

Schill, Wolf-Peter

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**Electric Vehicles in Imperfect Electricity
Markets – a German Case Study**

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DIW Berlin
German Institute for Economic Research
Mohrenstr. 58
10117 Berlin

Tel. +49 (30) 897 89-0
Fax +49 (30) 897 89-200
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Electric Vehicles in Imperfect Electricity Markets - a German Case Study

Wolf-Peter Schill^{a,1,*}

^a*Department of Energy, Transportation and Environment, DIW Berlin, Mohrenstraße 58,
10117 Berlin, Germany*

Abstract

We analyze the impacts of a hypothetical fleet of plug-in electric vehicles on the imperfectly competitive German electricity market with a game-theoretic model. Electric vehicles bring both additional demand and additional storage capacity to the market. We determine their effects on prices, welfare, and electricity generation for various cases with different players being in charge of vehicle operations. We find that vehicle loading increases generator profits, but decreases consumer surplus. If excess vehicle batteries can be used for storage, welfare results are reversed: generating firms suffer from the price-smoothing effect of additional storage, whereas consumers benefit despite increasing overall demand. Results however depend on the player being in charge of storage operations, and on battery degradation costs. Strategic players tend to under-utilize the storage capacity of the vehicle fleet, which may have negative welfare implications. In contrast, we find a small market power mitigating effect of electric vehicle recharging on oligopolistic generators. Overall, electric vehicles are unlikely to be a relevant source of market power in Germany.

Keywords: Electric Vehicles, Vehicle-to-Grid, Arbitrage, Electric Power Markets, Market power
JEL: Q40, Q41, L13, D43

*Corresponding author.

Email address: wschill@diw.de (Wolf-Peter Schill)

¹Tel.: +49 30 89789-675; Fax: +49 30 89789-113. The author is a member of the Graduate Center of Economic and Social Research, DIW Berlin.

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1. Introduction

In the light of tighter climate policy and a growing dependency on imported fossil fuels in the transportation sector, electric vehicles currently receive a lot of attention. They allow to utilize a broad energy resource base for mobility purposes, including renewable sources. In addition, electric vehicles promise to deliver a range of benefits compared to internal combustion engines, including higher energy efficiency as well as lower emissions of noise, CO₂, and other air pollutants (Samaras and Meisterling, 2008; Bradley and Frank, 2009). Yet the materialization of these benefits largely depends on the means of electricity generation. The interaction of electric vehicle fleets with electricity markets has not much been studied so far. In particular, there is little research on electric vehicles in imperfect electricity markets. This article intends to fill this literature gap.

Using a game-theoretic model, we examine the market impacts of a hypothetical fleet of one million plug-in electric vehicles (PIEV) on the imperfectly competitive German electricity market. We separately analyze the market effects of additional load and additional storage capacity on prices, welfare, and electricity generation. We also examine how different players in charge of electric vehicle operations differ regarding vehicle recharging and the utilization of storage capacity. In particular, the model allows to investigate the combined decisions of oligopolistic generating firms on generation, vehicle loading, and storage. We also analyze the utilization of excess vehicle battery capacity for arbitrage, i.e. storing electricity in periods of low prices and selling it back to the market in times of higher prices. We examine if arbitrage is a viable strategy in the light of existing pumped hydro storage and battery degradation costs.

The analysis shows that the introduction of PIEV generally increases generator profits and decreases consumer surplus. This is particularly true if vehicles are recharged in an uncontrolled way. In case of controlled loading of the PIEV fleet, welfare distortions as well as vehicle loading costs decrease substantially. If battery capacity that is not needed for daily average driving requirements can be used for grid storage, welfare effects are very different: generator profits decrease, while consumer surplus and overall welfare substantially increase due to a price-smoothing effect of additional storage capacity. Yet battery degradation costs may diminish arbitrage opportunities and related welfare effects. In addition, strategic generating firms tend to under-utilize their battery storage capacity, which may have negative implications for consumers. In contrast, consumers may benefit from a market power mitigating effect of vehicle and storage loading on strategic generators. Finally, electric vehicles increase the utilization of emission-intensive low-cost technologies, in particular if an oligopolistic generator is in charge of PIEV operations.

The remainder is structured as follows. First, we briefly discuss the relevant literature. Section 3 describes the model and the main assumptions. Sections 4 and 5 include all relevant data and define different cases of PIEV operation. The results section discusses the impacts of different players controlling PIEV fleet on market prices, welfare and electricity generation. We also perform a sensitivity

analysis regarding battery degradation costs. The last section summarizes and concludes.

2. Literature

While there are many different designs of electric vehicles, they share a common feature of complementing or completely substituting a conventional internal combustion engine with a battery-electric drive.³ Future PIEV fleets will have substantial impacts on electricity markets. On the one hand, they increase overall demand. This could have negative impacts on network stability, electricity prices, and emissions. For example, Gerbracht et al. (2009) find that uncontrolled loading of electric vehicles will increase German peak load to dangerous levels even if PIEV fleets are rather small. Vehicle recharging should thus be carried out in off-peak hours in order to minimize negative impacts. On the other hand, future PIEV fleets could also offer valuable services to the electricity system, if they were connected to the grid in a bi-directional way and intelligently controlled. Kempton and Tomic (2005a) have first developed the idea of integrating electric vehicle fleets into the power system with a ‘Vehicle-to-Grid’ (V2G) concept. Drawing on the empirical fact that around 90% of all vehicles are in a parking position any given time of the day, an implementation of the V2G concept could realize large synergies between the electric vehicle fleet and the electricity system (compare also Kempton and Tomic, 2005b). Guille and Gross (2009) provide a framework for integrating PIEV into existing power systems. Within a V2G concept, PIEV fleets could smooth the load curve by recharging batteries at nighttime, or they could deliver peak load by feeding electricity back to the grid in times of high demand. Moreover, PIEV could provide valuable ancillary services like primary, secondary or tertiary control (Tomic and Kempton, 2007). Galus et al. (2010) examine the provision of secondary control services by PIEV fleets. Andersson et al. (2010) find that providing regulating power with PIEV fleets in Germany and Sweden may be an economically viable strategy. Sioshansi and Denholm (2009) demonstrate that the provision of spinning reserves by electric vehicles could increase the efficiency of thermal electricity generation, which in turn decreases emissions. It has also been suggested that PIEV fleets may be able to balance fluctuating renewable energy feed-in, for example by taking up excess wind generation (compare Lund and Kempton, 2008; Ekman, 2011). Although an implementation of the V2G concept could bring a range of benefits, Sovacool and Hirsh (2009) argue that it might face large social barriers.

In this article, we focus on the interaction of electric vehicles and imperfect electricity markets. Imperfect competition in power markets has been exten-

³In our model analysis, we do not care about different electric vehicle concepts, as long as they recharge their batteries from the power grid. We are only interested in the cumulative market impact of grid-connected vehicle fleets. For example, we do not distinguish between hybrid electric cars and pure battery electric drives. Schill (2010) provides an overview of different vehicle concepts.

sively studied. Amongst others, Green and Newbery (1992) and Borenstein et al. (2002) have made seminal contributions. Hortaçsu and Puller (2008) and Mansur (2008) empirically study market power problems in different U.S. electricity markets. Puller (2007) and Bushnell et al. (2008) provide empirical support that Cournot pricing is a reasonable assumption for electricity market modeling. Weigt and Hirschhausen (2008) find empirical evidence of imperfect competition on the German power market. Note that our analysis focuses on the wholesale market. Ancillary services that are traded on other markets are excluded, for example the provision of regulating power.

In contrast to previous studies, we explicitly model a real interaction of PIEV operations and the German wholesale market. We endogenously determine the timing of vehicle recharging and storage operations by profit-maximizing players while taking care of market price reactions. Moreover, we allow for imperfect competition, which complements earlier analyses that assume perfectly competitive markets, for example Göransson et al. (2010) for Denmark or Sioshansi et al. (2010) for the Ohio power system. Moreover, we explicitly quantify the effect of different players being in charge of PIEV operations. We thus quantitatively support the argument brought forward by Andersen et al. (2009) and Guille and Gross (2009), according to which the ‘aggregator’ - i.e. the actor in charge of vehicle operations - plays a crucial role for integrating electric vehicle fleets into power markets.

More generally speaking, our analysis also enlarges the understanding of how flexible resources are used in imperfect electricity markets. We not only study strategic electricity storage, as for example Schill and Kemfert (2009) or Sioshansi (2010) do, but also the strategic allocation of dispatchable load and its interaction with oligopolistic generation. Although the analysis is motivated by electric vehicles, results may be interpreted in a more general way, as additional storage and dispatchable demand could also be introduced to the market by other technologies.

3. The model

We assume that PIEV operations (i.e. battery recharging and the utilization of excess battery capacity for arbitrage) are either controlled by individual vehicle owners or by service providers. Importantly, all these PIEV operators also act as players on the electricity market: they have to buy electricity for recharging their vehicles, and they may sell stored electricity back to the market. We further assume that there is a fixed amount of electricity that has to be delivered to the electric vehicle fleet each day in order to recharge their batteries. Players in charge of PIEV operations have a ‘commitment to deliver’ the daily amount of recharging electricity, whereas the car owners face some kind of ‘take or pay’ situation. We do not further specify the contractual relationship between PIEV service providers and individual car owners. We just assume that the operators responsible for vehicle recharging try to acquire the necessary electricity at the lowest possible cost. This procedure allows to obtain fairly general results. Note that we do not analyze the relationship or the exertion of market power between

vehicle service providers and individual vehicle owners. Rather, we are interested in the role that PIEV operators might play in an imperfectly competitive electricity market, and in their strategic interaction with other actors in that market.

We use a game-theoretic electricity market model. Its solution represents a Cournot-Nash equilibrium. We build upon the ElStorM model developed by Schill and Kemfert (2009) and extend it by introducing additional variables, parameters and constraints related to electric vehicles. Table 4 in the Appendix lists all model sets, indices, parameters and variables. The set of players may include firms that generate electricity only (i.e. traditional utilities), players that are only involved in PIEV operations, or players that combine both activities. Individual vehicle owners may also be players, if they are able to respond to hourly wholesale market prices while recharging their vehicles.⁴

Equations (1a-1m) describe individual players' constrained maximization problems. Player's indices $f \in F$ are omitted in order to improve readability. The players maximize profits by deciding on a set of hourly ($t \in T$) decision variables, including electricity generation $x_{i,t}$ of various technologies $i \in I$, the timing of vehicle loading $vload_t$ and loading $stin_{j,t}$ as well as discharging $stout_{j,t}$ of different storage technologies $j \in J$. Equation (1a) represents the profit function. It includes revenues from selling electricity, which was either generated by a specific technology ($p_t x_{i,t}$) or previously stored ($p_t stout_{j,t}$). It also includes technology-specific variable generation costs (vgc_i), variable costs of storage operation ($vstc_j$), costs of storage loading ($p_t stin_{j,t}$), and costs of vehicle recharging ($p_t vload_t$). The latter terms reflect the fact that electricity stored at period t had to be bought or could have been sold on the market at the price of the respective period. The decision variables are subject to a range of constraints, which are shown in (1b-1m). Due to the complexity of the model, we abstract from including network constraints or different voltage levels.

$$\max_{\substack{x_{i,t} \\ vload_t \\ stin_{j,t} \\ stout_{j,t}}} \sum_{t \in T} \left[p_t \left(\sum_{i \in I} x_{i,t} - vload_t + \sum_{j \in J} (stout_{j,t} - stin_{j,t}) \right) - \sum_{i \in I} vgc_i x_{i,t} - \sum_{j \in J} vstc_j stout_{j,t} \right] \quad (1a)$$

⁴In addition, players may own other electricity storage technologies. In the model application, we include pumped hydro storage, as this technology is the only large-scale storage technology that is economically feasible today.

$$\begin{aligned}
s.t. \quad & x_{i,t} - \bar{x}_i^{gen} \leq 0, \quad \forall i, t \quad (\lambda_{gen,i,t}) & (1b) \\
& x_{i,t} - x_{i,t-1} - \xi_{up,i} \bar{x}_i^{gen} \leq 0, \quad \forall i, t \quad (\lambda_{rup,i,t}) & (1c) \\
& x_{i,t-1} - x_{i,t} - \xi_{down,i} \bar{x}_i^{gen} \leq 0, \quad \forall i, t \quad (\lambda_{rdo,i,t}) & (1d) \\
& \sum_{t \in d} vload_t - vldaily_d = 0, \quad \forall d \quad (\lambda_{vldaily,d}) & (1e) \\
& stin_{PIEV,t} + vload_t - \bar{st}_{PIEV}^{in} \leq 0, \quad \forall t \quad (\lambda_{stin,PIEV,t}) & (1f) \\
& stin_{j,t} - \bar{st}_j^{in} \leq 0, \quad \forall j \neq PIEV, t \quad (\lambda_{stin,j,t}) & (1g) \\
& stout_{j,t} - \bar{st}_j^{out} \leq 0, \quad \forall j, t \quad (\lambda_{stout,j,t}) & (1h) \\
& \sum_{\tau=1}^t stout_{j,\tau} - \sum_{\tau=1}^{t-1} stin_{j,\tau} \eta_{st,j} \leq 0, \quad \forall j, t \quad (\lambda_{stlo,j,t}) & (1i) \\
& \sum_{\tau=1}^t stin_{j,\tau} \eta_{st,j} - \sum_{\tau=1}^{t-1} stout_{j,\tau} - \bar{st}_j^{cap} \leq 0, \quad \forall j, t \quad (\lambda_{stup,j,t}) & (1j) \\
& x_{i,t} \geq 0, \quad \forall i, t & (1k) \\
& vload_t \geq 0, \quad \forall t & (1l) \\
& stin_{j,t}, stout_{j,t} \geq 0, \quad \forall t & (1m)
\end{aligned}$$

Condition (1b) demands that a player's electricity generation never exceeds its available generation capacity \bar{x}_i^{gen} . (1c) is a 'ramping up' restriction: between two subsequent time periods, electricity generation of a specific technology can only be increased to a certain degree, depending on the total available capacity and a technology-specific parameter $\xi_{up,i}$, which takes on values between 0 and 1. Likewise, condition (1d) represents a technology-specific 'ramping down' restriction. Note that we relate ramping restrictions to the total available technology-specific capacity of a firm and not to starting up and shutting down of individual plants. In doing so, we avoid a unit commitment problem with a mixed-integer formulation, which would be very hard to solve in a game-theoretic framework.

Condition (1e) specifies the daily vehicle recharging requirement. We assume that the electric vehicle fleet requires a certain amount of energy for driving purposes, which has to be recharged at some point in time over 24 hours. $vldaily_d$ is the daily vehicle recharging requirement (in MWh) that each player has to fulfill ($vldaily_d = 0$ for players without PIEV operations). Note that (1e) does not further restrict the timing of vehicle loading: It might take place during any hour of the day, or it could be split up over all 24 hours. Conditions (1f-1h) describe the power rating of vehicle fleets and pumped storage facilities. (1f) ensures that the PIEV battery loading rate never exceeds the fleet's cumulative connection power \bar{st}_{PIEV}^{in} (in MW). Note that battery loading consists of vehicle recharging for driving purposes and the loading of unused battery capacity for arbitrage. (1g) is a similar loading condition for all other storage technologies, for example pumped hydro storage. Likewise, (1h) ensures that selling electricity back to the market from storage never exceeds the available storage

discharging capacity \overline{st}_j^{out} , i.e the fleet connection power in case of PIEV.

(1i) ensures that storage output never exceeds the net of previous storage inputs and outputs. (1j) represents an upper storage capacity constraint. For each period t , the amount of electricity that can be stored cannot exceed the total available capacity of a given storage technology \overline{st}_j^{cap} (in MWh), minus previous inflows plus previous outflows.⁵ Condition (1i) demands that selling previously stored electricity to the market stops once the batteries are empty. As neither batteries nor pumped hydro storage have perfect roundtrip efficiencies, (1i) and (1j) include efficiency losses: only a share $\eta_{st,j}$ of previously stored electricity can be sold back to the market. Finally, conditions (1k-1m) ensure non-negativity of the decision variables.

A market clearing condition is required in order to link the players' constrained maximization problems. Equation (2) defines total hourly supply to the wholesale electricity market, consisting of total electricity generation minus vehicle recharging plus storage output minus storage input. (3) demands that supply equals demand in all periods. We assume that demand is characterized by an iso-elastic function with price elasticity σ , drawing on exogenous hourly reference demands $d0_t$ and prices $p0_t$. In other words, we assume that electricity demand on the wholesale market is elastic, whereas the daily vehicle recharging requirement is fixed.

$$X_t = \sum_{f \in F} \left[\sum_{i \in I} x_{f,i,t} - vload_{f,t} + \sum_{j \in J} (stout_{f,j,t} - stin_{f,j,t}) \right], \quad \forall t \quad (2)$$

$$X_t = d0_t \left(\frac{p_t}{p0_t} \right)^{-\sigma}, \quad \forall t \quad (3)$$

We formulate the optimization program as a mixed complementarity problem (MCP), which is the suitable formulation for this type of problem. The definition of a MCP, its application to economic analyses and its implementation in GAMS has been described by Rutherford (1995) and Ferris and Munson (2000). We combine the market clearing condition (3) with (2), solve for p_t and insert the expression into (1a). We then derive the Karush-Kuhn-Tucker (KKT) optimality conditions (6a-6n), which are listed in the Appendix. The KKT conditions form a nonlinear mixed complementarity equation system, which we implement in the General Algebraic Modeling System (GAMS), drawing on the data described in section 4. In the numerical application, the problem consists of more than 140,000 equations and variables. We solve with the solver PATH, which represents a generalization of Newton's method, including a path search (Ferris and Munson, 2000).

After solving the model, we calculate consumer and producer surplus on the electricity market. Consumer rent of period t is determined according to

⁵Note that we consider $\overline{st}_{PIEV}^{cap}$ as a fraction of the overall vehicle battery capacity that is - on average - not utilized for driving purposes and that is thus available for arbitrage.

equation (4) by integrating the demand function and subtracting the amount actually paid. Producer rent for each player is calculated according to equation (5) by summing up revenues and subtracting costs. Note that we determine welfare outcomes only for the electricity market, but not for the market for vehicle recharging, as we do not specify the contractual relationship between the service providers responsible for vehicle recharging and individual car owners.⁶ Accordingly, we do not determine costs, revenues or consumer surplus related to the recharging business. Instead, we focus on PIEV-related welfare effects on the electricity market, which are caused by increasing electricity demand and additional storage capacity. The arbitrage profits made by PIEV operators from using excess battery capacities are explicitly included in (5), as arbitrage activities take place on the wholesale electricity market. Focusing welfare considerations on the electricity market allows to compare welfare outcomes between different cases with electric vehicles and the Baseline without such vehicles in a meaningful way.

$$crent_t = \int_0^{X_t} p0_t \left(\frac{x}{d0_t} \right)^{-\frac{1}{\sigma}} dx - p_t X_t, \forall t \quad (4)$$

$$prent_{f,t} = \sum_{i \in I} x_{f,i,t} (p_t - vgc_i) + \sum_{j \in J} (stout_{f,j,t} (p_t - vstc_j) - stin_{f,j,t} \cdot p_t), \forall t \quad (5)$$

4. Data

We apply the model to the German wholesale electricity market and run it for two consecutive weeks (336 single hours) in order to reflect different load situations. Reference demand and price data ($d0$ and $p0$) for each hour is taken from the German energy exchange (EEX). We draw on two characteristic winter weeks between 16 and 29 January 2009, as the effect of additional electricity demand should be largest in winter, when demand is high. We start the model on a Friday in order to and generate meaningful storage patterns during the two weekends. As in Schill and Kemfert (2009), we assume a price elasticity of demand of $\sigma = 0.45$. This value allows a good replication of the reference data. For reasons of simplicity and traceability, σ is assumed to be time-invariant.

We include seven players, among them four oligopolistic generating firms: EnBW, E.ON, RWE, and Vattenfall. Combined, these firms hold more than 80% of total German generation capacity. The remaining conventional generation capacity is assigned to a price-taking generating firm named ‘Fringe’. Accordingly, $\theta_{f,i,t}^{gen} = 1$ for $f = \text{EnBW, E.ON, RWE, Vattenfall}$ and $\theta_{Fringe,i,t}^{gen} = 0$

⁶Note that vehicle recharging could also be carried out by individual car owners without the help of a service provider.

	EnBW	E.ON	RWE	Vattenfall	Fringe	RES	NoGen
Available generation capacity:							
Nuclear	3,974	7,553	3,496	1,402	946	0	0
Lignite	398	1,302	8,494	7,201	403	0	0
Hard coal	1,570	5,833	2,615	979	3,604	0	0
Natural gas	686	2,543	1,959	1,382	4,302	0	0
Oil	103	348	5	152	127	0	0
Hydro	299	1,055	447	0	625	0	0
Wind	0	0	0	0	0	25,777	0
Available pumped hydro storage capacity:							
Loading/discharging rate in MW	503	509	512	1,447	228	0	0
Capacity in MWh	1,440	1,358	1,392	3,428	440	0	0

Table 1: Available generation and pumped hydro storage capacity in MW

in the KKT conditions (Appendix). Another price-taking player named ‘RES’ holds the total installed wind capacity ($\theta_{RES,wind,t}^{gen} = 0$). In addition, we include a player ‘NoGen’ without any generation capacity, which may only engage in vehicle operations. This idea follows Andersen et al. (2009), who argue that new PIEV players will emerge. The NoGen player may either act as a price-taker or in a strategic way, depending on the scenario as defined in 5. We include the generation technologies nuclear, lignite, hard coal, natural gas, oil, and hydro power. Natural gas is an aggregate of combined cycle, steam, and gas turbines. Hydro power includes run-of-river and other hydroelectric plants, but excludes pumped storage. Table 1 lists generation capacity available to each players. Data is derived from Traber and Kemfert (2009) and adjusted with technology-specific plant availabilities in order to reflect regular maintenance and outages. Note that the wind capacity listed in the table (BMU, 2010) hardly matters as wind generation is exogenously set according to hourly feed-in levels between 16 and 29 January 2009 in order to reflect the German regulation which grants priority feed-in to renewable power sources. Hourly wind generation data comes from publicly available sources provided by German transmission system operators. Table 1 also includes available pumped hydro storage capacity in Germany according to Schill and Kemfert (2009). We assume that 50% of the cumulatively installed loading/discharging rate and only 20% of the total pumped hydro storage capacity are available for arbitrage in any given hour. These values are based on interviews with industry experts and reflect the fact that a substantial share of the German PHS capacity is reserved for frequency control, reactive power supply, and seasonal storage. $\theta_{f,PHS,t}^{st} = 1$ for f =EnBW, E.ON, RWE, Vattenfall and $\theta_{Fringe,PHS,t}^{st} = 0$. Table 2 lists ramping parameters and variable costs for all generation technologies (Schill and Kemfert, 2009). Variable generation costs reflect fuel and other operational costs as well as emission costs. Data sources include dena (2005), Wissel et al. (2008), EEX and the International Energy Agency.

As for a hypothetical electric vehicle fleet, we draw on the official target of the German government of having one million electric vehicles on the road by the year 2020 (Bundesregierung, 2009). We derive the characteristics of fu-

	Nuclear	Lignite	Hard Coal	Natural Gas	Oil	Hydro
Ramping parameters						
$\xi_{up,i}$	0.05	0.07	0.22	0.28	0.68	0.22
$\xi_{down,i}$	0.10	0.06	0.18	0.26	0.72	0.19
Variable generation costs vgc_i in €/MWh	10	25	30	40	50	10

Table 2: Parameters for conventional generation technologies

ture PIEV fleets from scenarios developed by Wietschel and Dallinger (2008). Accordingly, one million PIEV have a cumulative connection power of around 5 GW ($\sum_f \overline{st}_{f,PIEV}^{in}$ and $\sum_f \overline{st}_{f,PIEV}^{out}$). The average daily recharging requirement amounts to 4 GWh ($\sum_f vldaily_{f,d}$). The overall battery capacity is around 13 GWh, such that around 9 GWh should be available on average for arbitrage ($\sum_f \overline{st}_{f,PIEV}^{cap}$).⁷ These numbers certainly represent only rough estimates of future PIEV fleet characteristics. We are, however, more interested in general effects than in absolute numbers in our numerical application.

We estimate that around 80% of all electric vehicles are not on the road, but in a parking position in any given hour (Kempton and Tomic, 2005a, even assume 90%). We furthermore assume that all parking cars are connected to the electricity grid. Thus 80% of the PIEV capacity is available any point in time. Drawing on Sioshansi et al. (2010), we assume a round-trip efficiency of $\eta_{st,PIEV} = 0.9$ for vehicle batteries. Accordingly, for each MWh that is stored in PIEV batteries, only 0.9 MWh can be retrieved again later. As for pumped hydro storage, we assume an average round-trip efficiency of only $\eta_{st,PHS} = 0.75$ (Tiedemann et al., 2008). Regarding variable storage costs (aside from opportunity costs $p_t stin_{j,t}$), we initially set $vstc_j = 0$ for both vehicle batteries and pumped hydro storage. We relax this assumption in section 6.4 in order to assess the sensitivity of results to non-negligible battery degradation costs.

5. Scenarios

We define eight different cases as indicated by Table 3. They bear some similarity to scenarios used by Göransson et al. (2010). The ‘Baseline’ (BL), which does not include any electric vehicles, serves as a point of reference. In the ‘Uncontrolled Loading’ (UL) scenario, we exogenously assign the daily vehicle recharging requirement of the PIEV fleet to the evening hours between 4pm and

⁷Tomic and Kempton (2007), Lund and Kempton (2008), and Ekman (2011) argue that PIEV could provide much-needed flexibility for integrating fluctuating renewable generators into the electricity system. The numbers used in our analysis, however, indicate that the potential of electric vehicles for integrating renewables should not be overestimated: the battery capacity not required for average daily driving of one million vehicles is only 9 GWh. For comparison: the installed German wind capacity of 2009 was around 25 GWh, i.e. vehicle batteries would be completely loaded within less than half an hour during periods with high wind feed-in.

8pm (1 GWh per hour). In a stylized way, UL represents the behavior of vehicle owners which plug in their cars for recharging when they get home from work (compare Galus et al., 2010; Göransson et al., 2010). Furthermore, we define different cases with controlled vehicle loading, which differ with respect to the availability of unused battery capacity for grid storage. In the ‘Loading Only’ (LO) cases, the PIEV fleet only represents additional, dispatchable load. In the ‘Loading and Storage’ (LS) cases, it also brings additional storage capacity to the market, which can be used for arbitrage. Note that there may be barriers to implementing this option due to technical and institutional constraints. In contrast to PIEV storage, pumped hydro storage is available in all scenarios.

Cases also differ with respect to the players being in charge of PIEV operations. It may either be the NoGen player, which does not own any electricity generation capacity, or an oligopolistic generator. The scenarios in which the NoGen player carries out PIEV operations in a non-strategic way (LO1, LS1) represent on the one hand a situation in which several PIEV service providers act as price takers on the electricity market (just like the Fringe player among the generating firms). On the other hand, LO1 and LS1 also represent cases in which individual car owners recharge their vehicles in a decentralized, cost-minimizing way. In LO2 and LS2, the NoGen player carries out PIEV operations as a centralized, strategic player that anticipates the market’s reactions to its decisions. We could think of it as a monopolistic service provider that has contracted the whole PIEV fleet.⁸ In LO3 and LS3, a strategic generating firm has a monopoly on PIEV operations. We chose RWE as an illustrative example due to the company’s recent activities in the electric vehicle business.

6. Results

6.1. Price effects

Figure 1 shows the effect of electric vehicles on electricity prices for a characteristic day (Tuesday) and a selection of cases. We find the highest evening peak prices in the uncontrolled loading case (UL) because of additional electricity demand during these hours. In the case of controlled loading (LO1), vehicles are being recharged in periods with the lowest prices. Market prices thus increase slightly in off-peak periods in LO1, while peak prices remain unchanged compared to the Baseline. In the LS1 case, in which excess battery capacity can be used for grid storage, batteries are loaded during off-peak periods and discharged in the periods with the highest prices in order to maximize arbitrage profits. As a result, prices are smoother than in LO1. Additional model runs indicate that PIEV fleets much larger than one million vehicles could be recharged with the existing German power plant fleet without increasing peak prices, if loading is carried out in a controlled way.

⁸The LO1 and LS1 cases are conceptually closely related to scenarios in which the price-taking Fringe generator controls vehicle operations. We obtain the same results for NoGen and for Fringe being in charge of PIEV operations, with the exception of different producer rents.

	PIEV resources	Player in charge of PIEV fleet	Market power assumption
BL	-	-	-
UL	Loading only	NoGen	Loading exogenous (non-optimal)
LO1	Loading only	NoGen	Price taker $\theta_{NoGen,PIEV,t}^{vload} = 0$
LO2	Loading only	NoGen	Strategic $\theta_{NoGen,PIEV,t}^{vload} = 1$
LO3	Loading only	RWE	Strategic $\theta_{RWE,PIEV,t}^{vload} = 1$
LS1	Loading and storage	NoGen	Price taker $\theta_{NoGen,PIEV,t}^{vload} = 0$ $\theta_{NoGen,PIEV,t}^{st} = 0$
LS2	Loading and storage	NoGen	Strategic $\theta_{NoGen,PIEV,t}^{vload} = 1$ $\theta_{NoGen,PIEV,t}^{st} = 1$
LS3	Loading and storage	RWE	Strategic $\theta_{RWE,PIEV,t}^{vload} = 1$ $\theta_{RWE,PIEV,t}^{st} = 1$

Table 3: Overview of scenarios

6.2. Welfare effects

Figure 2 indicates welfare changes compared to the Baseline in different cases. In the uncontrolled loading case (UL), the introduction of PIEV into the market leads to an increase in producer profits because of higher peak prices. In contrast, consumer rent decreases. We find the same effect for the cases with controlled vehicle loading (LO1-LO3), although to a much lower extent. Accordingly, the introduction of PIEV harms electricity consumers less if they are loaded in a controlled way. Interestingly, if a strategic generator is in charge of PIEV operations (LO3), consumer rent and overall welfare are slightly higher than in the cases LO1 and LO2. This is because being in control of additional dispatchable load has a market power mitigating effect on the oligopolistic generator. In LO3, RWE strategically decreases market prices in periods of vehicle loading by increasing generation from its low-cost technologies.⁹

If excess battery capacity of the PIEV fleet can be used for grid storage, we find very different welfare effects. In LS1-3, producers overall suffer from the introduction of PIEV due to the price-smoothing effect of additional storage capacity in the market. In contrast, consumer surplus and overall welfare increase substantially. Note that consumers benefit from introducing PIEV despite the fact that overall demand increases. The price-driving effect of additional demand is outweighed by the price-smoothing effect of additional storage. In particular, consumers benefit from the decreasing effect of storage on peak prices, which has a larger effect than price increases in off-peak hours, as demand is

⁹This effect is also visible in the player's first-order condition: note the negative sign for $\vartheta_{f,t}^{vload}$ in equation (6a).

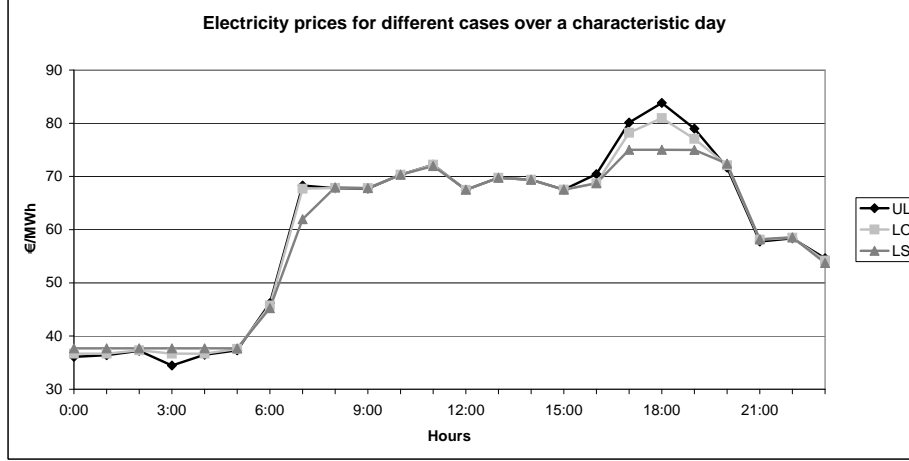


Figure 1: Electricity prices for different cases over a characteristic day

higher in peak hours. In addition, storage loading mitigates market power exertion of strategic generators, leading to slightly higher consumer surplus and overall welfare in LS3 compared to LS1 and LS2.¹⁰

During the two weeks modeled here, overall welfare increases between € 2.6 and 3.2 million in LS1-3 compared to UL, whereas consumers are € 5.2-5.8 million better off. A rough extrapolation of these values to a whole year leads to overall yearly welfare gains in the range of € 86-83 million (€ 86-83 per vehicle) and consumer benefits of around € 135-151 million (€ 135-151 per vehicle). These welfare gains may justify public support for integrating electric vehicles into the electricity system. However, PIEV-related welfare effects are small compared to welfare losses related to strategic electricity generation. Comparing the Baseline to a scenario with perfectly competitive generation ($\theta_{f,i,t}^{gen} = 0$ for all players), we find welfare losses of around € 62 million over the two modeled weeks.

Figure 3 shows producer rent changes of single firms compared to the Baseline. All players are better off in the uncontrolled loading case (UL) compared to controlled loading (LO1-3). In LO3, RWE manages to increase its profit compared to LO1-2 by strategically adjusting generation in off-peak periods, whereas all other generating firms suffer. If excess PIEV battery capacity can be used for storage, the respective operator makes a sizeable arbitrage profit, while all other producers suffer from the price-smoothing effect of storage.

Cases also differ with respect to the costs of providing electricity that is required for daily vehicle recharging. Figure 2 shows that vehicle loading costs are much lower in the cases of controlled loading compared to the uncontrolled UL case. This is because PIEV operators in LO1-3 and LS1-3 charge their

¹⁰Again, this effect is indicated by the negative sign of $\vartheta_{f,t}^{in}$ in equation (6a).

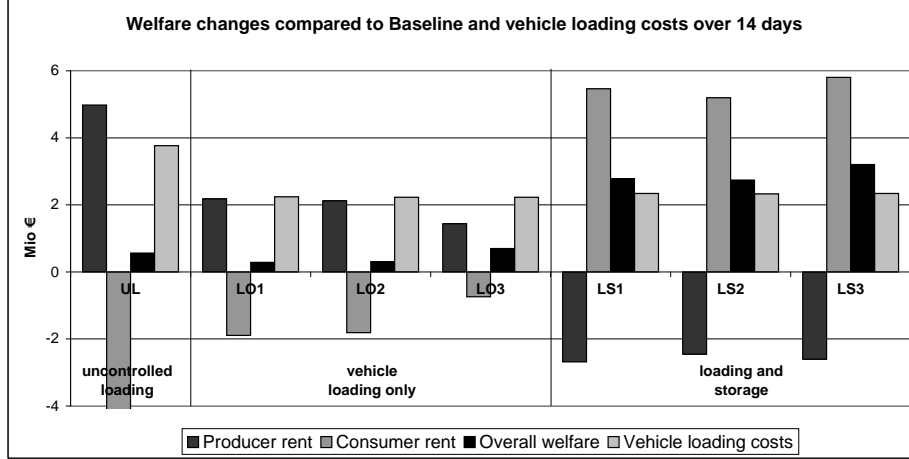


Figure 2: Welfare changes compared to Baseline and vehicle loading costs over 14 days

vehicles with cheap off-peak electricity. Average loading costs in these cases are around €0.04/kWh. With an assumed average electricity consumption of around 20 kWh/100km (compare Sioshansi et al., 2010), energy costs of electric vehicles would be around only €1/100km. Although this value does not include taxes, distribution, infrastructure costs, and retailer profits, it indicates that the electricity required for electric vehicles could be supplied at very low costs.

6.3. Effects on electricity generation

Figure 4 shows that the introduction of electric vehicles increases electricity generation in all cases compared to the Baseline because of additional demand. Generation is generally higher in the cases in which batteries are used for arbitrage (LS1-3), as the decreasing effect of storage on peak prices leads to additional demand in these periods. We find the highest increases in generation for the cases in which an oligopolistic generator controls the PIEV fleet (LO3 and LS3). In these cases, RWE increases generation during periods of vehicle and storage loading in order to strategically decrease market prices.

Figure 4 also indicates variations in the mix of additional generation among different cases. In the uncontrolled loading case (UL), most additional generation is provided by hard coal, as this is the technology with the lowest costs that is largely available in the evening hours between 4pm and 8pm. In the cases with controlled loading, vehicle recharging is carried out during nighttime. In these periods, some lignite capacity is available, such that the amount of lignite increases in all cases with controlled loading compared to UL. We find the largest increase in lignite generation in the scenarios in which the strategic player RWE is in charge of vehicle operations. In particular, RWE substantially increases its lignite generation in LS3 in order to strategically decrease market prices during the periods of vehicle recharging and battery loading.

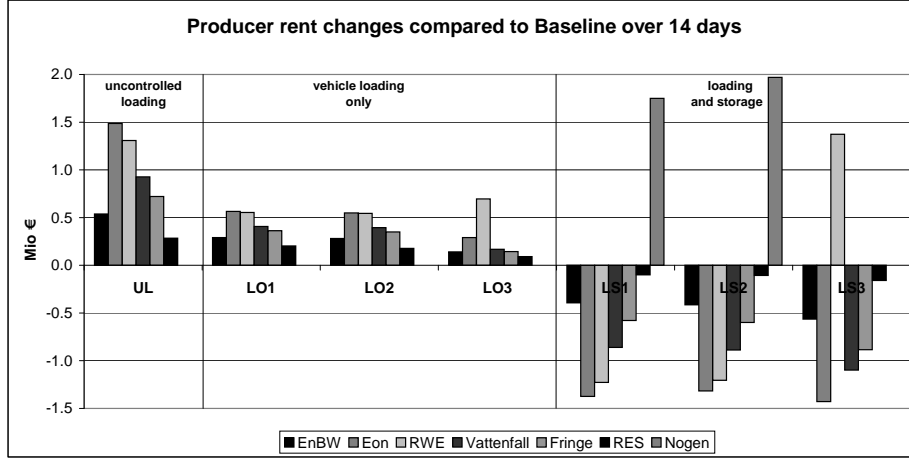


Figure 3: Producer rent changes compared to Baseline over 14 days

In contrast to Göransson et al. (2010), we do not find that electric vehicles increase the feed-in of wind power. In all model runs, hourly wind generation is equal to the historic feed-in pattern of the modeled two weeks. A PIEV fleet could only increase wind power feed-in, if there was some wind curtailment in the Baseline. For example, wind curtailment could be required if overall demand was lower than wind generation, or if there were extreme ramping constraints. However, there is no curtailment in the Baseline during the modeled 336 hours. Accordingly, PIEV do not increase overall wind generation. We consider this finding to be largely representative for the situation in Germany during the year 2009, as there were only very few periods of excess wind supply, which furthermore were largely restricted to specific regions. Consequently, it is unlikely that electric vehicles would have substantially increased wind feed-in in Germany. However, this situation might change in the future. If installed wind generation capacity increases further, cases of excess wind generation could become more frequent, and electric vehicle fleets might be able to foster their network integration.

Controlled PIEV loading also smoothes generation patterns of conventional technologies. This effect is expressed by a lower number of binding ramping constraints. In the LO cases, the additional dispatchable load of PIEV decreases the number of binding ramping constraints by around 5% compared to the Baseline over 14 days. In the LS cases, the number decreases up to 15% because of the smoothing effect of additional storage capacity in the market.¹¹ Figure

¹¹Note that ramping-related costs are only indirectly included in our analysis by means of shadow prices $\lambda_{rup,f,i,t}$ and $\lambda_{rdo,f,i,t}$. An explicit consideration of ramping-related costs, for example due to part load inefficiencies or ramping-related depreciation, was not possible, as this would require a bottom-up modeling approach with individual power plants and a mixed integer problem formulation. Yet including such costs might increase the positive effects of

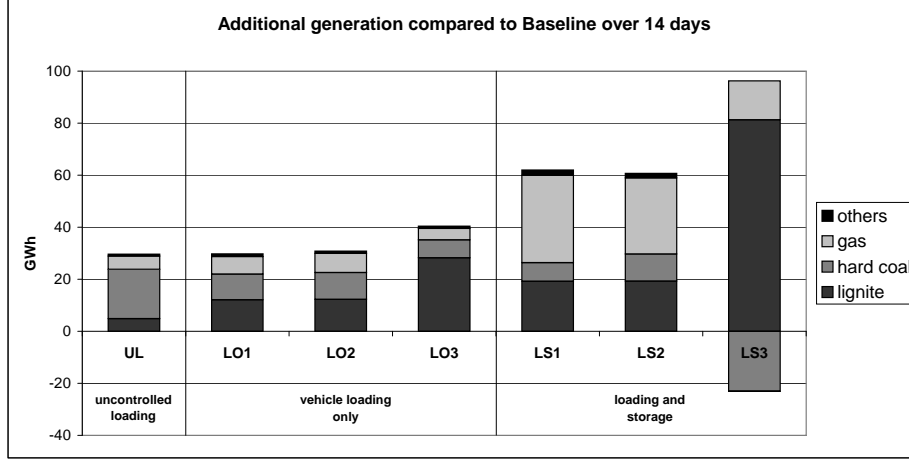


Figure 4: Additional generation compared to Baseline over 14 days

7 in the Appendix shows the overall pattern of electricity generation, vehicle loading, and storage utilization for LS1 over two weeks.

Summing up, controlled loading of electric vehicles will increase the utilization of least-cost generation technologies, which tend to be emission-intensive in Germany (lignite, hard coal). While this effect has already been described, for example by Sioshansi et al. (2010), we find evidence that it may be even stronger in imperfect electricity markets. If an oligopolistic generating firm is controlling PIEV operations, generation with emission-intensive low-cost technologies may increase even stronger compared to cases in which other players are in charge of the PIEV fleet. Accordingly, the emission performance of electric vehicles in imperfect electricity markets may be worse than previously thought.

6.4. Storage utilization and sensitivity to battery degradation costs

So far, we have assumed zero variable costs of battery storage ($vst_{PIEV} = 0$). Yet utilizing vehicle batteries for arbitrage may lead to battery degradation costs. As battery degradation heavily depends on battery technology, the depth of discharge, and the kind of loading and discharging cycles, it is difficult to provide a solid number for variable storage costs of future PIEV fleets. For older battery types, Tomic and Kempton (2007) assume values between 80-90 US\$/MWh. For lithium-ion batteries, Andersson et al. (2010) assume depreciation costs of 30-100 €/MWh. These costs may decrease substantially with improving battery technologies. We thus perform a sensitivity analysis for different battery degradation costs vst_{PIEV} . Figure 5 shows battery storage utilization for values of 0, 5, 10, 20 and 50 €/MWh. It can be seen that the use of PIEV batteries for arbitrage decreases substantially with increasing degradation costs.

PIEV on overall welfare.

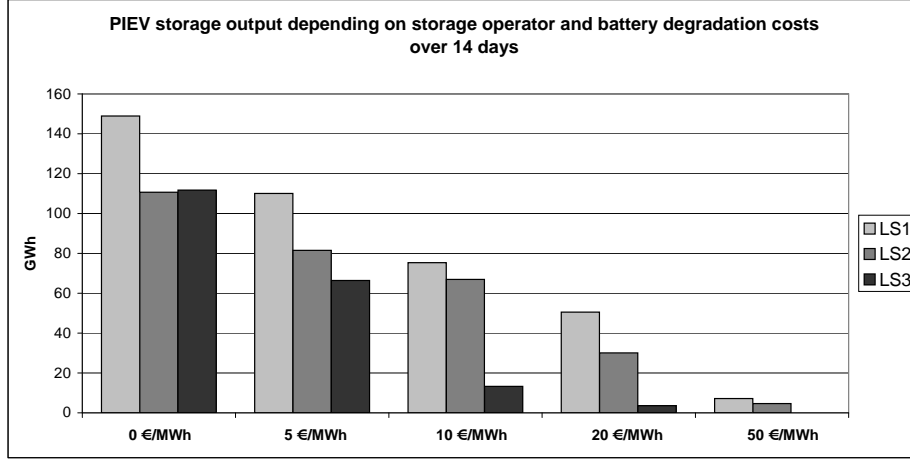


Figure 5: PIEV storage output depending on storage operator and battery degradation costs over 14 days

For 10 €/MWh, only around half the storage capacity is used compared to the case with zero variable storage costs (LS1). For 50 €/MWh, hardly any battery storage is used for arbitrage in all cases.

In addition, battery storage utilization depends on the player being in charge of PIEV operations. A strategic player (LS2) without generation assets always utilizes less storage capacity than a price-taking one (LS1). This is because of the price-smoothing effect of storage: a strategic player withholds some storage capacity in order not to smooth prices too much, which in turn increases arbitrage profits (compare Schill and Kemfert, 2009). This effect is even more pronounced if PIEV operations are concentrated with a strategic generating firm. Such a firm is even less interested in smoother prices, as they would decrease peak-load profits of all other generation assets. Accordingly, PIEV storage utilization is lowest in the LS3 cases. In our model, RWE hardly uses any storage if degradation costs are larger than 10 €/MWh.

As shown in Figure 6, variable storage costs also have welfare implications, as lower storage utilization leads to less smooth prices. Accordingly, the beneficial impact of electric vehicles on consumer rents and overall welfare decreases. For $vstc_{PIEV} = 50$, welfare results are close to the LO cases, in which arbitrage with vehicle batteries is assumed to be impossible. For $vstc_{PIEV} = 0$ and $vstc_{PIEV} = 5$, the LS3 case - in which the oligopolistic generating firm RWE controls the PIEV fleet - leads to desirable consumer rent outcomes. This is because of the previously described market power mitigating effect of storage loading on the strategic generator. Interestingly, consumers are much worse off in LS3 compared to LS1 and LS2 for $vstc_{PIEV} = 10$ and $vstc_{PIEV} = 20$. In these cases, RWE hardly uses any battery storage, as arbitrage profits are too small compared to the decreasing effect of storage on peak prices and the related decrease in profits of RWE's other generation assets. As a result, consumers

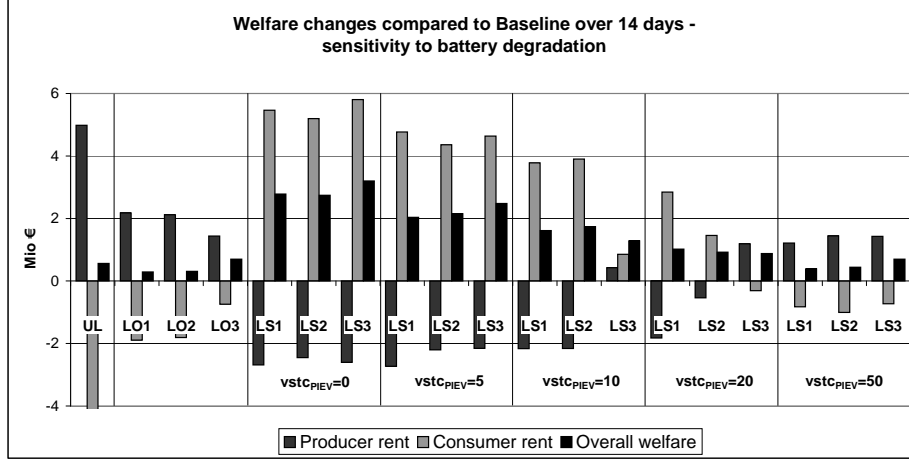


Figure 6: Welfare changes compared to Baseline over 14 days - sensitivity to battery degradation

hardly benefit from the additional battery storage capacity in the market. In contrast, the NoGen player still finds it profitable to carry out some arbitrage in the cases of $vstc_{PIEV} = 10$ and $vstc_{PIEV} = 20$, as this player does not own other generation capacity. Accordingly, prices are smoother in LS1 nad LS2 compared to LS3, and consumers are better off.

Drawing on these results, we conclude that storage utilization and welfare outcomes of the LS cases depend substantially on battery degradation costs. Higher variable storage costs generally decrease arbitrage opportunities. Current battery degradation costs may thus impose serious obstacles to utilizing PIEV fleets for arbitrage. This is even more true in the light of additional fixed costs for setting up bi-directional loading and discharging infrastructure, which we have neglected in this analysis. As a consequence, the price-smoothing effect of PIEV storage and the consumer benefits outlined in section 6.2 may not materialize. Other markets with higher revenue streams may be more promising for PIEV operators than arbitrage. For example, providing regulating power might be more profitable (compare Andersson et al., 2010).

The analysis also shows that the player in charge of PIEV operations has a large impact on consumer surplus in some cases. Yielding control over PIEV batteries to a single strategic generating firm may lead to undesirable results from a consumer perspective, despite the market power mitigating effects of vehicle recharging and storage loading described earlier.

7. Conclusions

We study the interaction of electric vehicles and imperfectly competitive electricity markets with a game-theoretic Cournot model, which we apply numerically to Germany. We find that uncontrolled vehicle recharging, for example

by individual vehicle owners, increases already existing evening peak loads and prices. In contrast, players that are able to respond to hourly wholesale market prices will carry out vehicle recharging in off-peak periods. If unused PIEV battery capacity can be used for arbitrage, this will smooth electricity prices, as batteries will be loaded in off-peak periods and discharged in peak periods.

These price effects have direct welfare implications. In general, the introduction of PIEV increases generator profits and decreases consumer surplus because of additional electricity demand. These welfare distortions, however, are much lower in the case of optimal loading compared to uncontrolled loading. We thus conclude that individuals or service providers that are responsible for recharging electric vehicles should be enabled to respond to hourly market prices. If vehicle batteries can be used for arbitrage, welfare effects are reversed: generator profits decrease, while consumer surplus and overall welfare increase substantially. The analysis indicates that the additional storage capacity of a PIEV fleet has potentially larger welfare implications in an imperfect electricity market than its additional demand. Storage-related welfare gains, although moderate, may provide a rationale for public support of electric vehicles and their grid integration that complements other reasons like lower emissions or lower oil import dependencies. However, a sensitivity analysis indicates that using excess vehicle battery capacity for arbitrage is only viable if variable storage costs are negligible. Current real-world battery degradation costs may seriously diminish arbitrage opportunities and related welfare gains. Providing regulating power may be a more profitable strategy for PIEV operators than arbitrage.

If vehicle operations are controlled by a strategic generating firm, we find two effects with different welfare implications. On the one hand, there is a market power mitigating effect of vehicle loading which benefits consumers. On the other, strategic generators tend to under-utilize PIEV storage capacity, which has negative consumer rent implications. All things considered, it is not possible to make a clear recommendation on which player should be in charge of PIEV operations. However, our analysis shows that the player controlling the vehicle fleet is of minor importance in most cases, as long as electric vehicle recharging is carried out in a controlled way. Furthermore, the potential welfare distortions related to different players being in charge of the PIEV fleet are small compared to the welfare effects of market power exertion with conventional generation technologies. Electric vehicle fleets are thus unlikely to be a relevant source of market power in Germany, no matter who controls them. Accordingly, economic regulation of PIEV operations is currently not required with respect to the electricity market. However, there may be potentials for market power exertion on markets for PIEV services. For example, firms could exploit natural monopolies related to charging infrastructure or billing standards. Future research should focus on these market power potentials.

Finally, we find that controlled loading of electric vehicles increases the utilization of low-cost generation technologies, which tend to be emission-intensive. CO₂ emissions of future electric vehicles should thus be calculated drawing on emission-intensive generation technologies rather than on the average power plant mix. Additional storage capacity further increases low-cost generation.

These effects are particularly pronounced if an oligopolistic generator is in charge of PIEV operations. In the light of ambitious climate policy targets, we thus conclude that a shift towards electric mobility has to be accompanied by a complementary expansion of low-emission, renewable electricity generation. Note that electric vehicles do not increase wind power feed-in in our model analysis, because wind generation is already running at full capacity in the Baseline scenario. This finding has a general character for the German market in 2009, as wind curtailment was rare and restricted to certain regions. In the future, however, this might change, as the number of hours with excess wind supply is likely to increase. The interaction of future electric vehicle fleets with fluctuating renewable generation should be studied in more detail. We recommend using models that allow for imperfect foresight for this purpose.

References

- Andersen, P. H., Mathews, J. A., and Rask, M. (2009). Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles. *Energy Policy*, 37:2481–2486.
- Andersson, S. L., Elofsson, A. K., Galus, M. D., Göransson, L., Karlsson, S., Johnsson, F., and Andersson, G. (2010). Plug-in hybrid electric vehicles as regulating power providers: Case studies of sweden and germany. *Energy Policy*, 38(6):2751–2762.
- BMU (2010). Erneuerbare Energien in Zahlen: Nationale und internationale Entwicklung. Technical report, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), Berlin. http://www.erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/broschuere_ee_zahlen_bf.pdf; last accessed 17 November 2010.
- Borenstein, S., Bushnell, J. B., and Wolak, F. A. (2002). Measuring market inefficiencies in california’s restructured wholesale electricity market. *American Economic Review*, 92(5):1376–1405.
- Bradley, T. H. and Frank, A. A. (2009). Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews*, 13(1):115 – 128.
- Bundesregierung (2009). Nationaler Entwicklungsplan Elektromobilität der Bundesregierung. Government report, Bundesregierung. <http://www.bmwi.de/Dateien/BMWi/PDF/nationaler-entwicklungsplan-elektromobilitaet-der-bundesregierung>; last accessed 17 November 2010.
- Bushnell, J. B., Mansur, E. T., and Saravia, C. (2008). Vertical arrangements, market structure, and competition: An analysis of restructured US electricity markets. *American Economic Review*, 98(1):237–66.

- dena (2005). Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland an Land und Offshore bis zum Jahr 2020 (dena-Netzstudie). Technical report, dena (German Energy Agency). <http://www.dena.de/de/themen/thema-reg/projekte/projekt/netzstudie-i/>; last accessed 17 November 2010.
- Ekman, C. K. (2011). On the synergy between large electric vehicle fleet and high wind penetration - an analysis of the danish case. *Renewable Energy*, 36(2):546–553.
- Ferris, M. C. and Munson, T. S. (2000). Complementarity problems in GAMS and the PATH solver. *Journal of Economic Dynamics & Control*, 24:165–188.
- Galus, M. D., Zima, M., and Andersson, G. (2010). On integration of plug-in hybrid electric vehicles into existing power system structures. *Energy Policy*, 38(11):6736–6745.
- Gerbracht, H., Möst, D., and Fichtner, W. (2009). Elektromobilität - Auswirkungen auf das Energiesystem. *Energiewirtschaftliche Tagesfragen*, 59(11):66–69.
- Göransson, L., Karlsson, S., and Johnsson, F. (2010). Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. *Energy Policy*, 38(10):5482–5492.
- Green, R. J. and Newbery, D. M. (1992). Competition in the british electricity spot market. *Journal of Political Economy*, 100(5):929.
- Guille, C. and Gross, G. (2009). A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy Policy*, 37(11):4379–4390.
- Hortaçsu, A. and Puller, S. L. (2008). Understanding strategic bidding in multi-unit auctions: a case study of the texas electricity spot market. *The RAND Journal of Economics*, 39(1):86–114.
- Kempton, W. and Tomic, J. (2005a). Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources*, 144(1):268–279.
- Kempton, W. and Tomic, J. (2005b). Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. *Journal of Power Sources*, 144(1):280–294.
- Lund, H. and Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy*, 36(9):3578–3587.
- Mansur, E. T. (2008). Measuring welfare in restructured electricity markets. *Review of Economics and Statistics*, 90(2):369–386.
- Puller, S. L. (2007). Pricing and firm conduct in california’s deregulated electricity market. *Review of Economics and Statistics*, 89(1):75–87.

- Rutherford, T. F. (1995). Extension of gams for complementarity problems arising in applied economic analysis. *Journal of Economic Dynamics and Control*, 19:1299–1324.
- Samaras, C. and Meisterling, K. (2008). Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy. *Environmental Science & Technology*, 42(9):3170–3176.
- Schill, W.-P. (2010). Elektromobilität in Deutschland - Chancen, Barrieren und Auswirkungen auf das Elektrizitätssystem. *Vierteljahreshefte zur Wirtschaftsforschung*, 79:139–159.
- Schill, W.-P. and Kemfert, C. (2009). The effect of market power on electricity storage utilization: The case of pumped hydro storage in germany. *DIW Discussion Paper*, 947.
- Sioshansi, R. (2010). Welfare impacts of electricity storage and the implications of ownership structure. *Energy Journal*, 31(3):1–22.
- Sioshansi, R. and Denholm, P. (2009). Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. *Environmental Science & Technology*, 43(4):1199–1204.
- Sioshansi, R., Fagiani, R., and Marano, V. (2010). Cost and emissions impacts of plug-in hybrid vehicles on the ohio power system. *Energy Policy*, 38(11):6703–6712.
- Sovacool, B. K. and Hirsh, R. F. (2009). Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy*, 37(3):1095–1103.
- Tiedemann, A., Srikantham, C., Kreutzkamp, P., Roth, H., Gohla-Neudecker, B., and Kuhn, P. (2008). Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken. Abschlussbericht. Technical report, dena (German Energy Agency). <http://www.dena.de/de/themen/themasesd/publikationen/publikation/pumpspeicherstudie/>; last accessed 17 November 2010.
- Tomic, J. and Kempton, W. (2007). Using fleets of electric-drive vehicles for grid support. *Journal of Power Sources*, 168(2):459–468.
- Traber, T. and Kemfert, C. (2009). Impacts of the german support for renewable energy on electricity prices, emissions, and firms. *The Energy Journal*, 30:155–178.
- Weigt, H. and Hirschhausen, C. v. (2008). Price formation and market power in the german wholesale electricity market in 2006. *Energy Policy*, 36(11):4227–4234.

- Wietschel, M. and Dallinger, D. (2008). Quo Vadis Elektromobilität? *Energiewirtschaftliche Tagesfragen*, 58(12):8–16.
- Wissel, S., Rath-Nagel, S., Blesl, M., Fahl, U., and Voß, A. (2008). Stromerzeugungskosten im Vergleich. Technical report, Institut für Energiewirtschaft und Rationelle Energieanwendung, Stuttgart. http://www.ier.uni-stuttgart.de/publikationen/arbeitsberichte/Arbeitsbericht_04.pdf; last accessed 17 November 2010.

8. Appendix

8.1. Sets, indices, parameters and variables

Item	Description	Unit
Sets and indices		
F	Players with $f \in F$	
I	Generation technologies with $i \in I$	
T	Time with $t \in T, \tau \in T$	hours
D	Time with $d \in D$	days
Parameters		
σ	Price elasticity of electricity demand	
$d0_t$	Hourly reference demand	MWh
$p0_t$	Hourly reference prices	€/MWh
$vldaily_{f,d}$	Daily vehicle loading requirement	MWh
$\bar{x}_{f,i}^{gen}$	Available generation capacity	MW
$\bar{st}_{f,j}^{out}$	Available storage discharging capacity	MW
$\bar{st}_{f,j}^{in}$	Available storage loading capacity	MW
$\bar{st}_{f,j}^{cap}$	Available storage capacity	MWh
$\xi_{up,i}$	Ramping up parameter for technology i	
$\xi_{down,i}$	Ramping down parameter for technology i	
vgc_i	Variable generation costs	€/MWh
$vstc_j$	Variable storage costs	€/MWh
$\eta_{st,j}$	Storage round-trip efficiency	
$\theta_{f,i,t}^{gen}$	Market power parameter for generation	0 or 1
$\theta_{f,t}^{vload}$	Market power parameter for vehicle loading	0 or 1
$\theta_{f,j,t}^{st}$	Market power parameter for storage	0 or 1
Variables		
Π_f	Profit of player f	€
p_t	Price of period t	€/MWh
$x_{f,i,t}$	Generation of player f by technology i in period t	MWh
X_t	Total supply in period t	MWh
$vload_{f,t}$	Vehicle loading in period t of firm f	MWh
$stout_{f,j,t}$	Generation of firm f in period t from storage	MWh
$stin_{f,j,t}$	Storage loading of firm f in period t	MWh
$\lambda_{gen,f,i,t}$	Shadow price of generation capacity constraint	€/MWh
$\lambda_{rup,f,i,t}$	Shadow price of ramping up constraint	€/MWh
$\lambda_{rdo,f,i,t}$	Shadow price of ramping down constraint	€/MWh
$\lambda_{vldaily,f,d}$	Shadow price of daily vehicle loading requirement	€/MWh
$\lambda_{stout,f,t}$	Shadow price of storage discharging capacity constraint	€/MWh
$\lambda_{stin,f,t}$	Shadow price of storage loading capacity constraint	€/MWh
λ_{stup}	Shadow price of upper storage capacity constraint	€/MWh
λ_{stlo}	Shadow price of lower storage capacity constraint	€/MWh
$\vartheta_{f,i,t}^{gen}$	Market share of firm f - generation	
$\vartheta_{f,t}^{vload}$	Market share of firm f - vehicle loading	
$\vartheta_{f,j,t}^{out}$	Market share of firm f - storage discharging	
$\vartheta_{f,j,t}^{in}$	Market share of firm f - storage loading	
$crent_t$	Consumer rent of period t	€
$prent_{f,t}$	Producer rent of firm f in period t	€

Table 4: Sets, indices, parameters and variables

8.2. The mixed complementarity problem

$$\begin{aligned}
0 \leq & vgc_i + \lambda_{gen,f,i,t} + \lambda_{rup,f,i,t} - \lambda_{rup,f,i,t+1} - \lambda_{rdo,f,i,t} + \lambda_{rdo,f,i,t+1} \\
& - p_t \left(1 - \frac{\sum_{i \in I} \vartheta_{f,i,t} \theta_{f,i,t}^{gen} - \vartheta_{f,t}^{vload} \theta_{f,t}^{vload} + \sum_{j \in J} (\vartheta_{f,j,t}^{out} \theta_{f,j,t}^{st} - \vartheta_{f,j,t}^{in} \theta_{f,j,t}^{st})}{\sigma} \right) \\
& \perp x_{f,i,t} \geq 0, \forall f, i, t \quad (6a)
\end{aligned}$$

$$\begin{aligned}
0 \leq & \lambda_{vldaily,f,t} + \lambda_{stin,f,PIEV,t} \\
& + p_t \left(1 - \frac{\sum_{i \in I} \vartheta_{f,i,t} \theta_{f,i,t}^{gen} - \vartheta_{f,t}^{vload} \theta_{f,t}^{vload} + \sum_{j \in J} (\vartheta_{f,j,t}^{out} \theta_{f,j,t}^{st} - \vartheta_{f,j,t}^{in} \theta_{f,j,t}^{st})}{\sigma} \right) \\
& \perp vload_{f,t} \geq 0, \forall f, t \quad (6b)
\end{aligned}$$

$$\begin{aligned}
0 \leq & vstc_j + \lambda_{stout,f,j,t} + \sum_{\tau=t}^T \lambda_{stlo,f,j,\tau} - \sum_{\tau=t}^{T-1} \lambda_{stup,f,j,\tau+1} \\
& - p_t \left(1 - \frac{\sum_{i \in I} \vartheta_{f,i,t} \theta_{f,i,t}^{gen} - \vartheta_{f,t}^{vload} \theta_{f,t}^{vload} + \sum_{j \in J} (\vartheta_{f,j,t}^{out} \theta_{f,j,t}^{st} - \vartheta_{f,j,t}^{in} \theta_{f,j,t}^{st})}{\sigma} \right) \\
& \perp stout_{f,j,t} \geq 0, \forall f, j, t \quad (6c)
\end{aligned}$$

$$\begin{aligned}
0 \leq & \lambda_{stin,f,j,t} - \sum_{\tau=t}^{T-1} \lambda_{stlo,f,j,\tau+1} \eta_{st,j} + \sum_{\tau=t}^T \lambda_{stup,f,j,\tau} \eta_{st,j} \\
& + p_t \left(1 - \frac{\sum_{i \in I} \vartheta_{f,i,t} \theta_{f,i,t}^{gen} - \vartheta_{f,t}^{vload} \theta_{f,t}^{vload} + \sum_{j \in J} (\vartheta_{f,j,t}^{out} \theta_{f,j,t}^{st} - \vartheta_{f,j,t}^{in} \theta_{f,j,t}^{st})}{\sigma} \right) \\
& \perp stin_{f,j,t} \geq 0, \forall f, j, t \quad (6d)
\end{aligned}$$

$$0 \leq -x_{f,i,t} + \bar{x}_{f,i}^{gen} \quad \perp \quad \lambda_{gen,f,i,t} \geq 0, \quad \forall f, i, t \quad (6e)$$

$$0 \leq -x_{f,i,t} + x_{f,i,t-1} + \xi_{up,i} \bar{x}_{f,i}^{gen} \quad \perp \quad \lambda_{rup,f,i,t} \geq 0, \quad \forall f, i, t \quad (6f)$$

$$0 \leq -x_{f,i,t-1} + x_{f,i,t} + \xi_{down,i} \bar{x}_{f,i}^{gen} \quad \perp \quad \lambda_{rdo,f,i,t} \geq 0, \quad \forall f, i, t \quad (6g)$$

$$0 = -\sum_{t \in d} vload_{f,t} + vldaily_{f,d} \quad , \quad \lambda_{vldaily,f,d} \text{ free}, \quad \forall f, d \quad (6h)$$

$$0 \leq -stin_{f,PIEV,t} - vload_{f,t} + \bar{st}_{f,PIEV}^{in} \quad \perp \quad \lambda_{stin,PIEV,t} \geq 0, \quad \forall f, t \quad (6i)$$

$$0 \leq -stin_{f,j,t} + \bar{st}_{f,j}^{in} \quad \perp \quad \lambda_{stin,j,t} \geq 0, \quad \forall f, j \neq PIEV, t \quad (6j)$$

$$0 \leq -stout_{f,j,t} + \bar{st}_{f,j}^{out} \quad \perp \quad \lambda_{stout,j,t} \geq 0, \quad \forall f, j, t \quad (6k)$$

$$0 \leq -\sum_{\tau=1}^t stout_{f,j,\tau} + \sum_{\tau=1}^{t-1} stin_{f,j,\tau} \eta_{st,j} \quad \perp \quad \lambda_{stlo,f,j,t} \geq 0, \quad \forall f, j, t \quad (6l)$$

$$0 \leq -\sum_{\tau=1}^t stin_{f,j,\tau} \eta_{st,j} + \sum_{\tau=1}^{t-1} stout_{f,j,\tau} + \bar{st}_{f,j}^{cap} \quad \perp \quad \lambda_{stup,f,j,t} \geq 0, \quad \forall f, j, t \quad (6m)$$

$$0 = X_t - d0_t \left(\frac{p_t}{p0_t} \right)^{-\sigma} \quad , \quad p_t \text{ free}, \quad \forall t \quad (6n)$$

Equations (6a-6d) include market shares $\vartheta_{f,i,t}$, $\vartheta_{f,t}^{vload}$, $\vartheta_{f,j,t}^{out}$, and $\vartheta_{f,j,t}^{in}$ as defined in (7a-7d). They indicate a player's ability to raise prices beyond marginal costs. (6a-6n) also include market power parameters $\theta_{f,i,t}^{gen}$, $\theta_{f,t}^{vload}$, and $\theta_{f,j,t}^{st}$. By exogenously assigning the values 0 or 1, we can 'switch' off and on market power for specific firms regarding generation, PIEV recharging, and storage.

$$\vartheta_{f,i,t} = \frac{x_{f,i,t}}{X_t}, \quad \forall f, i, t \quad (7a)$$

$$\vartheta_{f,t}^{vload} = \frac{vload_{f,t}}{X_t}, \quad \forall f, t \quad (7b)$$

$$\vartheta_{f,j,t}^{out} = \frac{stout_{f,j,t}}{X_t}, \quad \forall f, j, t \quad (7c)$$

$$\vartheta_{f,j,t}^{in} = \frac{stin_{f,j,t}}{X_t}, \quad \forall f, j, t \quad (7d)$$

Equations (6a-6d) include a standard Cournot result: In case of positive generation market shares $\vartheta_{f,i,t}$, market prices exceed the sum of marginal generation costs and shadow prices of player f . The larger $\vartheta_{f,i,t}$, the larger is the player's ability to raise prices beyond marginal costs. Whereas this is a common feature of Cournot models, we follow the approach of Schill and Kemfert (2009) by adding storage-related market shares $\vartheta_{f,t}^{out}$ and $\vartheta_{f,t}^{in}$. In addition, we introduce the PIEV-related market share $\vartheta_{f,t}^{vload}$. Note that positive market shares

$\vartheta_{f,i,t}$ and $\vartheta_{f,t}^{out}$ allow a player to raise prices beyond marginal costs, as they enter with positive signs. In contrast, positive $\vartheta_{f,t}^{vload}$ and $\vartheta_{f,t}^{in}$ have a price-decreasing effect, as they enter with a negative sign. The higher these market shares of a player, the larger its interest in low prices during the periods of vehicle recharging and/or storage loading. Electric vehicle loading activities thus mitigate a strategic electricity generator's incentives to exert price-driving market power during the periods of vehicle loading.

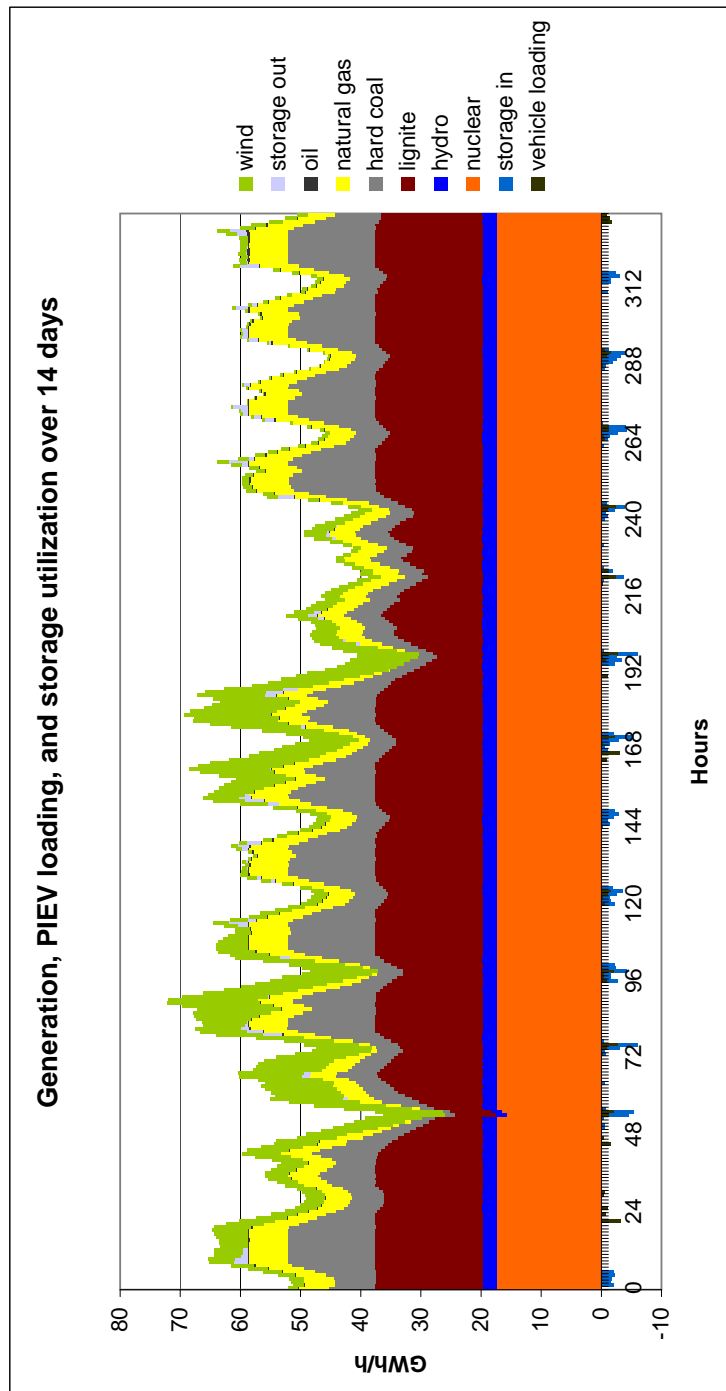


Figure 7: Generation, PIEV loading, and storage utilization over 14 days