A FRAMEWORK FOR INVESTIGATING THE IMPACT OF PHEVS

Galus M[1], Waraich R[2], Balmer M[2], Andersson G[1], Axhausen KW[2]

[1]Power Systems Laboratory, ETH Zurich, Switzerland
[2]Institute for Transport Planning and Systems (IVT), ETH Zurich, Switzerland

Abstract

The paper proposes a framework to investigate impacts of wide-scale Plug-In Hybrid Electric Vehicle (PHEV) utilization on power- and transportation systems. It consists of two interacting parts, a power systems- and a transportation simulation. The latter one finds an equilibrium representing vehicle behavior used as an input for power system simulations incorporating distribution power network bounds. These results are fed back for renewed transportation simulation until system convergence.

Introduction

Increased CO2 expulsion, the proceeding scarcity of crude oil and political discussions about future energy security initiated a so called green economy. Out of this ambience the promise for more efficient individual transportation is partly represented by Plug-In Hybrid Electric Vehicles (PHEV), mitigating vehicle technology to an increased electrification. However, the mitigation process intuitively entails several impacts for the transportation as well as for the power sector which need to be investigated and resolved. Crucial changes for the transportation sector include behavioral pattern changes of the population as well as changes to the existing parking infrastructure, which are captured by transportation frameworks such as [1]. The challenges faced by today‘s power system are also severe. It is designed for moderate load increase due to long time investments in electricity generation, lines and cables but faces in the future a large new load with different patterns. The energy generation supplying this new load has been investigated for several countries and findings implicate that the generation mix is able to supply the PHEV load [2]. Potential dangerous impacts which are intuitive to utilities are line congestions, transformer overloads and other not foreseen problems on the different grid levels, mainly in distribution grids [3, 4]. These are the ones that will encounter the new load as a heavy impact even if it is small in the beginning, whereas the transportation and medium voltage grid will just see a slight load increase easily manageable when not occurring at peak times and in large quantities. Evidently, also the last objection needs to be explored in order to fully understand the impact of the upcoming technology affecting both sectors. However, this is not the only problem recent power system research is dealing with, as increased utilization of distributed renewable energy generation, local load management, energy carrier interconnection (via microCHP), liberalization of the electricity market as well as the smart grid are other main topics, nowadays. A system view is not only expedient but imperative to tackle all those problems simultaneously.

Due to the system integration, it is important to use a hybrid tool, comprising transportation and power system simulations, to study the impacts. This paper proposes a framework for such a hybrid tool able to study syndetic repercussions on both systems. The tool will integrate two well know programs e.g. concepts in the transportation as well as in the power sector. The transportation part of the tool will rely on agent based optimization already implemented in the MATSim (Multi Agent Transport Simulation) tool [1]. The power systems side is based on the energy hub approach [5] offering the possibility to study the consequences for multi energy carrier networks with an increased utilization of renewable energy generation. The important advantage of this specific approach is that it is flexible but can easily be reduced to standard power system computations like optimal power flows, etc. representing only the electricity network.

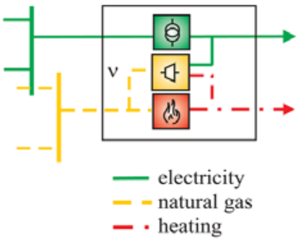
The rest of the paper is structures as follows. The next section will introduce the energy hub concept and the approach how to introduce large amounts of PHEV into the energy network in an administrable way using PHEV managing entities. First results are shown and explained for this concept and an outlook is given how the system can be reduced to offer electricity system studies, especially for distribution grids. The third section introduces the MATSim environment, explains the functionality, described the analytical powers and displays results. The fourth section describes the concept for the integration of both approaches. The fifth section gives an outlook which questions can be answered using this powerful tool. And the paper ends with a section on future work.

Materials and Methods

The Energy Hub and Power Systems Computations

The energy hub is a concept that is capable of investigating multi energy carrier systems via a relatively simple mathematical formulation allowing a high flexibility system modelling. The attributes of an energy hub are the existence of inputs, outputs, energy conversions within the entity and storage. For each hub converters are apparent transforming one energy carrier into one or several others. The basics of the modelling concept can be found in [5-7] and addition of renewable energy generation and feed in is explored in [8]. A typical hub is displayed in figure 1 at the left hand side. At the right hand side the mathematical formulation for inputs, outputs and converters as well as the formulation for optimal power input dispatch is found. Here, L is the load vector, P is the input vector and C is the conversion matrix. While optimally dispatching the inputs, an objective function (e.g. cost function) is minimized subject to constraints represented by the energy hub equation, total power inputs for the hub P, converter input bounds Pc and dispatch factors N. The formulation can be extended to investigate a whole energy hub network through expanding the set of constraints adequately as described in [7].

$$\underbrace{\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}}$$



Min $\quad f(\mathbf{P})$

s. t.

$$\mathbf{L} - \mathbf{C}\,\mathbf{P} = \mathbf{0}$$

$$\underline{\mathbf{P}} \leq \mathbf{P} \leq \overline{\mathbf{P}}$$

$$\underline{\mathbf{P}}_c \leq \mathbf{N}\,\mathbf{P} \leq \overline{\mathbf{P}}_c$$

$$\mathbf{0} \leq \mathbf{N} \leq \mathbf{1}$$

Fig. 1: Energy hub including transformer, microCHP, furnace and general mathematical formulation for hub and optimal energy dispatch

Now, for each energy hub representing a node in the power network a managing entity can be introduced which is clustering and controlling the charging of vast amounts of PHEVs. It is called PHEV Manager and is based on an economic optimization scheme [9]. The manager features a knowledge base including arrival times, state of charges (SOC) at arrival, PHEV identity numbers and connection capacities as well as the maximal power capacity available at the hub for distribution under connected PHEVs. The distribution scheme is based on the presumptions that PHEVs are modelled as independent, autonomous agents, implying different goals. However, their main goal is to have a certain SOC of their battery at their individual departure time. Their valuation of energy attainment is therefore rising over time based on their SOC when possibly not recharged. This implicates that the individual valuation of energy attainment is highest when leaving the location, e.g. the vehicle owners are willing to pay more for electricity when they are close to their departure time. For instance, for working locations this would mean late in the day. Figure 2 visualizes the integration concept for a power network. In this case it consists of 4 nodes modelled as hubs incorporating the same architecture as introduced via figure 1. At each node one PHEV Manager is found managing the connected PHEVs. Different areas such as industrial, commercial or residential areas are displayed, obviously having different behavioral arrival and departure schedules which are resulting in different load patterns. The nodes are connected via electricity lines and gas pipelines modelled through a DC line model and the gas line model introduced in [6], respectively.

Figure 3 displays results at the business area after management of connected PHEVs. Figure 3(a) shows the base load for electricity and heat at the business hub whereas 3(b) shows the hub electricity load for the connected PHEVs after active management over time. In this case 3000 PHEVs are simulated. Figures 3(c) and 3(d) show the hub output including the PHEV load and the hub inputs, respectively. It can be seen that the transformer constraint, which is set to 1 p.u. maximum, is not violated over the simulation period. Figure 3(f) apportions the hub inputs for the various converter inputs. It can clearly be seen that in the PHEV case a substantial part of the natural gas input is dispatched to the microCHP increasing the electricity supply at the energy hub. Figure 3(e) shows the difference of converter inputs between the PHEV case and the base load case for a converter overload (here, the transformer). The blatant difference is the increase of microCHP utilization replacing furnace usage. Such investigations can be performed for each of the energy hub nodes as well as for the utilization degree of the power lines. It is easily understood that with fully functional PHEV Managers at the power nodes a complete power system optimization can be performed for large networks investigating power line constraints, converter utilization and load pattern development for various urban areas. The agent based approach assures compatibility to the transportation systems optimization.

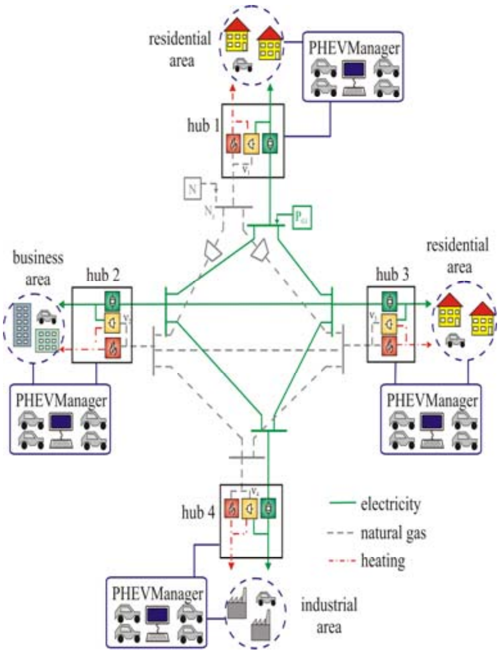


Fig. 2: Energy hub network including PHEV Managers integrating vast amounts of PHEVs

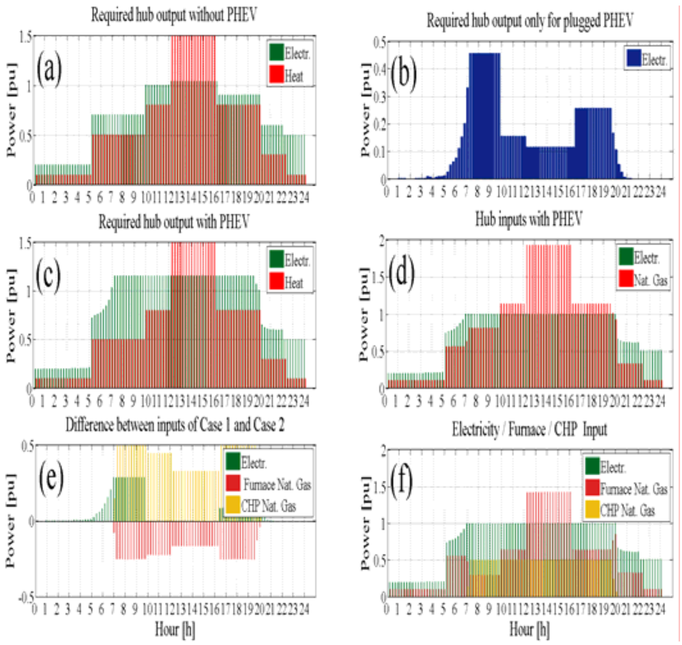


Fig. 3: (a) Base load for one hub,
(b) PHEV load distributed after management,
(c) hub base load including PHEV load,
(d) hub inputs,
(e) difference between base and PHEV case of converter utilization,
(f) converter utilization for PHEV case

MATSim

Traffic simulations can be performed on different levels of detail. One the one hand side, traffic can be modeled as traffic flows consisting of accumulated number of cars; on the other hand it can be modeled as detailed as on an individual vehicle's level. 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 an assigned a utility. This allows individual decision modeling, such as choosing the path to drive or choosing location for refilling gasoline.

MATSim [4] is a traffic simulation framework, where vehicle owners are modeled as agents. Figure 4 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, networks and facilities are modeled in the initial demand. The plans of all agents are executed by a micro-simulation, resulting in traffic on roads and perhaps traffic jams.

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 his daily plan by "replanning" its day, which is based on a co-evolutionary algorithm [10]. A co-evolutionary algorithm generally tries to find the maxima of a "fitness" function (in our case the utility function) using “crossovers” and “mutations”. In the MATSim context, the utility function depends on 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 with low performance, resp. 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 and its scoring is called *iteration*. The simulation is an iterative process, which approaches a point of rest corresponding to an user equilibrium. The relaxed state can then be analyzed.

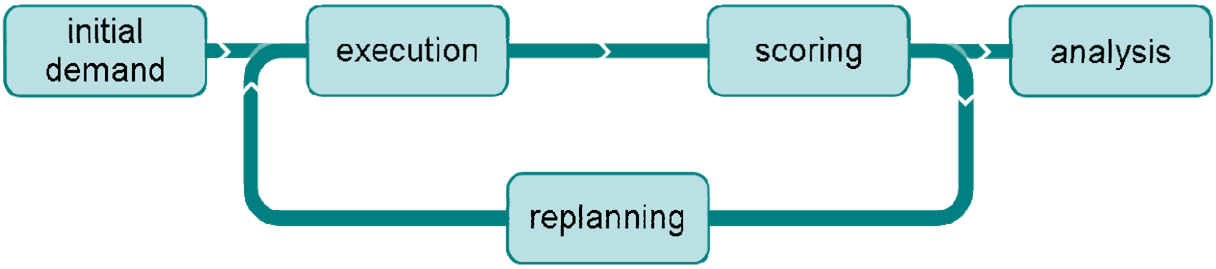


Fig. 4: MATSim simulation process consisting of several steps implemented in different modules

Extending MATSim

The presented work proposes the extension of MATSim in several ways in order to incorporate PHEVs. First of all, data about parking infrastructures and street parkings in the area of Zurich has been collected, in order to model the current parking infrastructure. Also the agent plans need to be adapted, so they use parking infrastructure before they actually arrive at their target location.

Furthermore, the energy consumption of PHEVs is being modeled, such that these vehicles are able to charge electric energy and drive both using electric energy and gasoline. PHEVs can charge electric energy both at home as well as in designated parking infrastructures. While driving, a PHEV is using electricity, because it’s cheaper than gasoline. If a PHEV runs out of electricity, it has to use gasoline. This fact gives an incentive to PHEV owners to charge electric energy. The price for electric energy depends on the location and the time of the day. This variation in price is due to the law of supply and demand of electricity which not only depends on the day time, but also on bottlenecks in the existing electricity infrastructure. Extensions in the replanning part of MATSim (see fig. 4) are made, such that the cars can change the parking location and charge electric energy at different times. This is an extension of the search domain of the co-evolutionary algorithm, so that the utility function is adapted to take the cost of charging electricity and that of using gasoline into consideration. The co-evolutionary algorithm does not have a problem with such higher complexity of the utility function, but often increases the number of iterations before equilibrium is reached. As such after each iteration the PHEVs are trying to improve their utility, by getting cheaper parking and charging conditions (among others replanning strategies). The price of electric energy for different locations and day times is defined by the power system simulation.

Integration of the Power System Simulation and the Transport Simulation

The integration of both simulation tools is done iteratively where they interact after separately finding a solution. The results are an input for the respective other system as shown in fig. 5. This approach was chosen because both simulations find their optimum after a large number of iterations. Furthermore with this structure the simulation is more robust and flexible. Therefore, a MATSim simulation is run first, generating the complete behavior of the vehicle fleet of the city or country under investigation. After relaxation, vast amounts of micro information about the vehicle fleet behavior are available. This includes detailed location information as well as time behavior for each vehicle, e.g. where each vehicle is located at which time and for how long. Further on, it is assumed for the transport simulation that each PHEV will instantly connect and recharge as soon as it is at a position where the infrastructural situation allows it to do so. MATSim therefore generates start-/end charging times for each PHEV in the system. Also, individual electricity consumption of the PHEVs is currently calculated based on data generated by a PHEV energy hub model using drive cycles for urban and city agglomerations [11]. This results in known battery levels of each PHEV at each location.

For the PSS the location, the time, the PHEV agent-ID, the respective state of charge (SOC) of the battery and the start/end charging times are transferred via an interface. Parking locations situated in the same area are assigned to be represented by a hub. The definitions of different hubs will be based upon the particular power system infrastructure (distribution network) in the urban agglomeration. The PSS simulates the power system of the particular urban agglomeration as it is described in the second paragraph. However, slight modifications will be implemented. The PHEV managing system will be changed. It will not incorporate anymore the individual willingness to value being scheduled for recharging as modeled through microeconomic concept of mechanism design as in [9]. This will be tackled by the individual replanning in MATSim. In contrary, the PHEV agents will incorporate well known linear marginal load curves [12], where the maximal price for scheduled power will be the price for gasoline divided by the average internal combustion engine efficiency. This is derived from the intuitive fact that PHEV owners will merely pay more for electricity then they would for gasoline. The load curve is directly dependent on the total scheduled power for each vehicle. Simulation of the power system, under the premise of minimizing total costs while supplying the forecasted base load at each node at each time and meeting technical constraints like power line capacities, results in nodal, time dependent prices [12]. These nodal prices are then fed back to MATSim and become a part of the utility function. MATSim is then started again to find a new relaxation where may be some PHEV have made the decision to park somewhere else to not to pay congestion based, increased electricity prices. The total system is deemed relaxed when the utility of agents in MATSim cannot be improved significantly and stable nodal, electricity prices are calculated.

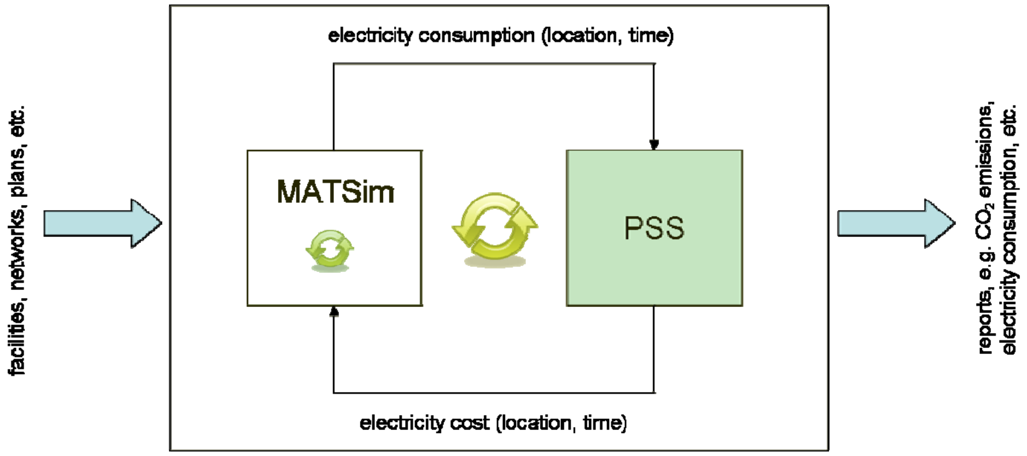


Fig. 5: The integration of MATSim with the Power System Simulation is shown.

Results and Discussion

Test Scenario and Setup

Using MATSim a small network of 20 roads was simulated with 10000 vehicles. The network contains a home location, a working location and a shopping location. Agents start at their home location in the morning and drive to work, performing 8 hours of work activity. Then they go to their shopping location and finally travel back home. Agents arriving at the parking infrastructure start charging immediately their car if electric energy is needed. The micro information is then loaded into PSS and an optimization was performed in order to minimize total system costs for a multi energy carrier infrastructure. The PSS optimization is currently still based on the concepts presented in [9]. However, basic investigations can already be conducted when focusing on the energy system only without looking into the repercussions to the transport side. Typical findings can then include power line loading, energy hub load and the mixture of supply depending on the time distribution of PHEV arrival and departure.

Results and Discussion

In fig. 6 several measurements of the mentioned artificial scenario are shown. They include CO_2 emissions over time at a specific location (linked 107), individual energy SOC and the power consumption at a parking facility located at the working place. Just one car type was used with assumed average CO_2 emissions of 180 gram per km. The measurements show, that the framework is powerful enough to predict area wide CO_2 emission changes. For example if 20% of the car drivers of the city of Zurich and 10% of the surrounding rural areas would switch to PHEVs, how would this effect CO_2 emissions in time and space? This becomes even more interesting, as PHEVs vehicles can perform parts of a trip without and parts with CO_2 emissions, depending on the length of the journey among other factors. Several simulation runs on real data for the greater Zurich area are being prepared.

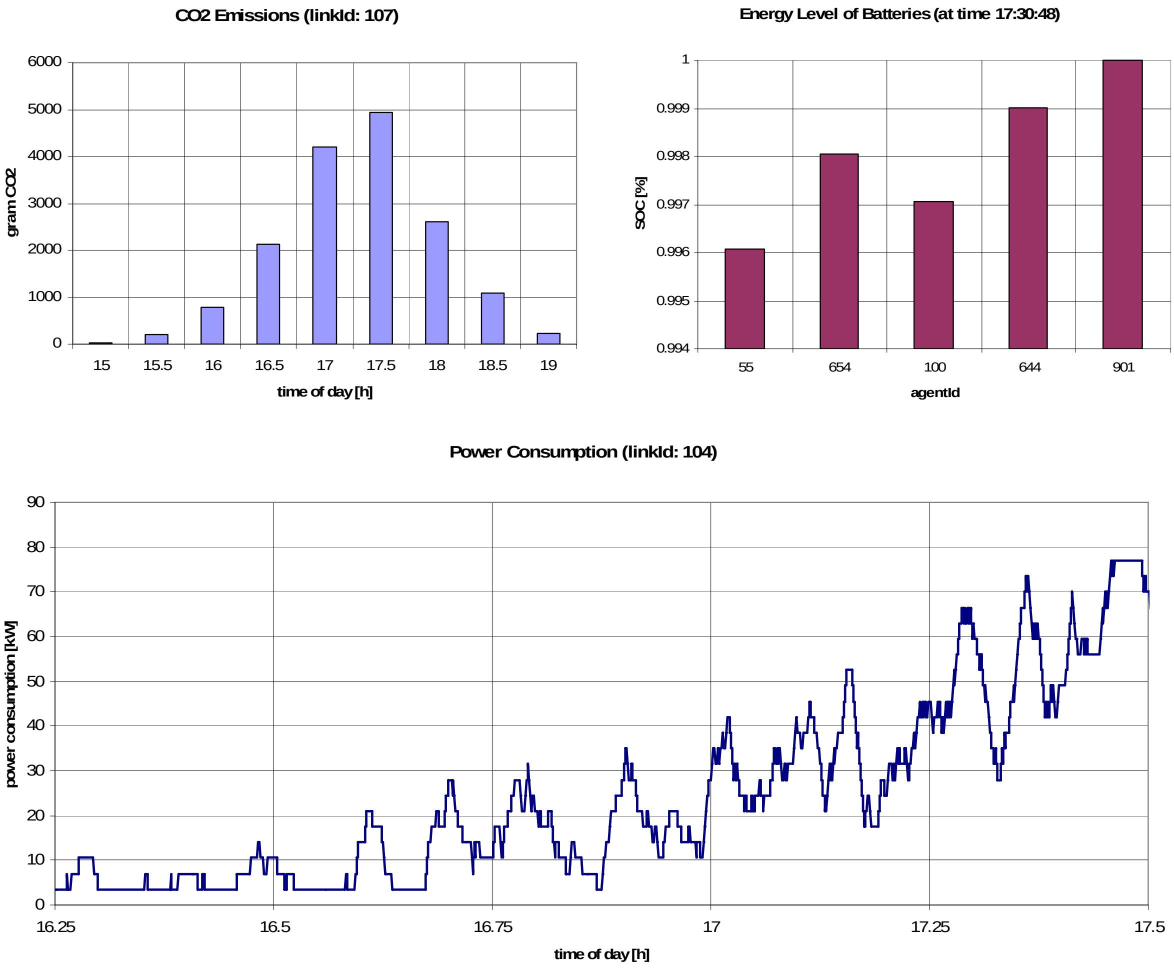


Fig. 6: The graph on the top left side shows CO_2 emissions measured at link number 107 of the simulation scenario, for 30 minutes intervals. The top right graph shows the energy level of a few cars at time 17:30:48, called state of charge, SOC. And the bottom graph shows the power consumption at link 104 (work location).

Furthermore, typical PSS results are shown in fig 7. They show the difference between a base case with no PHEV in the system and a PHEV case where the vehicles need to be recharged. The differences are visualized here for energy hub electric load (blue) as well as input (green) in the left plot and for power line loading in the right plot. The peaks at 6 a.m. are due to the assumption that lots of PHEVs arrive early in the morning at their first location of their day plan. Simulations were performed with a test result extracted from MATSim for 3000 vehicles which was not yet completely relaxed as the extension of MATSim is still in a development phase. However, the plots impressively show the capability of PSS to deliver results in order to answer pressuring question initiated by PHEV introduction. Power line and transformer loading, increased utilization of distributed energy generation for PHEV recharging, intelligent demand management based on electricity pricing and V2G concepts are just a few areas of interest which the presented framework can cover. Furthermore, MATSim's environmental sociological and mobility impacts can interactively be studied. As parts of the framework, such as extending the replanning part of MATSim and developing the PSS and its PHEV managers to incorporate pricing schemes are under construction, the results demonstrated here are just a proof of concept.

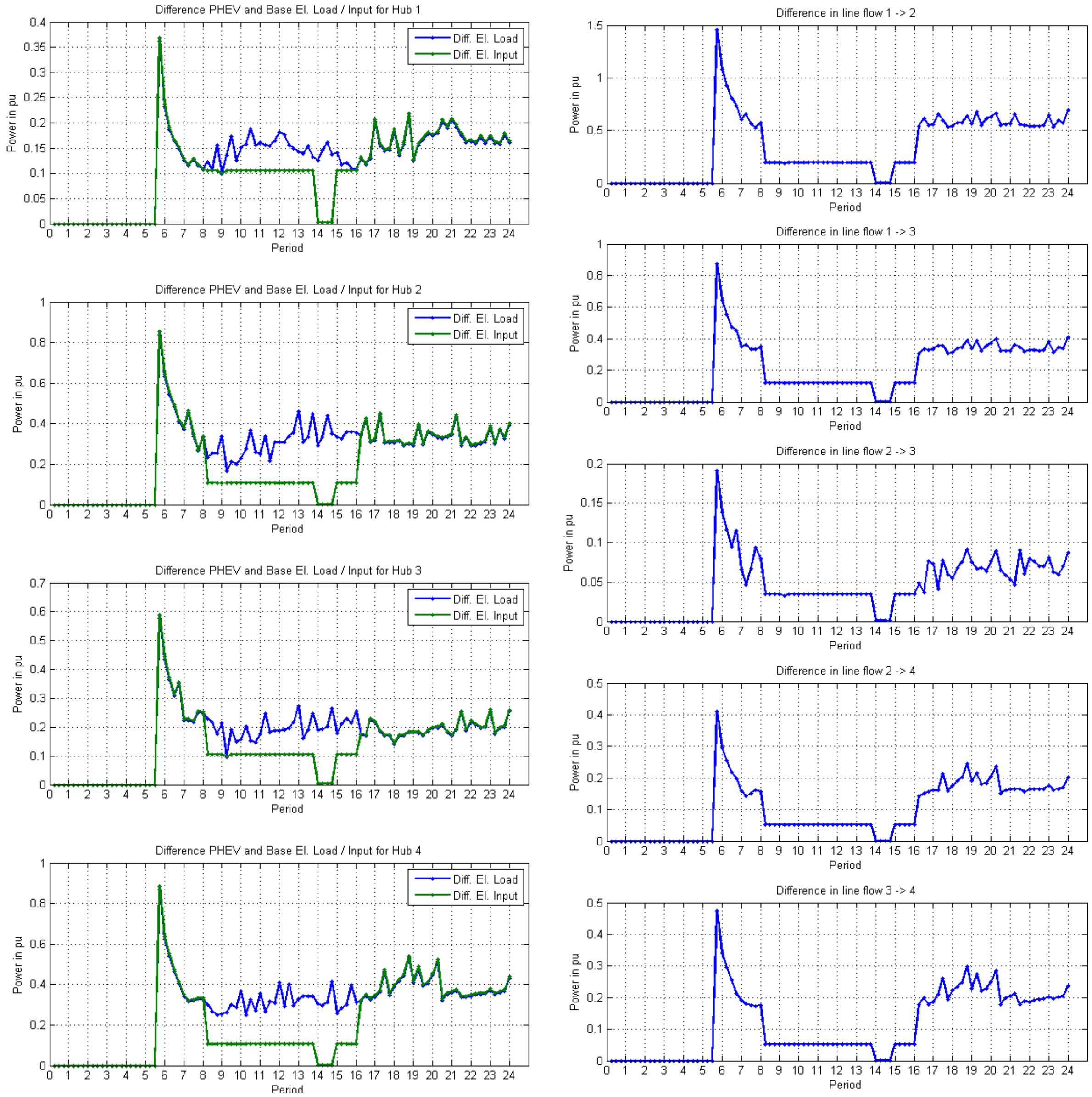


Fig. 7: Difference between base- and PHEV case of electric load and input for four hubs (*left*). Difference between base and PHEV-case of electric line flows (*right*).

Future Work

The tool is currently under construction and several extensions are being implemented to perform simulations for realistic systems. MATSim will be extended such that scoring and replanning modules can cope with PSS. As for power systems simulations, the manager will be altered to aggregate connected PHEVs to a linear marginal load curve. The distribution network will be modeled via well known modeling techniques, realistic electricity prices will be investigated and implemented into PSS to result in realistic nodal prices for a PHEV case and finally the transfer of the prices for a subsequent MATSim iteration will be included. Several case studies will be performed (e. g. for Zurich) and V2G considerations and impacts for renewable energy generation are planned as well. The later facilitation mode of PHEVs will incorporate investigation on voltage stability as well.

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