MATSim-PMPSS iteration. Real base load information available to the charging module. **(b)** The PMPSS price signals based on the electricity demand in iteration 1. **(c)** Electricity demand by the PHEVs in iteration 5 does not cause any peak price signals. **(d)** The PMPSS price signal peaks for the first four iterations. **(e)** The same experiment using a bad base load assumption. A charging pattern is found after 7 iterations, which does not result in any peak price signals. **(f)** The maximum input power of hub one is reduced by 0.5MVA 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.

changing the maximum power of hub one to 8.5MVA, the smart charging scheme finds a solution after 15 iterations even under the tighter grid conditions (see Figure 9e). The solution looks similar to the previous ones. Only minor energy consumption peaks needed to be reduced in order to find a charging pattern which did not violate any grid constraints.

3.4.3 Load Balancing of the Base Load

The PMPSS only provides information, if energy system bottlenecks are apparent, for the rest of the time it gives back a constant signal (with value 9.0). Clearly, the base load is not constant while the price signal is. The load is composed of base- as well as PHEV load. Additional information about the base load in an area is crucial, especially when no grid constraint violations occur. In this case as information about the base load is missing, the smart charging algorithm would just distribute the vehicles as uniformly as possible over the day, which is not optimal. Therefore the smart charging algorithm makes use of the base load curve for better load balancing.

3.4.4 How can the System Relax?

The smart charging algorithm uses the PMPSS as a black box to receive information about grid constraint violations for a certain charging pattern. The system can never relax, if just the price signals from the PMPSS would be taken as input to the smart charging algorithm. Because 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. If the charging module is given such input, it is as if no information would be given from the PMPSS and the system would potentially again produce peaks.

To achieve system relaxation, the smart charging algorithm has been extended to learn about the constraints of the grid, which is done by keeping an internal price signal in the charging module. This price signal is based on the MATSim-PMPSS iterations. For example, if there is a constraint violation from 6:15am to 6:30am, the charging module remembers the intensity of the constraint violation. In the next MATSim-PMPSS iteration the charging module will adapt the charging pattern and fewer vehicles will charge between 6:15am and 6:30am.

The internal price signal from the first smart charging experiment is shown in Figure 10 just after the 5th iteration. At this state the PMPSS price signal is just a constant of 9.0 as there are no constraints violations happening in the grid. This internal price signal of the charging module contains information about both the base load, the vehicle energy consumption, and at which PMPSS price signal level constraints violations could happen. Utilizing it, the charging module achieves a relaxation of the system including load balancing.

4 Discussion and Future Work

4.1 Vehicle-To-Grid

Although the presented system and its output can help to do rough estimates about the potential of V2G in case of power system emergencies, the

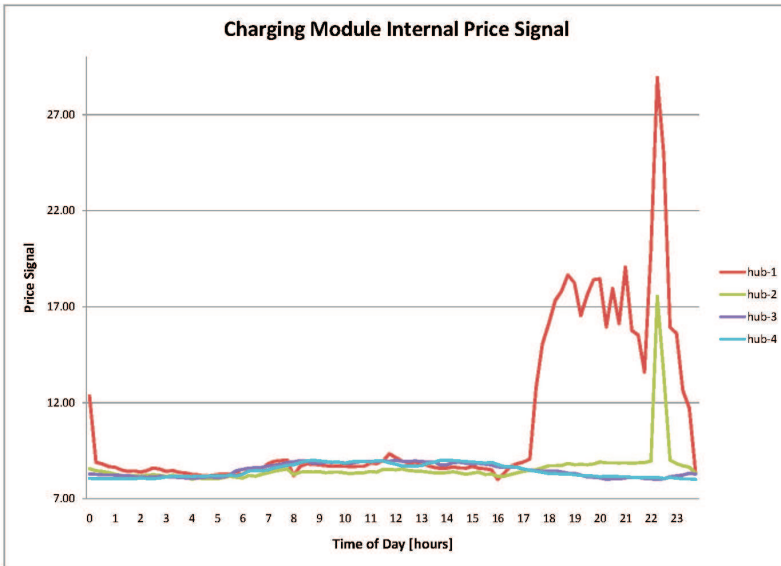


Figure 10: The internal price signal of the charging module after the 5th iteration of the first smart grid experiment.

smart charging module is still lacking the ability to simulate discharging. The V2G ability adds a new dimension, because PHEVs can act as buffers for renewables, such as solar power and wind power. In MacKay (2009) the electricity prices for the UK are reported for 2006 and 2007 and within a day the range of electricity can range between 20 and 120 £/MWh. Therefore being able to store electricity and feed it back to the grid can become profitable both for PHEV owners and utilities.

Furthermore as in future more and more intermittent energy sources such as wind and solar should replace fossil ones, the role of V2G becomes even more important. One might argue, that the intermittency of wind is only given for single windmills and wind farms spread geographically have a stable average output, but this is not fully true. Again in MacKay (2009) the collective output from 1632 windmills in UK is reported for 5 months. In that time period on 17 days the collective output was less than 10% of the windmills full capacity. In this case collective PHEVs could be used as a large distributed energy storage.

A future grid should be able to cope with distributed energy generation (National Energy Technology Laboratory, 2007). If energy is generated from a solar roof on the top of a house or excess energy from the roof of an electric vehicle, it should be possible to feed it back into the grid. Whereas traditionally energy was transported using power lines, within a

V2G enabled smart grid, energy can be charged in one area of the network, transported via PHEVs and fed back at a different spot in the electric network. For example, if a person charges his car from his solar panel and discharges some of the energy at a nearby shop of a parking lot. The presented MATSim-PMPSS solution provides a solid basis for analyzing the dynamics in time and space of the future smart grid in connection with mobility, although several extensions are needed in future.

4.2 *Dimensioning the System*

By using the charging module presented within the MATSim-PMPSS iterations, it can be investigated how electricity networks need to be dimensioned in order to supply additional PHEV load. Even if some city parts do not have the grid capacity to support PHEV vehicle charging from the beginning, applying a smart charging algorithm could help: The charging of such PHEVs could already be done during the day at another location, e.g. the working place could become the primary charging place for such vehicles.

4.3 *Unexpected Demand*

In many parts of life, there is a reward for being able to predict correctly, e.g. predicting the weather or stock market prices. It seems reasonable, that such people should be rewarded by the electric grid owners, who can predict their daily plans and adhere to it more precisely. For defining a fair price for this ability, it is important to find out, how much uncertainty the system could handle. For example is it possible for the smart charging algorithm to handle the case, when people's plans change slightly in order of 15 to 30 minutes at random? Furthermore if for example 5% of the people would change their daily activity plan initially set during the day, e.g. going for sports instead of working, how would this impact the grid? How does the electric grid behave, if less data is available about peoples activities (e.g. only information about the next activity of a day)?

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

4.4 *Simulating Heterogeneous Vehicle Fleet*

In the paper all vehicles simulated were PHEVs. In future this should change. At the moment data about vehicle energy consumptions for a whole

range of vehicle types is being prepared for Switzerland. The data produced depends on maximum road speed, average speed driven and vehicle engine type. This will allow to simulate both the energy consumption and the green house gas emissions of the vehicle fleet in Switzerland much more precisely than with the model utilized here.

4.5 Utility of Agents

In the paper the MATSim runs have been used to generate a relaxed traffic demand for the charging module. In figure 8 it was shown, that by increasing the electricity price excessively, electric vehicle users might change their travel behavior and travel earlier to work. Smart charging till now, has only little effect on the overall utility of an agent in MATSim, e.g. using shorter route and thereby consuming less energy. In future when people are allowed to switch vehicle types in MATSim, they might do so. For example if an agent is using an electric vehicle and he is unable to reach his destination because he runs out of electricity, the agent might change to a different vehicle type or transportation mode (if no electric fueling stations are introduced). Or when gasoline prices are high, people might want to switch to PHEVs or EVs. This would require good estimations of the utility parameters, which could be obtained for example from a stated preference survey.

With future versions of the smart charging schemes including V2G, the utility might even have more influence on the travel behavior of people. Because with centralized smart charging, people might get paid for how long they remain plugged to the grid. With decentralized smart charging where people pay and earn different prices for different parking times, locations and durations the effect on the agent utility could be much more broader. Because in this case the cost associated with charging and discharging has direct influence on the activity times and durations of the agents.

4.6 Improving Load Balancing

At the moment, the load balancing in the charging module is quite coarse. In future the charging module could be extended, so that it takes the actual base load as input and takes it into account, when assigning charging slots. At the moment just the shape of the base load curve is given as input.

4.7 PHEV and EVs

Whereas PHEVs can run both on gasoline and electricity, EVs do not have this advantage. PHEVs can continue driving on gasoline, if the electricity price rises but EV users might even pay higher prices for electricity than gasoline during peak demand. This distinction needs to be taken into ac-

count in a future model.

4.8 Comparing Smart Charging Schemes

The cost estimates for modernizing the electric grid to a smart grid ranges from hundreds of billions to trillions of USD for the United States alone (Gold, 2009). At the moment, even for vehicle charging it is unclear, what type of smart grid algorithms should be incorporated into cars and the utility grid to reach optimal gains for all parties involved. Therefore it seems quite reasonable to simulate and compare different types of charging strategies and how they can handle different types of situations. One of the next steps therefore is to generalize the concept presented and to provide a framework, in which many types of charging schemes can be evaluated, as proposed in Waraich (2009). For example comparing centralized vs. decentralized charging schemes.

5 Conclusions

Previously, aggregated traffic models have been used for modeling PHEV electricity demand. Such models often fail to uncover grid constraints, for which high resolution electric demand data is required, both in terms of space and time. To the best of the authors' knowledge, this paper is the first approach using a micro-simulation to model detailed traffic and electricity demand to investigate charging of PHEVs and EVs. An iterative method is proposed, in which decisions and behavioral changes of car owners are based on individual utility scores.

It is demonstrated, that although dual tariff charging schemes are effective in changing user behavior, their application within the PHEV context might cause more harm than good. By proposing a centralized smart charging method, it is shown how a charging pattern is found, which does not violate physical grid constraints. By applying this method, grid owners can analyze, if their electrical grid is prepared for a certain penetration of PHEVs and EVs. For the future grid, this paper proposes a framework for investigating a variety of smart charging schemes.

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