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Locational Marginal Pricing Based Impact Assessment of Plug-in Hybrid Electric Vehicles on Transmission Networks

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SUMMARY

The electrification of transportation could be an effective strategy for reducing CO_2 emissions. At the same time, a large-scale introduction of plug-in hybrid electric vehicles (PHEVs) and electric vehicles also constitutes a challenge to power systems: Uncontrolled charging would lead to increased load peaks thus potentially overloading system assets. In this paper we take into account the potential flexibility of these new loads and propose a smart charging scheme based on endogenous Locational Marginal Prices. We also assess the potential of Vehicle To Grid (V2G) for peak-shaving by using vehicles to arbitrage intertemporal energy price differences. The method employed is an Optimal Power Flow (OPF), which considers supply and demand side as well as network infrastructure simultaneously. The OPF thus constitutes an appropriate framework to assess the impact of PHEVs on network operation, prices and the energy supply. Within this OPF framework vehicles place demand bids according to their driving patterns and battery state of charge, which are then aggregated at each network location or node. Under V2G this scheme is extended and supply curves are defined taking into account battery degradation costs and round-trip energy losses. Vehicles are modeled individually and their driving patterns are obtained from an agent-based transport simulation. In case studies with one million PHEVs we show that the proposed smart charging method constitutes an improvement compared with uncontrolled charging and even a simple dual tariff, both in terms of load smoothing and lower generation costs. On the other hand battery degradation costs prove too high for a sizeable peak-shaving effect. The proposed framework could also be used for planning purposes as the impact of PHEVs on the infrastructure is assessed.

KEYWORDS

Plug-in Hybrid Electric Vehicles (PHEV), smart charging, smart grids, Vehicle to Grid (V2G), Optimal Power Flow (OPF), Locational Marginal Pricing (LMP)

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I. Introduction

Against the background of increasing awareness of climate change and geopolitical concerns regarding the availability of crude oil, the electrification of the transportation sector could be a powerful strategy to reduce CO_2 emissions and crude oil demand. Plug-in-hybrid electric vehicles (PHEVs) would play an important role in this strategy. Their main source of energy is an energy battery pack charged with electric power from the grid. Additionally to conventional electric vehicles, PHEVs can bridge larger distances with an ancillary internal combustion engine.

With the adoption of PHEVs several important issues arise concerning power systems. First, methods are needed to assess the impact of this new load, which has the specificity of being mobile. Moreover, smart charging strategies can be developed to reduce its impact by taking advantage of the flexibility of these loads. Finally a PHEV fleet can be regarded as a distributed storage resource which can discharge energy back to the grid under so called Vehicle to Grid schemes (V2G). These are the issues that will be addressed in this paper.

Some studies have concentrated on the utility impacts of PHEVs [1-5]. Most of these studies recognize the need for some sort of controlled charging to avoid increased peaks in demand, e.g. valley-filling algorithms [1-3]. However these studies do not address transmission constraints in particular and do not model vehicles individually. On the other hand smart charging schemes have been proposed at the distribution level, which take into account individual vehicle’s and distribution network constraints [6-9]. As these are rather local approaches they do not integrate supply side considerations. Both generation and grid aspects are considered in [10], where the impact on locational marginal prices (LMP) in the Pennsylvania-New Jersey-Maryland Interconnection has been assessed. However, in the latter publication individual PHEVs are price-insensitive, not taking into account the potential flexibility of these loads. This model is extended in [11] where decentralized and centralized recharging game-theoretic algorithms are presented. Peak-shaving potentials have been analyzed in [12] assuming vehicles as price-takers.

In this paper we adopt an LMP approach with flexible and adaptive PHEV loads to address the impact of PHEVs on transmission networks and to develop a smart charging scheme to reduce this impact. This approach has the advantage of considering both infrastructure and generation costs simultaneously, as capacity is implicitly bided for. Moreover generated prices are spatially differentiated in the case of congestion, which can be crucial when trying to define optimal demand side schemes for mobile loads. Within this framework PHEVs’ electricity demand and supply are modeled individually based on vehicle driving patterns derived from an agent-based transport simulation and taking into account battery degradation costs. Individual supply and demand curves are aggregated at each network node, allowing the modeling of large number of vehicles while at the same time making sure that the timing of charging (and discharging) is compatible with individual driving needs.

The following charging scenarios were simulated:

- Dumb charging, where vehicles start charging once they are parked.
- Dual tariff charging, where vehicles are offered a high and low price tariff.
- Smart charging, based on flexible demand bids (see section II).
- Smart charging with V2G, based on flexible demand and supply bids (see section II).

It will be shown that the presented smart charging scheme contributes considerably to the smoothing of the load profile and prevents vehicle charging during peak hours. PHEVs offer however a limited potential for peak-shaving due to high battery degradation costs. For any of the scenarios the impact of the additional load on transmission lines can be assessed in terms of line loading, which could be used for planning purposes.

This paper is structured as follows: The model is illustrated in section II, where the OPF formulation is described (II A) and then PHEV demand (II B) and supply (II C) are defined. Section III deals with the results of the case studies. Section IV concludes the paper.

II. Model description

To assess the impact of PHEVs, stepwise single-period optimal power flows are performed sequentially for a 24 hour cycle. These result in time profiles for nodal prices, line loadings, PHEV charging and generation. PHEV demand (and eventually supply) is shaped taking into account the driving behavior of the vehicles and the state of charge of the vehicles (SOC) obtained from the previous time step[1]. Driving patterns are obtained beforehand from a transport simulation called MATSim modeling daily driving cycles [13]. The simulation framework is depicted in Figure 1.

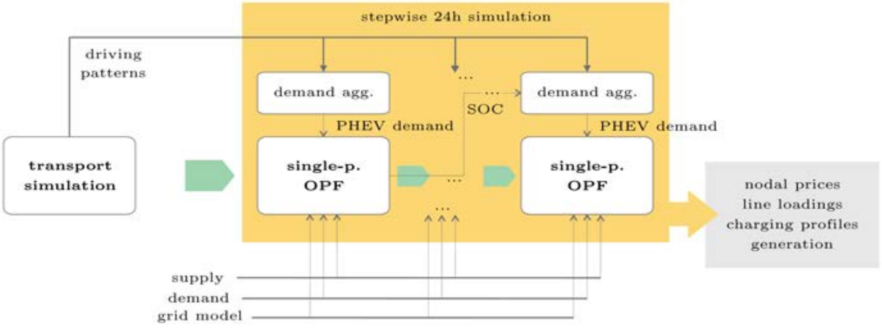

Figure 1 : Structure of the simulation model

The general OPF framework used in our model is defined in subsection A) while subsections B) and C) focus on the modeling of PHEV demand and supply respectively.

A) Optimal Power Flow Formulation with Flexible PHEV loads

To model the influence of PHEV loads on the transmission network as well as on electricity generation and consumption an Optimal Power Flow framework appears suitable. The OPF concept is well-known as a number of US electricity markets (e.g. the California, New York, Pennsylvania-New-Jersey-Maryland Interconnection etc.) rely on a so-called locational marginal pricing scheme for integrating network and market operation. The core of locational marginal pricing is an OPF problem, where generators and loads place bids for electricity production and consumption at a certain network location (node). In a further step the Independent System Operator (ISO) takes these bids and clears the market by maximizing social welfare while implicitly obeying network constraints. The outcome of this OPF is a welfare maximizing dispatch taking into account the capabilities of the network. In case of congestion it is very likely that different network nodes exhibit different prices (so-called nodal prices). These nodal prices can be used as incentives to either reduce electricity consumption or to invest into additional generation and/or network facilities. The advantage of such an OPF framework is the fact that the mutual influence of generators, loads and the network are expressed in a single optimization problem making it possible to assess how changes on one side affect the whole system. It is obvious that also for the assessment of PHEVs as flexible loads an OPF-based model formulation offers a useful analysis tool. With a future high penetration of PHEVs, electricity prices as well as the generation mix cannot be seen as exogenous variables. Using an OPF, the influence of PHEVs on network operation, prices and possible changes in the generation mix can be quantitatively assessed as the related variables are endogenous to the model. Below the optimization problem is defined.

$$\max\ w(P_{G_i}, P_{L_j}) = \underbrace{\sum_j \int_{P_{L_j,min}}^{P_{L_j}} D_{L_j}^{-1}(x)dx}_{demand} - \underbrace{\sum_i \frac{1}{2}(m_{G_i} \cdot P_{G_i} + n_{G_i}) \cdot P_{G_i}}_{supply} \tag{1}$$

loads L_j, $j = \{1, \dots, \mathrm{N}_L\}$, generators G_i, $i = \{1, \dots, \mathrm{N}_G\}$, lines l_m, $m = \{1, \dots, \mathrm{N}_l\}$, nodes $n = \{1, \dots, \mathrm{N}\}$

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[1] To obtain the initial SOC several iterations of daily cycles are performed until the initial and final SOC of individual vehicles converge to a certain extent.

$$\sum_j P_{L_j} = \sum_i P_{G_i} \tag{2}$$

$$P_{L_j,min} \leq P_{L_j} \leq P_{L_j,max} \quad \forall j \tag{3}$$

$$P_{G_i,min} \leq P_{G_i} \leq P_{G_i,max} \quad \forall i \tag{4}$$

$$\left| \sum_n PTDF_{n,l_m} \cdot \left(P_{G_i \in \Omega_n} - P_{L_j \in \Omega_n} \right) \right| \leq P_{l_m,max} \; \forall n \tag{5}$$

Eqn. 1 represents the objective function of the problem being the maximization of social welfare. Welfare is defined as the sum of consumer and producer surplus, where the problem can be formulated as shown in Eqn. 1. The supply is characterized by linear marginal costs. The definition of the inverse demand function or price function $D_{L_j}^{-1}\left(P_{L_j}\right)$ is treated in the following subsection II B). Eqs. 2-4 refer to the constraints of the optimization problem. Eqn. 2 is the overall balance constraint as total generation ($\sum_i P_{G_i}$) and total demand ($\sum_j P_{L_j}$) have to equal for each step of the optimization. Eqn. 3 states the upper ($P_{L_j,max}$) and lower ($P_{L_j,min}$) consumption constraints for the load side. Similarly Eqn. 4 captures the upper ($P_{G_i,max}$) and lower ($P_{G_i,min}$) generation constraints. Eqn. 5 states that all network flows (left part of Eqn. 5) must not exceed the maximum line limits ($P_{l_m,max}$). The formulation adopted here relies on the well-known Power Transfer Distribution Factors (PTDFs). A detailed derivation of the formulation can be found in [14, 15].

B) Defining PHEV Demand

Individual demand

PHEVs are modeled as flexible loads which adapt their demand elasticity to certain parameters, i.e. the status of their batteries and their daily plans. The demand function of each PHEV is assumed to be linear and is characterized by four parameters: the minimum and maximum demand for electricity at a given time step ($P_{V_k,min}$ and $P_{V_k,max}$ respectively) and the slope m_{V_k} and the intercept n_{V_k} of the inverse demand function or price function $D_{V_k}^{-1}(P_{V_k})$. This function is defined as the price p a vehicle V_k is willing to pay for an incremental unit of electricity. Exemplary price functions are depicted in Figure 2. The value of $P_{V_k,min}$ is either zero or a positive value if departure is imminent and charging is needed to achieve the required SOC level before departure. The value of $P_{V_k,max}$ is limited either by the connection capacity $P_{V_k,conn}$ or by the battery approaching its upper SOC bound. The slope of the price function has to be defined according to the status of the PHEVs. The parameters taken into account for this purpose are the following:

- *current SOC status*: PHEVs with a low SOC are willing to pay a higher price for the energy they consume, i.e. the lower the current SOC is, the lower the demand elasticity.
- *time to departure* $t_{V_k,dep}$: as the planned departure gets closer, the demand elasticity decreases.
- *time to charge* $t_{V_k,char}$: this parameter is defined as the minimum necessary time to charge the battery to the desired SOC level $SOC_{V_k,req}$ given the current SOC level, the battery capacity $C_{V_k,batt}$, the connection power $P_{V_k,conn}$ and the charge efficiency $\eta_{V_k,char}$. A higher time to charge means lower demand elasticity.

$$t_{V_k,char} = \begin{cases} \frac{(SOC_{V_k,req} - SOC_{V_k}) \cdot C_{V_k,batt}}{P_{V_k,conn} \cdot \eta_{V_k,char}} & if \; SOC_{V_k,req} > SOC_{V_k} \\ 0 & else \end{cases} \tag{6}$$

Taking into account these considerations we define the slope m_{V_k} as:

$$m_{V_k} = -\frac{k_{V_k,1}}{P_{V_k,max} - P_{V_k,min}} \left(1 - \exp\left(-\frac{k_{V_k,2}}{(t_{V_k,dep} - t_{V_k,char})} - \frac{SOC_{V_k,req}}{SOC_{V_k}} \right) \right) \tag{7}$$

In this equation $k_{V_k,1}$ and $k_{V_k,2}$ can be freely chosen to tune demand. The intercept is determined by the price at and below which a vehicle's demand will be maximal $D_{V_k}^{-1}\left(P_{V_k,max}\right)$ and by the slope m_{V_k}.

$$n_{V_k} = D_{V_k}^{-1}\left(P_{V_k,max}\right) - m_{V_k} \cdot P_{V_k,max} \qquad (8)$$

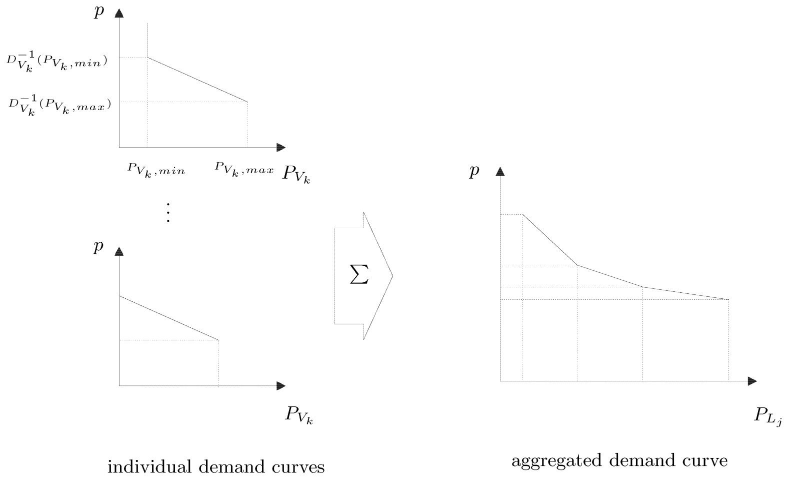
If the time to departure is equal or lower to the time to charge, an inelastic demand is defined where the minimum demand is set to equal maximum demand.

From individual demand to aggregated demand

The aim of aggregating demand at each node is to reduce the complexity of the optimization, as the demand of a group of PHEVs is represented by a single optimization variable at each node with its respective upper and lower bounds. By means of the aggregated demand individual driving constraints can be incorporated into the general OPF formulation. Given an (inelastic) reference load $P_{L_j,ref}$ for a load node L_j, the total aggregated demand can be obtained by horizontal summation of the individual inverse demand curves attached to that node L_j:

$$D_{L_j}\left(p_{L_j}\right) = P_{L_j,ref} + \sum\nolimits_{V_k \in \Omega_{L_j}} D_{V_k}\left(p_{L_j}\right) \qquad (9)$$

This process results in an aggregated inverse demand function $D_{L_j}^{-1}(P_{L_j})$ which is piecewise linear (see Figure 2), i.e. a different slope $m_{L_j}(P_{L_j})$ and an intercept $n_{L_j}(P_{L_j})$ are defined for each interval.



individual demand curves

aggregated demand curve

Figure 2: Individual and aggregated demand curves

From aggregated demand to individual demand

Conversely, a process of disaggregation is performed, where for each vehicle $D_{V_k}\left(p_{L_j}\right)$ is evaluated at the corresponding nodal price p_{L_j} given by the OPF to obtain individual charging. Then the SOCs are updated and the following step is run.

C) Defining PHEV Supply

Framework

Storage can be used to arbitrage intertemporal energy price differences, that is storing energy at times when prices are low and selling it back when prices are higher [16]. Other uses of storage would be ancillary services and stochastic renewable energy integration, but in this paper we concentrate on generation shifting or peak-shaving only. A fleet of PHEVs can be seen as a large storage device capable of delivering these services, provided driving patterns are not affected by this behavior.

Within the OPF framework, PHEVs can easily be modeled as load as well as generators extending their demand functions to negative load values.

Individual supply

Individual PHEV supply was derived taking into account the marginal costs of supplying energy back to the grid by the vehicles. A rather conservative approach was chosen here for PHEVs only participate in V2G if their SOC level is above required SOC before departure, which happens when electricity prices are low for a certain period of time. When vehicles are available for V2G the minimum charging power assumes negative values ($P_{V_k,min} < 0$).

When defining the supply curve of the individual PHEVs, two cost factors have to be considered: the cost of purchasing the energy sold $c_{V_k,e}$ and the cost of battery degradation $c_{V_k,d}$ [17]. The latter accounts for the fact that V2G services will result in additional cycling of the battery, i.e. cycling that is not related to the driving function of the vehicle itself. Total costs TC_{V_k} per hour can be written as:

$$TC_{V_k} = \frac{(c_{V_k,\mathrm{e}} + c_{V_k,d}) \cdot E_{V_k,G}}{\Delta t} \tag{10}$$

where $E_{V_k,G}$ is the energy delivered to the network during a time interval Δt. The cost of purchasing energy can be derived from the price of energy purchased $p_{V_k,buy}$ and the charge and discharge efficiency of the battery.

$$c_{V_k,e} = \frac{p_{V_k,buy}}{\eta_{V_k,char} \cdot \eta_{V_k,dis}} \tag{11}$$

Keeping track of the actual price paid for the energy sold is not obvious. However, its upper bound is easily derived from Eqs. 7 and 8.

$$\bar{p}_{V_k,buy} = D_{V_k}^{-1}\left(P_{V_k,max}\right) + k_{V_k,1} \tag{12}$$

On the other hand battery degradation costs are defined as the battery purchase price $p_{V_k,batt}$ times the fraction of battery lifetime consumed through discharging $E_{V_k,G}/L_{V_k,ET}$, where $L_{V_k,ET}$ (kWh) is the lifetime of the battery in terms of energy throughput.

$$c_{V_k,d} \cdot E_{V_k,G} = p_{V_k,batt} \cdot \frac{E_{V_k,G}}{L_{V_k,ET}} \tag{13}$$

The end of life of a battery is defined as the moment it cannot deliver over 80% of its rated capacity [18]. The lifetime of a battery is usually determined subjecting batteries to identical cycles with a given depth of discharge (DOD). Battery lifetime can then be defined in terms of number of cycles until end of life $L_{V_k,c}$ and the DOD.

$$L_{V_k,ET} = L_{V_k,c} \cdot C_{V_k,batt} \cdot DOD_{V_k} \tag{14}$$

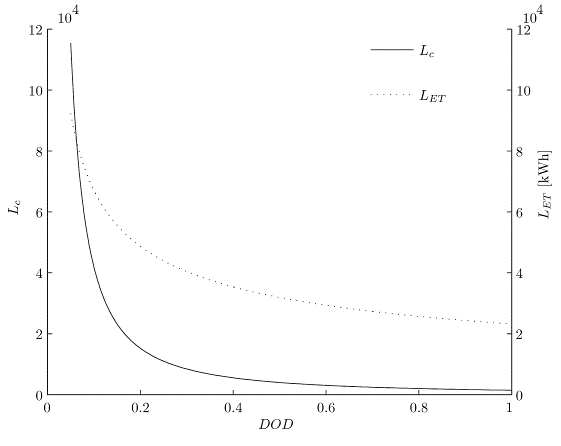


Figure 3: Relationship between the depth of discharge of the battery and its lifetime (in terms of energy throughput and cycles) for parameter values indicated in Table 1.

The relationship between the lifetime for a Lithium-ion battery and the DOD is shown in Figure 3 [19]. It is evident that shallow cycles have a lower impact on battery degradation than deep cycles. This relationship is given as:

$$L_{V_k,c} = a_{V_k} \cdot DOD_{V_k}{}^{-b_{V_k}} \tag{15}$$

The depth of discharge due to discharging energy to the grid is a function of the state of charge at the beginning of the time step and of the energy delivered during that time step.

$$DOD_{V_k} = 1 - SOC_{V_k} + \frac{E_{V_k,G}}{C_{V_k,batt} \cdot \eta_{V_k,dis}} \tag{16}$$

With Eqs. 11-16 marginal costs can be derived, which determine the shape of the supply curve.

$$MC_{V_k}\left(P_{V_k}\right) = \frac{dTC_{V_k}}{d(-P_{V_k})} = c_{V_k,e} + \frac{p_{V_k,batt}}{a \cdot C_{V_k,batt}} \cdot DOD_{V_k}{}^{b_{V_k}-1} \cdot \left(1 - \frac{P_{V_k} \cdot \Delta t}{C_{V_k,batt} \cdot \eta_{V_k,dis}} \cdot (b_{V_k} - 1) \cdot DOD_{V_k}{}^{-1}\right) \tag{17}$$

A linear approximation of this curve was used as supply curve in the simulation. Instead of fitting the curve to a linear function a more conservative approach was chosen where the linear approximation always lies above the true curve. Because of the concavity of the marginal cost function, any tangent to the function will satisfy this criterion. The tangent at $P_{V_k} = P_{V_k,min}/2$ was chosen.

Figure 4 shows that marginal battery degradation costs are very high for the given battery price and battery lifetime characteristics. This means that the price spread needs to be large enough for cars to participate in peak shaving.

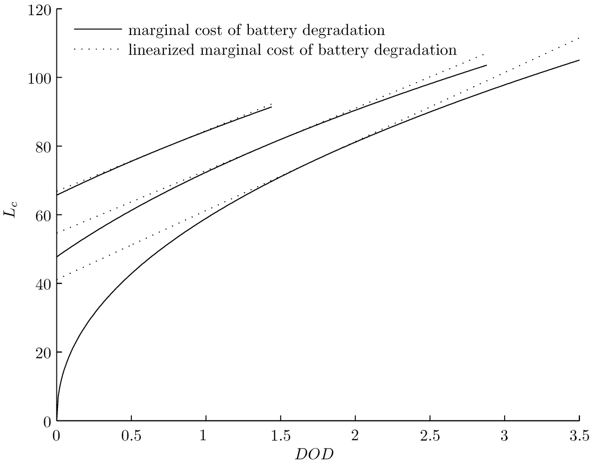


Figure 4: Marginal costs of battery degradation for parameter values indicated in Table 1.

III. Case Studies

To demonstrate the applicability of the proposed modeling framework several case studies where carried out. Subsection III A) summarizes the relevant input parameters regarding PHEV representation, the transmission network, the supply as well as the demand side together with the underlying assumptions for the different charging scenarios. In subsection III B) we study a so-called copperplate scenario, i.e. the influence of PHEVs on the power system is analyzed neglecting network constraints, whereas in subsection III C) transmission limits are introduced to evaluate the effect of congestion.

A) General Information

For the subsequent case studies we rely on a 10-bus network with 14 transmission lines as previously introduced in [14]. Figure 5 gives a graphical representation of the network. Generator and line data are contained in Table 4 and Table 5. For the demand side we have used the Swiss winter load [20]. The PHEV characteristics are summarized in Table 1. The assumptions used in terms of battery capacity, minimum SOC etc. correspond to typical values as found also in the literature.

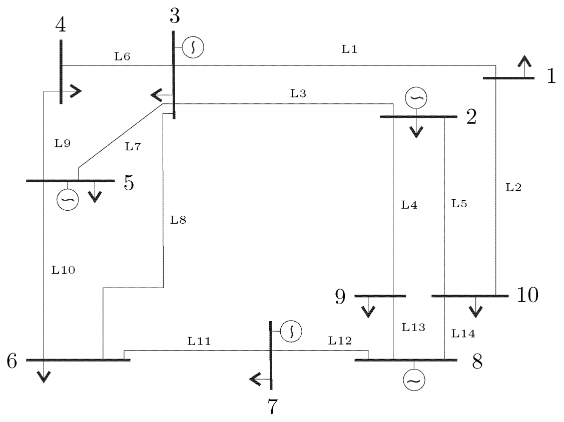


Figure 5: Graphical representation of the used network

We assume a fleet of four million vehicles. To evaluate different scenarios the PHEV penetration is varied, where simulations with a rate of 25% (one million PHEVs) and 10% (400.000 PHEVs) are carried out to show the influence of different penetration rates.

battery capacity	**minimum SOC**	**charge and discharge efficiency**		**connection capacity**	**battery lifetime parameters**		**battery price**
$C_{V_k,batt}$	$SOC_{V_k,min}$	$\eta_{V_k,char}$	$\eta_{V_k,dis}$	$P_{V_k,conn}$	a_{V_k}	b_{V_k}	$\frac{p_{V_k,buy}}{C_{V_k,batt}}$
16 kWh	0.2	0.9	0.9	3.5 kWh	1.4493e3	1.4611	200 €/kWh

Table 1: PHEV parameters

In a further step we analyze the implication of different charging modes, i.e. four different modes are distinguished as follows:

- **Dumb charging.** Vehicles start charging once they are parked. Ubiquitous charging possibilities assumed.
- **Dual tariff charging.** Vehicles are offered a high and low price tariff. The low tariff starts at midnight and ends at 5 in the morning.
- **Smart charging.** Flexible demand bids are used as described in see section II.
- **Smart charging with V2G.** Based on flexible demand and supply bids (see also section II).

B) Copperplate scenarios

In a first step we analyze a so-called copperplate scenario where we assume no transmission constraints, i.e. the lines can carry an arbitrary flow. Hence, the scenario describes only the influence of PHEVs on the supply and demand side. Figure 3 displays graphs for the two different penetrations rates (10% penetration on the left-hand side, 25% penetration on the right-hand side). The legend at the bottom summarizes the different charging modes. The reference load is indicated with an orange dotted line.

A PHEV penetration of 25% can be seen as an “amplification” of the effects seen also in the 10%-scenario. The shapes of the different profiles change only to a limited extend, whereas the effects observed are stronger in terms of system peak load. With dumb charging the morning and evening peak are increased by app. 2 GW due to the additional PHEV charging load. This effect originates from the mobility behavior. People usually drive to work early in the morning, they then park their car, stay at work and drive home again in the evening. As for dumb charging, cars start charging when they park the already existing peaks in the reference profile are increased. The situation changes for the dual tariff scenario where additional peaks during the day can be avoided. However, at the point when the tariff changes from high price to low price (midnight) a strong peak is introduced. Both modes – dumb charging as well as dual tariffs – do not seem favorable in terms of system operation as existing peaks are either "amplified" or an additional peak is created at midnight. Such a behavior can be avoided by smart charging where the additional load is shifted in a coordinated manner to off-peak hours in the afternoon or during nighttime.

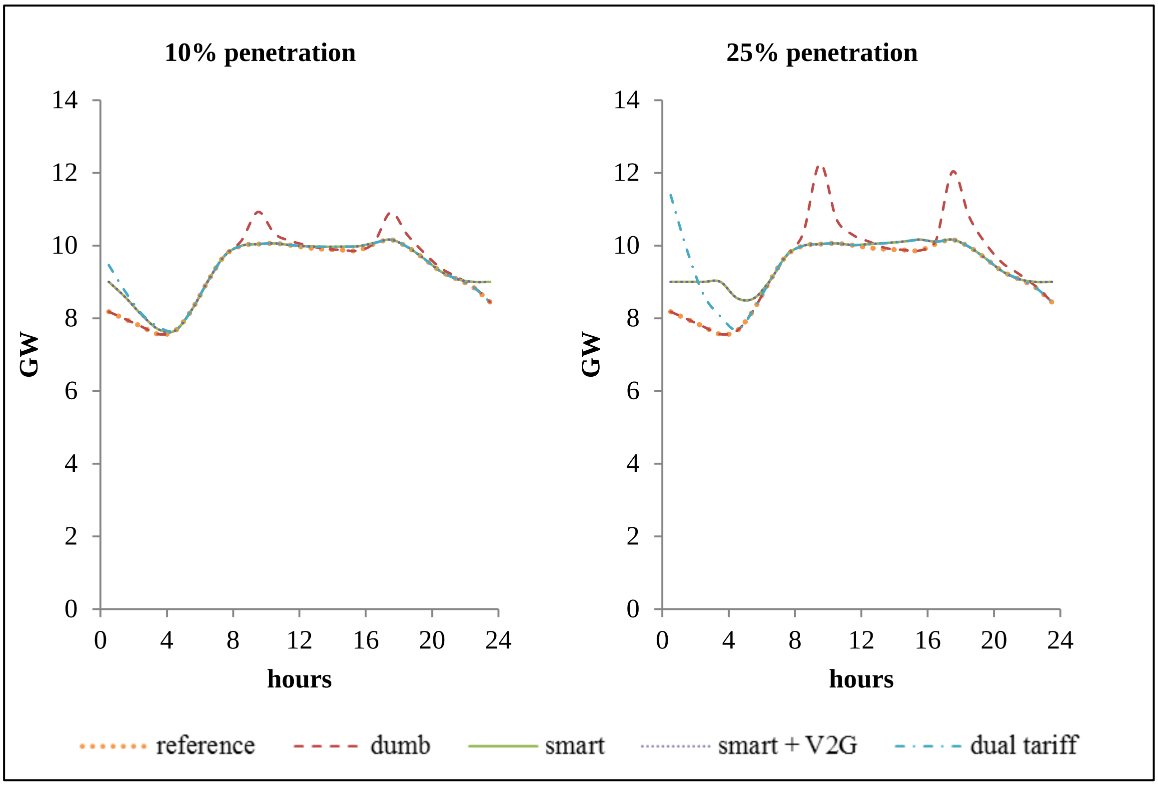


Figure 6: 24-hour load profiles for the different scenarios and different penetration rates

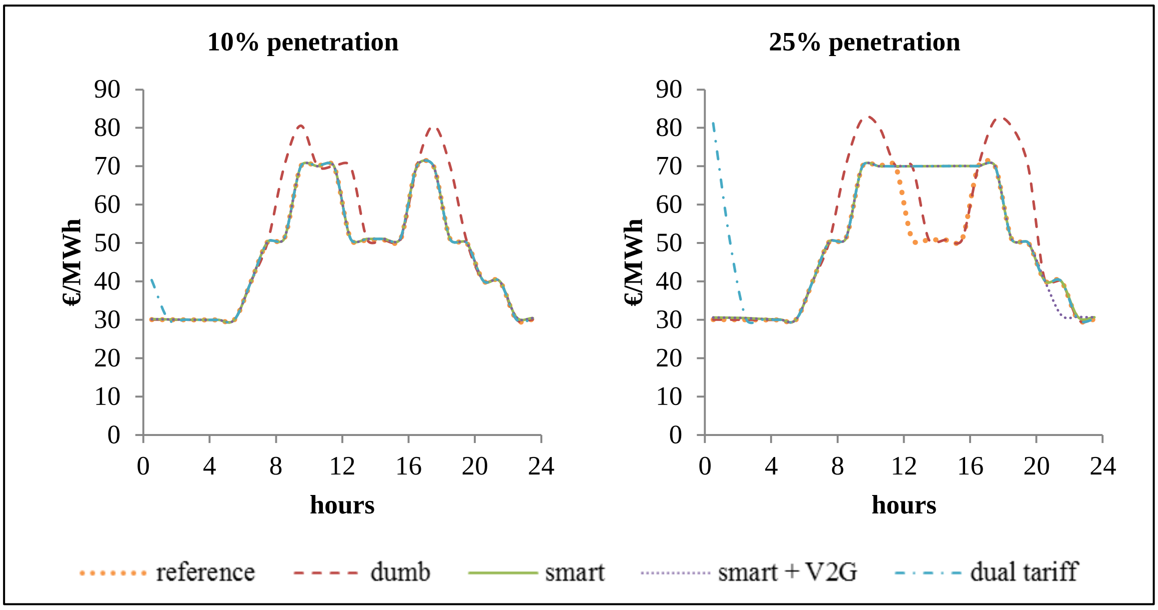


Figure 7: 24-hour price profiles for the different scenarios and different penetration rates

	dumb	**smart**	**smart+V2G**	**dual tariff**
10 % penetration	203'200	95'900	95'800	100'500
25% penetration	532'500	247'400	247'200	336'700

Table 2: Additional daily generation costs for the different scenarios [€]

Electricity prices (as displayed in Figure 4) exhibit a similar behavior. To cover the demand peaks introduced by dumb charging or dual tariffs more expensive generation has to be dispatched resulting in a price increase for peak hours. Note that for dumb charging also the duration of the peaking time changes, i.e. peak periods are prolonged. Smart charging to a great extend avoids such price effects. However, during the afternoon a price increase can also be observed, where during nighttime it is almost completely avoided. Table 2 presents an overview of the additional generation costs dependent on the individual charging modes. In terms of additional costs dumb charging performs worst, followed by dual tariff mode, with smart charging being the second-best option in terms of cost efficiency. The difference between the latter and the additional use of V2G services is small. This behavior is mostly due to the fact that V2G is only advantageous if the spread between off-peak and peak prices exceeds the costs for battery degradation. Otherwise the additional wear of the battery is not compensated for. As battery degradation costs are high it is in most cases unfavorable for individual PHEVs to feed energy back to the network. Thus, the influence of V2G is rather insignificant.

C) Smart charging under congestion

While in the previous case study network constraints have been neglected, we now introduce transmission limits as displayed in Table 4. Generally, the system behavior is similar for the different charging modes in comparison to the copperplate case. Figure 6 displays the results concerning the daily price profiles, where each diagram represents a different charging mode as well as the reference case. Dumb charging increases price peaks. The dual tariff creates a price spike during nighttime. Smart charging avoids further spikes, only during afternoon price levels rise. The differently colored lines in all diagrams represent the prices at the individual nodes in the system. During off-peak hours there is no congestion in the network hence prices are identical throughout the whole system. In case of congestion different nodal prices occur. It may appear counterintuitive that during peak hours in the dumb-charging case nodal prices are again identical, indicating that there is no congestion in the network. This situation arises as in peak hours a different generation dispatch is necessary deploying also expensive generators to satisfy overall demand. This dispatch “removes” congestion in the network although prices are generally high in the whole system. Table 3 summarizes additional daily generation costs for the different charging modes as already described in conjunction with Table 2. Note that the additional costs are slightly lower in comparison with the copperplate scenario. This effect originates from the fact that the additional costs are relative to the reference case. As prices in the reference case are already high the difference is smaller. Figure 7 illustrates the effect of nodal prices on the charging behavior. Bus number 5 is the bus with the lowest nodal price. Whereas in the copperplate scenario it is too expensive to charge in the congested case vehicles charge due to the lower nodal price in the period from app. 5 pm to 9 pm. This does not apply to the other buses in the system where the charging behavior remains almost identical.

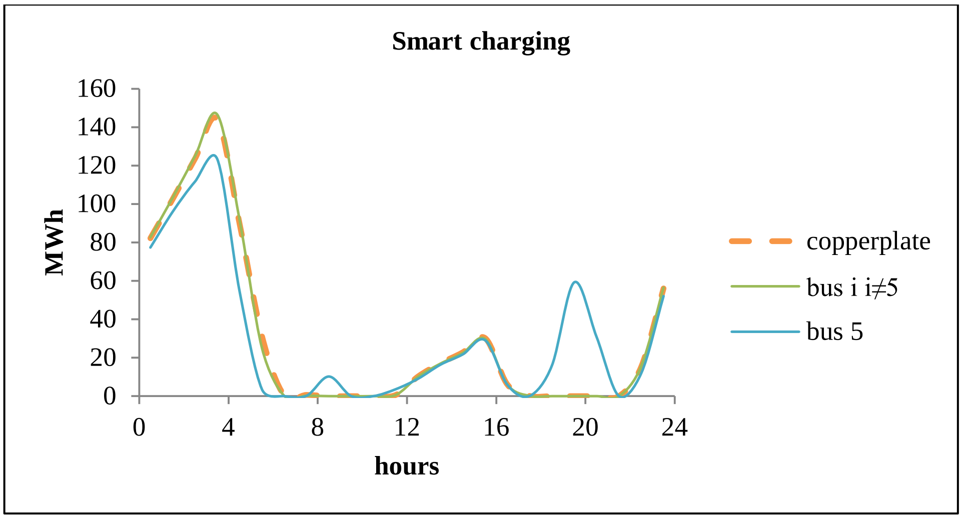


Figure 8: Aggregated charging profiles at different nodes compared to the copperplate scenario

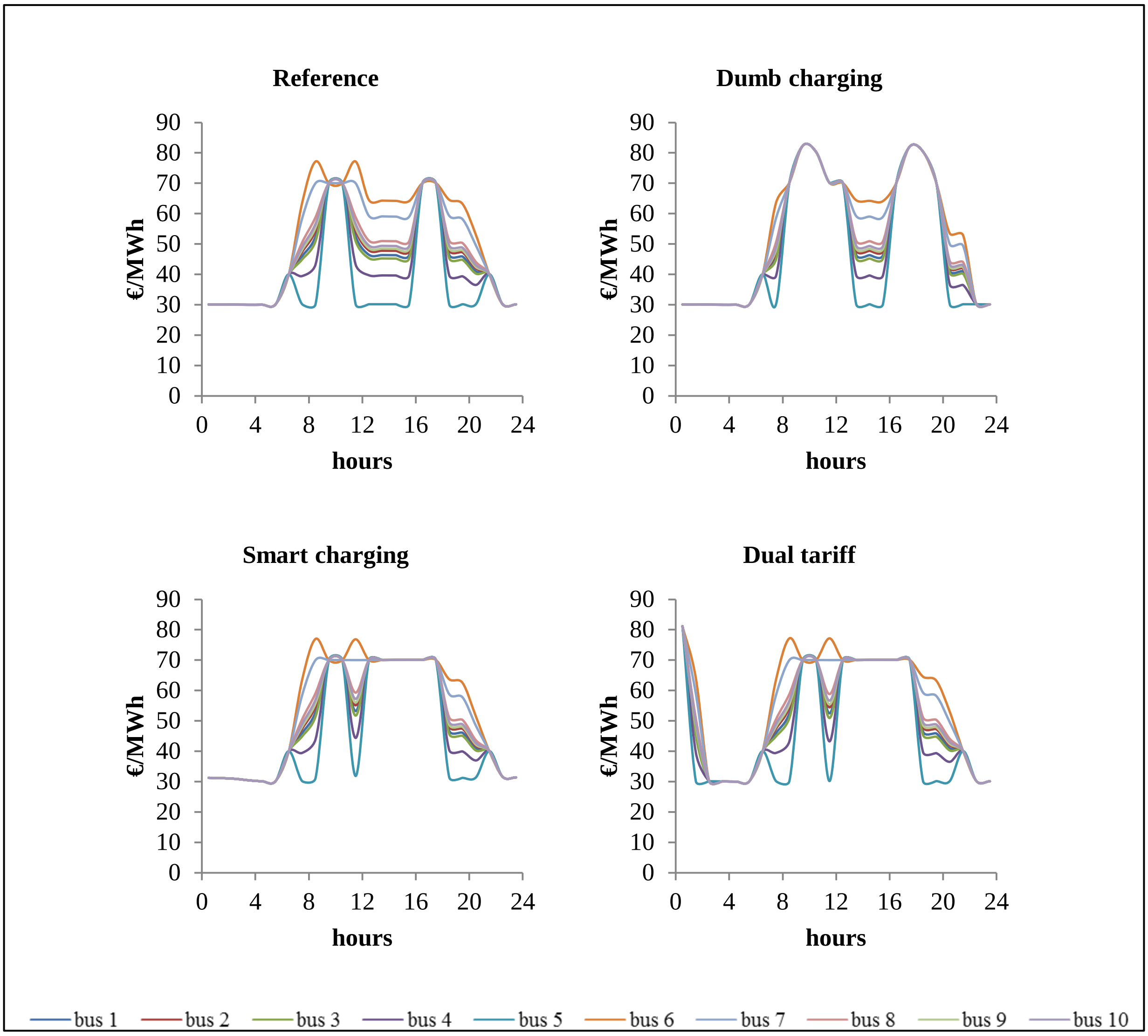


Figure 9: 24-hour price profiles for the different scenarios (25% penetration)

	dumb	smart	smart+V2G	dual tariff
10 % penetration	202'000	94'900	94'800	100'200
25% penetration	530'600	244'500	244'200	335'200

Table 3: Additional daily generation costs for the different scenarios [€]

IV. Conclusion

An increasing share of PHEVs in the vehicle fleet would pose the grid infrastructure under strain if no charging control strategy is implemented, as demand peaks and PHEV load peaks fairly coincide. Vehicles, being typically parked most of the time could be treated as flexible loads in a way that is both beneficial from a system perspective, reducing generation costs and flattening the load curve, and for the individual PHEVs, reducing their charging costs.

In this paper we have proposed a smart charging strategy based on LMPs where vehicles place demand bids according their status parameters, which reveal the urgency of their charging demand. Using a simulation of a large fleet of vehicles we have shown that this model contributes successfully to the smoothing of the load profile, prevents charging during peak hours and shows lower generation costs compared to a “dumb” charging scenario. It was also shown that simpler charging schemes, such as a dual tariff, are no longer useful at high penetration rates. Although the presented model focuses on the transmission system level and is hence highly aggregated, individual vehicles can be modeled accurately and at the same time efficiently through demand aggregation.

Moreover, it was shown that PHEVs offer however a limited potential for peak-shaving due to high battery degradation costs. However, further developments in battery technology concerning battery lifetime and costs could improve this potential.

Furthermore this model shows the impact of the additional load on transmission lines and could hence be used for planning purposes. Particular mobility phenomena such as commuting could potentially have an important effect on line loading patterns.

V. Annex – Grid data

Line nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14
X p.u.	0.10	0.27	0.12	0.07	0.14	0.10	0.17	0.17	0.17	0.17	0.16	0.25	0.25	0.07
$P_{l_m,max}$ [MW]	4500	3000	5250	3390	2370	2670	3225	5250	3225	2764	5250	3000	3390	5250

Table 4: Line parameters

Bus nr	Capacity $P_{G_i,max}$ [MW]	Intercept n_{G_i}	Slope m_{G_i}
2	5000	80	0.00067
3	600	40	0.00040
5	9000	29	0.00006
7	500	70	0.00026
8	400	50	0.00150

Table 5: Generator parameters

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