INTEGRATED ANALYSIS OF TRAFFIC AND POWER FLOWS

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ABSTRACT

This paper presents a new approach to assess the impact of electric vehicles on power distribution systems. Therefore a tool is developed, allowing a simultaneous and interacting simulation of traffic flows and electricity networks. Thereby various strategies for controlled charging can be examined. The expected result is the confirmation of a stringent necessity for this integrated modelling approach which particularly takes into account the spatiotemporal character of the subordinated optimization problem.

INTRODUCTION

The expected strong increase of electrical mobility represents a new challenge for network operators regarding the safe and reliable operation of energy networks. In particular, the individual and political expectations of a predominantly operation of electric vehicles with green energy will stimulate the further development of renewable energies and power grid infrastructure. Positive side effects can arise for network operators by vehicles providing ancillary services with their batteries. The design of load management strategies regarding the optimal operational management and integration of electric vehicle fleets in the electrical grid is of particular importance.

Nowadays in many countries the provision of a charging infrastructure for electric vehicles plays a minor role in energy supply system planning. This is due to independently conducted planning of transport infrastructure (roads etc.) and power supply networks in the past. Furthermore, the control of charging processes aiming at a better utilization of wind and solar energy can cause overloads in local network segments, especially in medium and low voltage networks. Taking local network constraints into account, while developing charging control strategies, it is therefore mandatory to consider the spatial distribution of electric vehicles. In the end mobility patterns and electrical supply infrastructure are linked by georeferencing. The idea to this approach has been discussed in [1] the first time.

TRAFFIC MODELLING

The traffic simulation software MATSim [2] allows conducting agent-based simulations. It is a mesoscopic model [3] in which each vehicle is represented by an agent. Hereby the first step is to generate a traffic demand, explicitly for each vehicle agent, in the form of activity chains. Therefore population data from a census is used, providing information about location, age, gender and employment status. Subsequently, activity chains are generated from this data. As a whole, the statistics of the population meet the data from traffic researchers. Additionally individual security needs can be modelled for example. A similar approach with a high spatial resolution of the traffic simulation has been proposed in [5]. The paper presented here is going one step further by extending the high spatial resolution to the electricity network and thus allowing to simulate charging strategies which do not only take into account grid constrains but also consider the spatiotemporal coupling of the charging processes and allow to optimize the operational management of the gird.

Geographical distribution of Vehicles

In order to create a realistic model, the street network was extracted automatically from existing, freely available geographic maps. This is done by using geographical information systems (GIS). In order to generate schedules for the vehicles, information is necessary about where the vehicle users live, where they go to work and to which destinations they do private journeys. Of particular importance for the new approach is the modelling of road networks and traffic. With a precise knowledge of the position of each vehicle, statements can be done concerning the availability and the potential of the vehicles and their storage capacity that are located in a certain region. In a further step, the knowledge on driving behaviour and driving destinations is used to control the charging processes.

The spatial data includes not only records about street routes, but also provides information on land use. This additional information is extracted into further layers. To improve the distribution of vehicles, another layer was introduced, which includes socio-economic data as shown in Figure 1. This data allows the detection of correlations between population structure, location factors and market activities. Especially for the analysis of local conditions, the purchasing power index can be used in a targeted manner. To perform an exact analysis of the impact with different penetration rates, socio-economic data has become a major focus of consideration. Based on these data, the influence of purchasing power of a household on the decision process of buying an electric vehicle, and thus the achievable penetration rates in geographic areas, can be analysed.

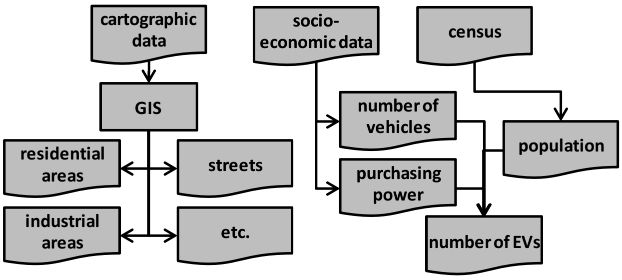

Figure 1: Processing of input data

Hereinafter follows the generation of traffic by creating a vehicle population, together with the behaviour of each vehicle. The parameters of the generated driving patterns such as "daily route", "use class" and "use frequency" base on statistics and distributions, which can be extracted from mobility studies such as "Mobilität in Deutschland" [4]. At a later stage, the synthetic driving patterns are complemented or replaced by real data. A detailed description of the algorithms used to generate the vehicle population is to be found in [1]. Figure 2 shows the superimposition of the layers streets, land use and socio-economic data and illustrates an activity chain for one vehicle.

Figure 2: Data layers and activity chain

Driving patterns from surveys

Surveys on the mobility behaviour of people only reflect the behaviour as it is today. It is characterized by journeys with conventional vehicles. Drivers may be consulted, with a driving behaviour that is not feasible for owners of electric vehicles. Also, departure times, mileage etc. can only be estimated by the interviewed persons. Another problem is the lack of geo-referencing. The only information which is obtained on driving destinations falls into categories such as "shopping", "to work" etc. Furthermore it would be interesting to know whether an EV-user connects its vehicle to the grid immediately after the end of a trip, how long the vehicle remains connected after the charging has terminated and how often vehicles are recharged between two trips anyway. Important to know are also the time and location of the charging process.

CONTROL STRATEGIES

With an analysis of uncontrolled charging and centrally or remotely controlled charging respectively a spatial and time- resolved identification of resulting network utilization and overload is carried out. Uncontrolled charging is likely to cause localized overloads in the power grid, especially in the evening during peak load, because of the characteristic driving behaviour. To overcome this, simple control strategies can be implemented to shift the charging process to off-peak times. But simple control mechanisms, following fixed rules, have the drawback of not reacting to external circumstances. In the case of many vehicles connected the same part of the grid with simple control, these vehicles can still cause overloads as a consequence of a large number of electric vehicles starting or stopping their charging process simultaneously, following these fixed rules.

Simple strategies

Simple control strategies, which can be managed without two-way communication, are all based on the time of use pricing principle. A financial contribution is hereby offered to the vehicles in return for a time displacement of their charging processes towards a certain time interval in which the energy price is lower. Due to the unilateral flow of information, this principle is applicable for V2G services in very limited way. Only very simple goals such as valley filling that can be pursued. To prevent the simultaneous beginning of many charging processes at the beginning of the time interval, vehicles can be charged with reduced power over a longer period and with random initial delay. An example of what happens when vehicles charge distributed over the whole night, can be seen in figure 3. The peak at noon can be explained by the many vehicles which have to partly recharge (assuming area-wide charging capability) during the day.

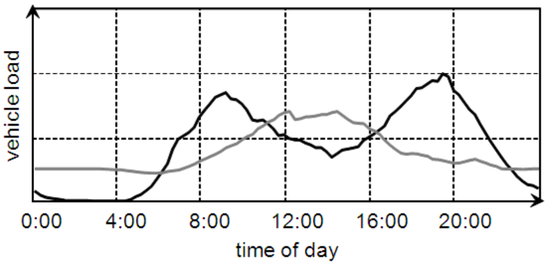

Figure 3: uncontrolled (black), controlled (grey)

If a two-way communication to the vehicles is available, more V2G services become available. Transmission system operators or other aggregators can pool a certain amount of parked vehicles, and thus offer control power or respond to the availability of energy from renewable sources. However, the goals of aggregators in particular, can lead to network congestion, since the provision of control power often requires many vehicles to be switched on or off at the same time.

Complex strategies considering space and time

Unlike simple optimization approaches where load curves are changed by a time shift of the charging processes or by an adjustment of the charging power over time, the optimization process of the proposed approach takes into account the spatiotemporal coupling of the problem. An example is illustrated in Figure 4. The intervention in the charging processes at time t_1 at node A, affecting vehicles a and b, has an impact on the SOC (state of charge) of vehicle batteries at nodes B and C at later times, and thus influences the potential for further interventions at nodes B and C at time t_n.

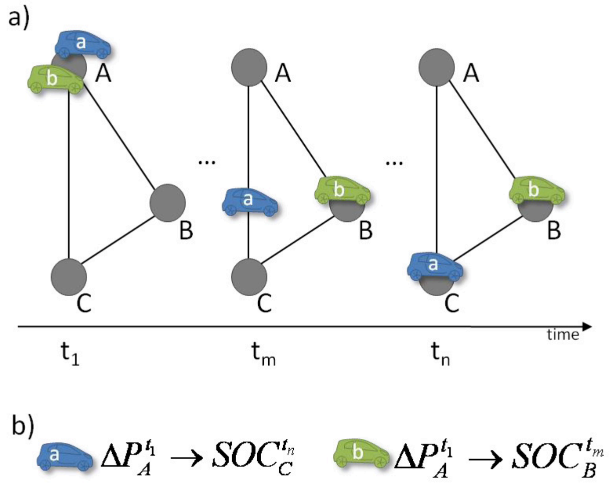

Figure 4: Spatiotemporal impact of interventions

This formulation of the problem furthermore allows modeling the obligatory side conditions that have to be fulfilled in any case.

$$\sum_{a,b,\ldots\exists V} P_N \leq \mathrm{P}_{\mathrm{N,Max}} \Big|_{t=1..n} \quad ; \forall \text{ nodes } \mathbf{N} \text{ and } \forall \text{ times } \mathbf{t}$$

The power P of all vehicles v at node N is limited by the rated power of the charging points at node N for every time step t.

$$\begin{matrix} {}^{v}SOC^{t} \leq 1 \\ {}^{v}P^{t} \leq {}^{v}P^{t}_{Max} \end{matrix} \quad ; \forall \text{ vehicles } \mathbf{v} \text{ and } \forall \text{ times } \mathbf{t}$$

Furthermore the state of charge SOC of every vehicle v can never exceed 100% battery capacity and the charging power of every vehicle is limited to the rated power of that vehicle for all time steps t as well.

$${}^{v}SOC^{t} \text{-} \Delta SOC^{\mathrm{t...t+i}}_{\mathrm{journey}} > \alpha \quad ; \forall \text{ vehicles } \mathbf{v} \text{ and } \forall \text{ times } \mathbf{t}$$

Also a lower bound for the state of charge can be defined, to ensure that always a minimum amount of energy α is kept in reserve after every journey.

Especially models, which want to give realistic statements on the benefits and impact of electric vehicles, i.e. including also charging infrastructure in public space in parallel to the widely available "charge at home" possibility, must consider the described spatiotemporal coupling in order to reflect the impact of any intervention in the charging management. The vehicle-specific modeling with agent based modeling also allows to implement soft factors, such as security needs of some users, which manifest itself in the willingness to pay higher prices to fulfill their energy needs at every time in a sufficient manner.

The approach described above shows interesting parallels to the problem class of hydraulic coordination, which has the optimal operating strategy for spatially coupled pump reservoirs. Solving methods coming from this research area have been adapted to the problem class described in this paper by the authors and will be published in following publications.

INTEGRATED SIMULATION

The described approach combines a traffic model with a model of the electricity network (see Figure 5). An integrated model of power and transport flows allows analyzing the impact of an area-wide integration of electric vehicles on power grids. Finally, the integrated model will be able to simulate a large number of vehicles, allowing a prediction of the impacts on any given power grid, so that recommendations can be given for the expansion of individual lines or the necessary charging control mechanism.

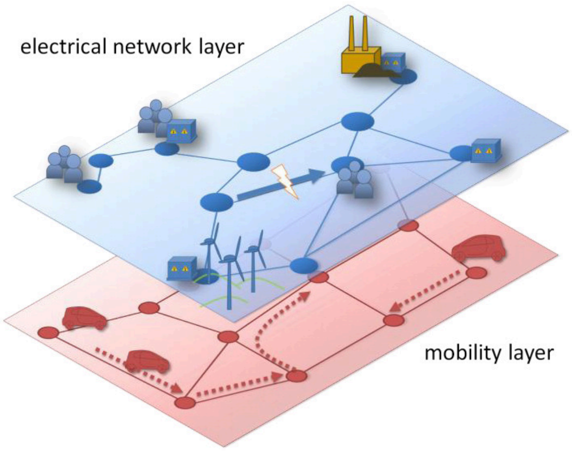

Figure 5: Integrated model

New findings by including spatial information

So far, barely enough studies exist which provide a geographic differentiated analysis of grid load factors and potential local bottlenecks. Results of country-wide analyses, however, often do not take into account regional specificities. With these simplifying assumptions only an average picture of the situation can be given. An overall assessment can only be done in a very limited way. With the aim to develop a model that accommodates a large number of regional data and allows an assessment of the grid impacts with a high spatial resolution such as in the example shown in figure 6, a traffic simulation had to be developed. The vehicle population with its regional distributions was calculated based on the geographical data layers and the socio-economic data.

Figure 6: Localised overloads of power grids

Effect on vehicles and infrastructure scenarios

Since an agent based approach is used to model the vehicles, the status of every vehicle and every charging process is known and can be observed, so that negative effects on vehicles due to controlled charging can be detected and evaluated. Besides this several scenarios regarding the availability of charging infrastructure can be simulated easily just by placing charging poles only in regions with a certain land use feature such as "residential" or "industrial". This leads to differing charging power curves caused by electric vehicles as shown in figure 7.

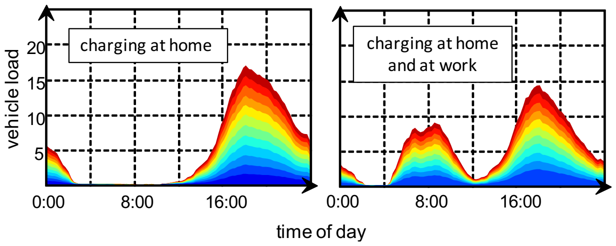

Figure 7: Different scenarios considered

SUMMARY AND OUTLOOK

The achieved results confirm a stringent necessity for the integrated modelling approach described above. It allows analysing the impact of different charging control strategies on energy distribution grids with a very high spatial and temporal resolution. The next step will be an improvement of the driving patterns that were used for the traffic simulation.

Real driving data will therefore be monitored and recorded within the frame of a government-funded research project. These patterns will be incorporated into the model, defining the specific vehicle charging times and places. The major advantage of this proceeding is the high temporal and spatial resolution of the recorded data. Additionally it allows collecting regional data, such as preferred driving destinations and the utilization of roads. In a similar manner the user behaviour regarding the handling of electric vehicles can also be analyzed. It can be determined exactly when a vehicle was parked, when it was connected to the grid, how long it has been charged, how much energy has been consumption, etc. Especially the time when a vehicle is not charged, but connected to the grid, is of particularly interest for the analysis of the potential of electric vehicles offering V2G services. Finally, it is planned to analyse the impact of e-mobility on local emissions of noise, CO_2, NO_x etc.

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