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Impact of different utilization scenarios of electric vehicles on the German grid in 2030

N. Hartmann*, E.D. Özdemir

University of Stuttgart, Institute of Energy Economics and the Rational Use of Energy (IER), Hessbrühlstr. 49a, 70565 Stuttgart, Germany

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ABSTRACT

Electric vehicles are commonly seen as one of the alternatives to reduce the oil dependency and the greenhouse gas emissions in the transport sector.

The aim of this paper is to evaluate the impact of different electric vehicle charging strategies on the national grid including the storage utilization of electric vehicles (V2G-vehicle to grid). Furthermore, an economic analysis of electric vehicle utilization is performed and the results are compared with the conventional diesel vehicle.

To accomplish this aim the availability of passenger cars in Germany to be plugged into the grid showed to be high at any time over the day (>89%), which is advantageous for the V2G concept.

The impact of the different electric vehicle charging strategies is investigated by employing three scenarios. The first scenario (unmanaged charging) shows that 1 mil. electric vehicles only impacts slightly on the daily peak electricity demand. In the second scenario (Grid stabilizing storage use) a maximum reductions of grid fluctuations of 16% can be achieved with the use of 1 mil. electric vehicles as storage. The last scenario (profit maximization by power trading) the maximum daily revenues from V2G activities are calculated to be 0.68 EUR_{2009}.

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1. Introduction

Recently researchers as well as politicians increasingly focus on the market penetration of battery electric vehicles (EVs) to get one step closer to an emission free mobility. In Germany the effort can be recognized in many programs such as “E-mobility pathway” [1], “Modelregion-Electromobility” [2] and many more. The introduction of EVs bears not only chances (e.g. emission free mobility, no local particle emission, etc.) but also some difficulties to be overcome (e.g. rising electricity demand, high investment costs of EVs, etc.).

Past and ongoing research focuses by the majority on technical improvement of EVs (e.g. [3–6]) and some on economic performance of EVs (e.g. [7,8]). The use of EVs as a storage (vehicle-to-grid, V2G) was analyzed generally in a number of publications (e.g. [9–12]) as well as the integration of renewable energies by V2G [13]. Generally also the impact of V2G on the grid was analyzed in [13–16]. However, the impact of EVs on the grid as well as the possibility for consumers to get a revenue through V2G was not examined in detail.

The aim of this paper is to evaluate the impact of EVs on the grid as well as the thereby resulting economic performance of the vehicles. The plug-in availability is calculated for the German passenger car sector (cf. Section 2.1). Hereby it is assumed that if a car is not being driven, it is connected to the grid. In the next step, different effects of storage usage on the grid as well as on the economic performance of the vehicles are investigated. Three storage usage strategies are examined (cf. Section 2.2).

1. Unmanaged charing
2. Grid stabilizing storage use
3. Profit maximizing storage use.

2. Method

To reach the aim a Matlab/Simulink based model was developed. With the model a simulation of different operation strategies of EVs, differentiated for their energy demand for driving and use of the residual storage capacity for V2G application was accomplished. The term V2G service hereby only accounts for the service of trading of energy at the stock exchange (European Energy Exchange, EEX) [17]. The effect of different storage utilizations on the demand within the grid and on the cost for electric vehicles was evaluated. Within the simulation no effects of the storage use of the vehicles on the energy price is taken into account. Assuming a high amount

* Corresponding author.
E-mail address: nh@ier.uni-stuttgart.de (N. Hartmann).

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of electric vehicles introduced to the grid as well as their usage to trade energy at the stock exchange an impact on the stock exchange price is likely. However, due to the considered low share of electric vehicles and therewith small increase in electricity requirement, this aspect was not considered in the analysis. The temporal resolution of the simulation is set to an hourly basis and the input data of the demand and energy prices are taken from the period between January 2007 till July 2009. The energy prices are further developed for the year 2030 on the basis of the input data according to [31]. The calculation is performed as an estimation of the implication of a considerable amount of electric vehicles as share of the passenger car fleet in Germany. Therefore, the cost assumptions are future estimations for the year around 2030 given in EUR_{2009}.

In Germany vehicles drive an average of 41.9 vkm d^{-1} (vehicle kilometer per day) [18]. As a restriction to the model the energy needed to drive 41.9 vkm d^{-1} is the limit to which the battery can be discharged. The average driven distance is calculated with the simulation described in Section 2.1. The maximum storage capacity of the EVs is depending on the State-of-Charge (SoC) of the electric vehicles which are plugged into the grid.

2.1. Calculation of EV plug-in availability

To determine the possible capacity of mobile storage systems the number of electric vehicles plugged into the grid is calculated with the potential to act as a storage device at any instant. Due to the fact that seasonal differences as well as special incidents such as traffic volume on holidays cannot be included, the calculation of the plug-in availability and energy demand for driving is realized with hourly values for an average week of the year. The number of passenger cars being used at any instance in Germany was analyzed based on data from "Mobilität in Deutschland" [19]. The calculations are based on the number of trips traveled each day in Germany. Each trip is further divided into motives of travel. On weekdays the average citizen in Germany covers 3.6 trips per day [19]. These trips are separated into different motives for traveling and each motive into six different modes of transport: a passenger car driver, a car passenger, per bike, on foot and with public transportation. Seven different types of motives for traveling were identified, namely:

1. Leisure (trips for leisure, e.g. meeting friends)
2. Shopping (daily needs)
3. Private errands (e.g. consultation or bureaucratic affairs)
4. Accompanying (bringing and picking up people)
5. Business trip (each trip which can be accounted to business reasons, except trips with the motivation of "Work")
6. Education (each trip to reach the training post or school)
7. Work (each trip from and to work).

For each motive, the percentage of trips which was performed as a passenger car driver, was calculated separately and taken as input data for the simulation. With the average speed of 32.8 vkm h^{-1} for passenger cars in Germany [19] and the distances driven, the time needed for each trip was calculated. The average speed was calculated including stops e.g. at traffic lights. Each travel was classified into one of the three groups according to the travel time:

1. Group 1, where time to travel is less than 30 min,
2. Group 2, where time to travel is between 30 min and 1 h 30 min and
3. Group 3, where time to travel is more than 1 h 30 min.

With the combination of average speeds, length of trips and the starting times, a simulation was performed which determined the number of passenger cars used during each hour of the day. The simulation is performed by calculating the number of passenger cars starting a trip each hour of the day. The calculating point is defined as the midway of specified hour e.g. a trip specified as starting in the hour between 1 pm and 2 pm is assumed to have started at 1:30 pm. This leads to the basic assumption for the simulation that e.g. a trip ending after 45 min end for the calculation in the subsequent hour. The calculations were performed for every hour with the following equations:

$$Y(t) = (X_{\max} - X(t)) \tag{1}$$

where $Y(t)$ is the passenger cars en route at time t; $X(t)$ is the passenger cars connected to the grid at time t; $X_{\max}$ is the total number of passenger cars; and t is the time step in hours.

The passenger cars en route are subsequently calculated by the difference of the vehicle population and passenger cars connected to the grid. In Germany the total amount of passenger cars $X_{\max}$ for 2009 was about 42 mil. [18]. It is assumed, that this number will stay constant until the year 2030, which is in line with [20]. The passenger cars connected to the grid $X(t)$ are determined as follows:

$$X(t) = X(t-1) + W(t) - V(t) \tag{2}$$

where $W(t)$ is the passenger cars ending their trips at time t and $V(t)$ is the passenger cars starting their trips at time t.

The number of passenger cars ending their trips is calculated from:

$$W(t) = W_1(t-1) + W_2(t-2) + W_3(t-3) \tag{3}$$

Due to the fact that the data of returning passenger cars, which end their trips after more than 3 h, was marginal or not present, the arriving passenger cars are divided into three groups concerning their time of trip termination. The values for the different trip termination times are assessed with the multiplication of the starting passenger cars and the percentage of vehicles $f_b(t)$ ending their trips.

$$W_b(t) = V(t) \cdot f_b(t) \tag{4}$$

where $f_b(t)$ is the percentage of passenger cars ending their trips at time t.

The index b can have an integer value between 1 and 3. This index describes the different percentages of passenger cars returning from one trip in the above described time groups according to their travel time. The index varies for the various days of the week and motives for traveling. In contrast, the hourly values of one day and inside one motive the factor remains at a constant value. The share of passenger cars en route was calculated by:

$$u(t) = \frac{Y(t)}{X_{\max}} \tag{5}$$

where $u(t)$ is the share of passenger cars en route at time t.

Additionally the driven kilometers of the vehicles can be determined by the multiplication of the number of passenger cars ending their trips with the driven distances during their trips. The different driven distances is calculated as a sum of the different distances driven within the three groups.

$$L(t) = \sum_{b=1}^{3} W_b(t) \cdot L_b(t) \tag{6}$$

where $L(t)$ is the cummulative driven distances of returning passenger cars at time t for all groups and $L_b(t)$ is the driven distance for passenger cars belonging to the group b at time t.

2.2. Simulation model and scenarios for the EV-storage utilization

To simulate the storage utilization for V2G service, first an upper boundary (UB) and a lower boundary (LB) are defined. If an input value falls below the lower boundary the storage will be charged and in contrast, if the input value rises above the upper boundary, the storage will be discharged. Within the simulation the upper and lower boundary were varied.

By means of the least square method the fluctuations of the national electricity grid are evaluated. With every variation step the sum of the squared values is calculated and subsequently minimized.

$$\mathrm{LSV} = \sum_{t=0}^{8760} (D(t) - D_{\mathrm{av}})^2 \quad (7)$$

where LSV is the annual least square value of the fluctuations of the grid; $D(t)$ is the resulting electricity demand on the national grid depending on hour t of the year; and D_{av} is the average electricity demand in Germany.

Additionally the difference of the maximum and minimum of the demand value of every day (daily difference of extrema) was calculated to quantify the reduction of extrema for the least square minima. If the lower boundary rises higher than the upper boundary, the result is shown as the value “zero”, due to the decision dispute of the operation strategy.

Three different storage utilization scenarios are analyzed in this paper:

1. Unmanaged charging – This represents a situation, where the electric vehicles are charged at an instance they get plugged into the grid. These vehicles are also charged until the maximum storage capacity and then held at the maximum until they are plugged out of the grid and used. In this examination the number of electric vehicles is varied between 1 and 42 mil. EVs. No active storage management is introduced in this strategy and therefore no upper and lower boundary were defined in this case.
2. Grid stabilizing storage use – This setting represents a storage use pattern which is controlled by signals from the public grid. The goal at using the storage for grid support is to reduce the fluctuations of the grid and achieve an energy demand in Germany, which is constant over time. Therefore, the upper and lower boundary is a constant value over time. The EVs are charged in times of low energy consumption and discharged in times of high energy consumption. The State-of-Charge is calculated by:

$$\mathrm{SoC}(t) = \mathrm{SoC}(t-1) + E_{cd}(t-1) \quad (8)$$

The value E_{cd} describes the amount charging energy E_c or discharging energy E_d, which is needed within 1 h. The demand (P) represents hereby the whole electricity demand in the public grid in Germany in GW.

$$E_{cd} = \begin{cases} E_c & \text{if } P < LB_P \\ E_d & \text{if } P > UB_P \\ 0 & \text{if else} \end{cases} \quad (9)$$

The reduction is analyzed with the least square method as described above.

3. Profit-maximizing storage use – This setting represents the case, that consumers try to maximize their benefit by trading energy at the energy stock exchange. To maximize the profit by energy trading the goal is to achieve the highest revenues. Hence the day ahead hourly values of the EEX energy price (EEX(t)) over the examined period was fitted with a polynomial 5th grade ($h(t, z) = 2.4 \times 10^{-19} t^5 - 1.0 \times 10^{-14} t^4 + 9.1 \times 10^{-11} t^3 + 4.1 \times 10^{-7} t^2 - 2.7 \times 10^{-3} t + z$). The value h represents the average energy price at time t. The value of z of the fitted curve is 34. For the upper and lower boundary definition, the value of z is varied.

$$E_{cd} = \begin{cases} E_c & \text{if } EEX(t) < [LB_{EEX} = h(t,z); z = z_1] \\ E_d & \text{if } EEX(t) > [UB_{EEX} = h(t,z); z = z_2] \\ 0 & \text{if else} \end{cases} \quad (10)$$

The State-of-Charge is calculated as in Eq. (8). By adding the variable benefits resulting from energy negotiation to the yearly fixed cost estimations the costs for a medium-sized electric vehicle is determined and compared to a conventional diesel engine vehicle. With the annuity method the costs per vkm are calculated.

Table 1
Assumptions on performance for the year 2030.

Average speed	32.8 vkm h^{-1} [a]
Average trip distance L_{av-Day}	41.9 vkm d^{-1} [b]
Electric vehicle parameters	
Storage capacity	32.8 kWh
$\eta_{storage}$	0.9 [c]
Battery depth of discharge (DoD)	80%
max. $P_{charging}$	3.6 kW
$P_{E-Motor}$	75 kW
Components lifetime	12 a (battery cycle life: 4500 cycles)
Energy consumption	0.59 MJ vkm^{-1}
Conventional diesel parameters	
Components lifetime	12 a
Energy consumption	1.56 MJ vkm^{-1}

[a] [19].
[b] [18].
[c] [21–24].

2.3. Assumptions on performance and economics

In the following section, the assumptions on performance (Table 1) and on economics (Table 2) are described. The energy efficiency (charge–discharge efficiency) of the storage is set to 90% which is in line with the literature values [21–24], including the voltage converter losses. Additionally to the above described operation of the storage, several constraints are introduced into the model. The maximal charging power for one vehicle is 3.6 kW. Basis for the maximal charging power is the presetting, that the vehicles are only charged at standard sockets in Germany with line voltage of 230 V. Also the charging of the vehicles, if they are connected to the grid below the SoC which is needed to drive the average daily distance, has priority to any V2G storage utilization.

The storage capacity is set to 32.8 kWh due to the presetting, that EVs should be able to drive 200 vkm with one battery load. Power $P_{E-Motor}$ of the vehicle is set to 75 kW according to the average power of “VW-Golf”, the top-selling medium-sized car in Germany [25]. As already stated, the maximal charging power is set to 3.6 kW and the average daily distance driven (L_{av-Day}) to 41.9 vkm d^{-1}. All vehicle components are assessed to have a lifetime of 12 years. The battery hereby exhibits a cycle lifetime of about 4500, which is slightly conservative than several literature values (cf. [26,27]). To avoid battery degradation due to deep cycling, the depth of discharge (DoD) is set to 80%. The energy consumption is calculated by the consumption of a medium-sized EV in 2007. For rural trips is 0.43 MJ vkm^{-1} and urban trips 0.65 MJ vkm^{-1}, whereas the allocation of trips is 2/3 in rural and 1/3 in urban areas [28]. For the future estimation a reduction of energy consumption of 20% is implied. This results in a future energy consumption of 0.59 MJ vkm^{-1}, which is consistent to [29]. The fuel consumption of a future conventional diesel vehicle is set to 1.62 MJ vkm^{-1}, which is based on own calculations based on [30].

The economic parameters (see Table 2) are based on literature values. The conventional ICE, including transmission, represents

Table 2
Assumptions on economics of conventional diesel and electric vehicle in 2030.

	ICE [a]	E-Motor	Battery	Control unit [b]	Tank	Carriage	Sum
EUR_{2009}							
Conv. diesel	4960 [c]	–	–	–	132 [c]	17,010 [c]	22,102
EV	–	1145 [d]	7118 [e]	1276 [f]	–	17,010 [c]	26,549

	Fuel costs and taxes	
	Diesel [EUR_{2009} GJ^{-1}]	Electricity [EUR_{2009} GJ^{-1}]
Fuel	16.7 [g]	36.0 [g]
Tax	20.4 [g]	24.9 [g]
Total	37.1	60.9
Annual maintenance	2% of invest. cost	
Annual tax and insurance	3% of invest. cost	
Interest rate	6%	

[a] Incl. transmission.
[b] Incl. DC/DC converter & charger.
[c] [32].
[d] [33,34].
[e] Spec. battery cost (217 EUR_{2009} kWh^{-1} [35,36])· storage capacity.
[f] [34,35].
[g] [31].

a direct injection compression ignition (DICI) with exhaust after treatment and a diesel particulate filter (DPF). It is assumed, that the battery costs per kWh will fall in the future to about 217 EUR_{2009} kWh^{-1} due to mass production. The battery degradation is accounted for within the simulation. Hereby the battery lifetime is depending on the cycles performed with the battery. One cycle is defined as the complete charging (until the DoD of 80%) and discharging of the battery. Therefore, the lifetime of the battery is determined by the calculation of the energy which can be charged and discharged within one cycle. If the battery is charged and discharged with a higher amount than what is calculated for a 12-year lifetime (due e.g. to the usage for V2G service) the lifetime of the battery is reduced, and a earlier battery replacement is needed, which is taken into account for the economic evaluation.

Within the “Control Unit”, a DC/DC converter, an inverter as well as the battery control unit is included. The conventional diesel as well as the EV exhibit the same investment cost for the carriage, which includes devices such as cooling system and wiring. The fuel and tax costs are taken from Ref. [31], the values represent a moderate price scenario based on an oil price of 75 $\$_{2007}$ bbl^{-1}. The diesel and electricity fuel costs include the costs for production, transportation and distribution. For electricity the costs for households are taken rather than the electricity costs for industry. Maintenance costs are assumed to be 2% of investment costs and 3% of investment costs for tax and insurance in Germany. The economic performance, which result out of the use of the electric vehicle is calculated by the annuity method. The interest rate hereby is set to 6%.

3. Results

3.1. Plug-in availability and energy use of vehicles

In Fig. 1 the number of vehicles en route is displayed as a percentage of the total vehicle population in Germany. The characteristic of passenger cars en route is similar for weekdays. For weekdays the percentages of vehicles en route varies between nearly zero at night up to about 10% between 3 pm and 5 pm. The highest number of passenger cars en route can be perceived with 10.2% on Fridays at 3 pm. The highest amount of vehicles en route is always reached in the early afternoon rush hour. However, it can be noticed that the maximum of vehicles en route on Mondays is slightly lower than on the other weekdays. Furthermore the peak share of vehicles en route is reached 1 h earlier on Fridays (at 3 pm) than on the other weekdays. On Saturdays the share of passenger cars en route increases from 3 am until 10 am to the daily maximum of about 9.7% and then decreases over the time of 10 h until it drops below 2% at 9 pm. After 9 pm the decrease declines and the minimum share of passenger cars en route is reached at about midnight. The percentage of vehicles en route on Sundays increases steadily in the morning until its maximum is reached at 2 pm with the value of 5.3%. In the afternoon the share of passenger cars en route decreases steadily until its default value at night.

In Fig. 2 the distances driven by 1 mil. EVs is shown. The calculation is performed at the time when they come back from one trip, separated into the three time groups described in Section 2.1. For 1 mil. EVs the simultaneous daily maximum of passenger cars en route is reached at 1 pm during the weekdays. Most trips hereby are performed within the first group. It can be seen that especially the motives Work and Shopping are responsible for the high amount of distances driven. In the second group more trips are performed with the motive Leisure and Work. However, the height of the distances driven within this group is lower than within the first group. Within Group 3 the main reason for trips is during the week Business trip and at the weekends Leisure. This group accounts for the lowest amount of distance driven.

3.2. Unmanaged charging

In Fig. 3 the development of difference of daily extrema of the electricity demand in Germany for an increasing amount of EVs is

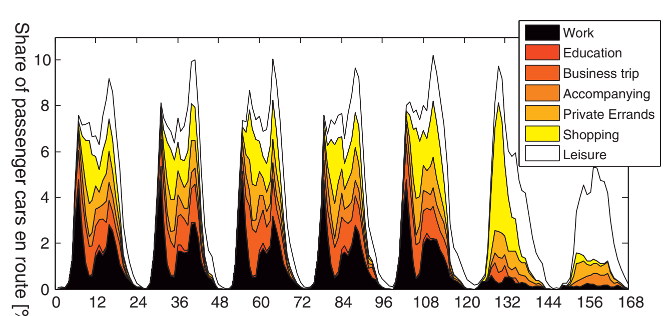

Fig. 1. Cumulated share of passenger cars en route in Germany for an average week, differentiated in travel motives [37].

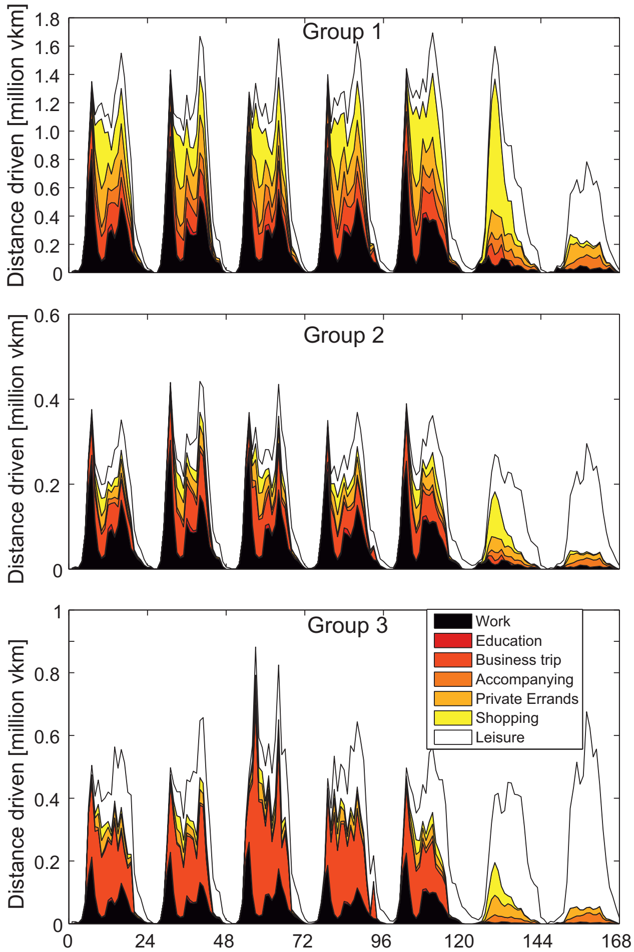

Fig. 2. Cumulated driven distance for 1 mil. passenger cars for an average week [38], differentiated in travel motives.

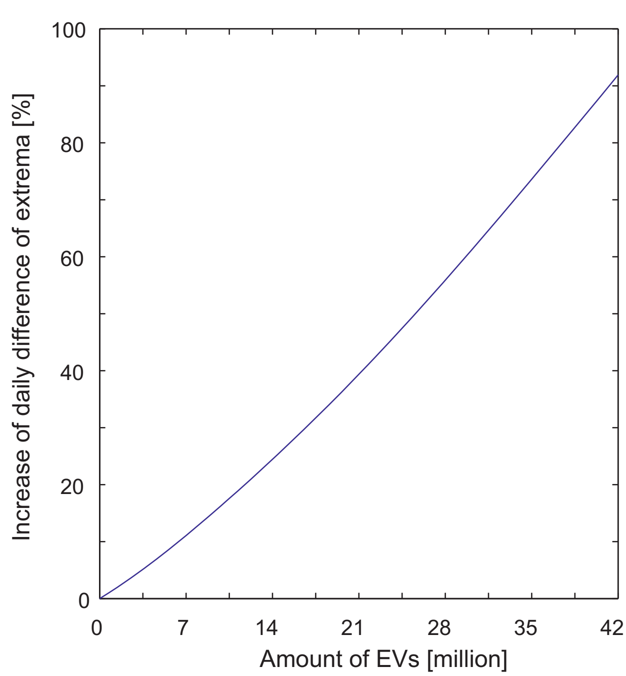

Fig. 3. Development of daily difference of extrema depending on the amount of EVs (unmanaged charging).

shown. The difference of daily extrema is calculated by the sum of the difference of the daily maximum and minimum for the examined 2.5- year period. The percentage in Fig. 3 hereby represents the amount by which the daily fluctuations of the grid increases compared to the fluctuations of the grid without any EVs introduced. Due to the fact that the energy demand of EVs correlates with the peak electricity demand in Germany, the difference between the daily demand extrema increases significantly with a rising amount of EVs. In Fig. 4 the impact of 1 mil. and 42 mil. EVs on the German grid is shown for an average week and compared to the situation with no EVs introduced. The impact on the grid seems low with 1 mil. EVs where the daily fluctuation increases only by 1.5% or by 0.3 GW. However, by replacing the whole fleet of conventional passenger cars in Germany (42 mil. vehicles) with EVs, the daily average fluctuation of the demand increases to 38.4 GW (an increase of 92%), compared to 20 GW without the introduction of EVs.

3.3. Grid stabilizing storage use

The calculation is performed with the goal to reach the lowest fluctuation of the national grid. The remaining capacity of the batteries which is not used for driving is allocated to support the grid. The least squares over the lower and upper boundary is calculated for 1 mil. EVs. The minimum is reached for the lower and upper boundary at 52 GW. The amount of reduced fluctuations by using the energy storage of the EVs can be shown with the help of the average daily difference of extrema (cf. Fig. 5). Especially if the upper and lower boundary vary between 50 and 60 GW the highest reduction of fluctuation (about 16%) is achieved. The average daily electricity consumption of the electric car is 24.7 MJ which correspond to a “fueling” cost of 1.5 EUR_{2009} day^{-1}. However, the V2G activities brings an additional revenue of about 0.5 EUR_{2009} day^{-1} to the car owner and therewith reduces the “fuelling costs” from 1.5 to 1.0 EUR_{2009} day^{-1}. The energy which is needed to support the grid is hereby bought and sold at the stock exchange.

3.4. Profit maximization by power trading (V2G)

The results show the revenues of vehicles which are used for V2G services as well as the differential costs between an diesel

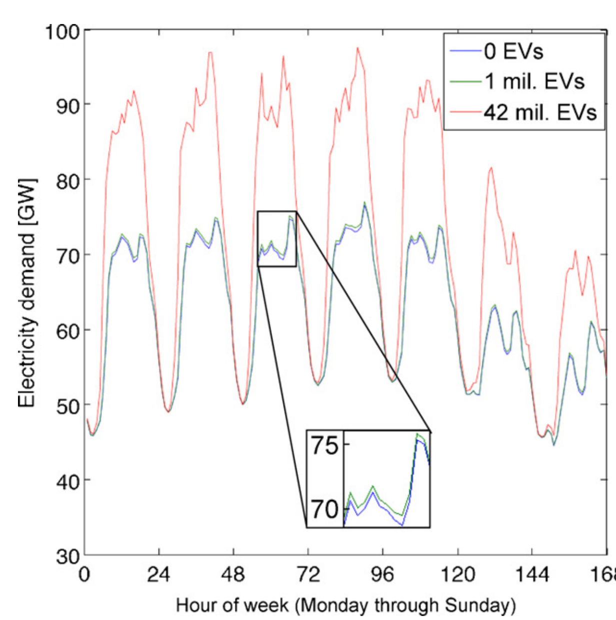

Fig. 4. Energy demand for different amounts of EVs in Germany for an exemplary week (unmanaged charging).

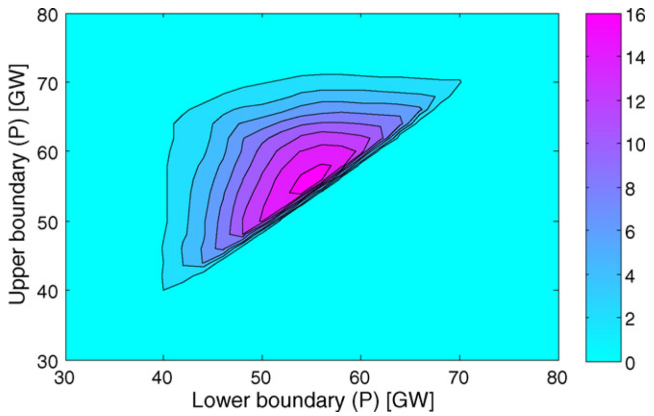

Fig. 5. Improvement of daily difference of extrema in percent for 1 mil. EVs.

and electric vehicle. Thereby the energy consumption of the vehicles is monetized by the diesel and electricity price described in Table 2. Taking the sum of energy consumption for the daily driven vkm as the lowest SoC of the battery the remaining battery capacity can be used for V2G services. In Fig. 6 the revenues through trading energy at the stock exchange EEX for 1 mil. EVs is shown. The value of the revenues describes just the returns after trading energy without any costs or battery degradation. The lower and upper boundaries in Fig. 6 are expressed in 5th grade polynomial $h(t, z)$ at time $t = 1$ (see Section 2.2, part 3). Different upper and lower boundary values are achieved for different z values. If the boundaries vary between the price of about 10 and 110 $\mathrm{EUR_{2009}\ MWh^{-1}}$ revenues can be achieved. The maximum is reached with a upper and lower boundary at time $t = 1$ for $z_1 = z_2 = 36\ \mathrm{EUR_{2009}\ MWh^{-1}}$ with yearly revenues of 247 mil. $\mathrm{EUR_{2009}}$ for 1 mil. EVs, which represents about 0.68 $\mathrm{EUR_{2009}\ EV^{-1}\ day^{-1}}$. The share of battery, which is used for V2G service is about 18%.

The differential driving costs of the EV minus the conventional diesel is calculated in $\mathrm{EURct_{2009}\ vkm^{-1}}$. If the upper boundary is set between 10 and 110 $\mathrm{EUR_{2009}\ MWh^{-1}}$ (at time $t = 1$) and the lower boundary between 10 and 90 $\mathrm{EUR_{2009}\ MWh^{-1}}$ (at time $t = 1$) negative differential costs (cost of conventional diesel is higher than cost of EV) can be achieved. The battery degradation reaches an impact on the economic performance for a high amount of energy traded. Therefore, if the upper and lower boundary is set between 20 and 65 $\mathrm{EUR_{2009}\ MWh^{-1}}$ (at time $t = 1$) the maximum cycles per battery are reached before the lifetime of the EV which makes an earlier battery replacement necessary. Hereby the lifetime of the battery

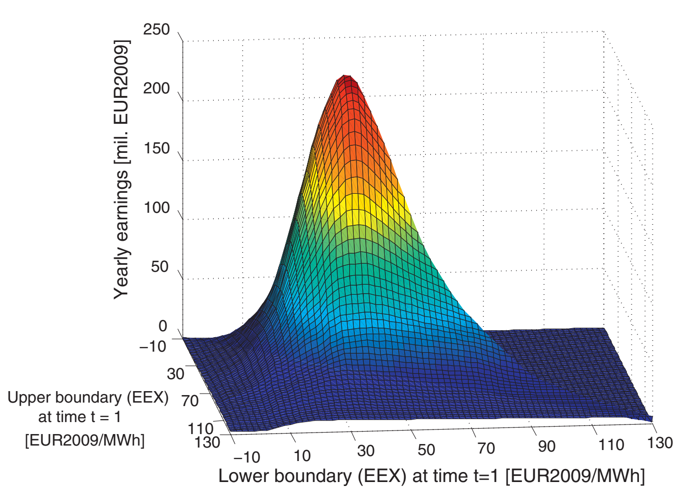

Fig. 6. Revenues of 1 mil. EVs through V2G within the examined period.

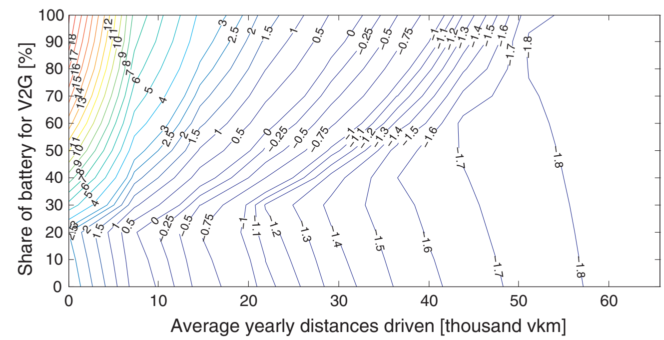

Fig. 7. Differential costs per kilometer of the electric vehicle minus conventional diesel.

drops till the minimum of 3.7 years, which results in higher yearly costs of the battery.

3.5. Discussion and parameter variation

In the following the results are discussed as well as a parameter variation of different input values for the battery degradation and battery costs is presented. The analysis of the availability of plug-in passenger cars in Germany showed that the overall plug-in availability in Germany is high at any time over the day (>89%). A significant difference between the daily characteristics of the availability on weekdays, Saturdays and Sundays was recognized. The main reasons for travel were identified as trips to and from work, for shopping and for leisure.

The unmanaged charging shows, that the times of energy demand of EVs correlates with times of high electricity demand in the national grid in Germany. However, up to an introduced number of 7 mil. EVs in Germany the difference between the daily extrema within the demand increases less than 10%. The introduction of 1 mil. EVs in Germany, which is the goal of the government until the year 2020 [39] exhibits only a low impact on the fluctuations of the demand (about 1.5%). Yet, with an increasing amount of EVs, the fluctuations of the grid increases above average, so that it is inevitable to research on methods to shift the charging into hours of low national energy use.

In contrast with a grid stabilizing storage strategy the potential of 1 mil. EVs to serve the grid as grid support is already noticeable. The daily reduction of difference of extrema of the fluctuations on the grid is 16%. Therefore, even with a low amount of EVs introduced, using EVs as grid support can have favorable effects on the demand. However, the financial incentives which have to be paid to vehicle owners to use their battery have to be determined.

One method to analyze the hight of financial incentives, which is presented in this paper, is to look at the possible revenues vehicle owners can achieve by trading energy at the stock exchange. With an optimized operation strategy revenues up to 0.68 $\mathrm{EUR_{2009}\ d^{-1}}$ per EV can be achieved in average. Due to the similarity of high energy prices with high energy demand in Germany, with an operation strategy of maximal revenues for vehicle owners, the average fluctuation of the national grid is additionally reduced by 12%.

In the following the parameter variation is shown for a varying share of the battery for V2G service and different yearly driven distances. An assumption is that enough battery storage capacity is available at any instance, so that the minimum amount of energy which is required to trade at the stock exchange is met. The incentives hereby for the utility supplier is, that he can use the storage for energy trading and therefore as grid support (with a maximum possible reduction of the fluctuations of the grid 12% for 1 mil. EVs). The incentives for the vehicle owner is, that he receives the V2G activity revenues due to trading at the stock exchange. In Fig. 7 the differ-

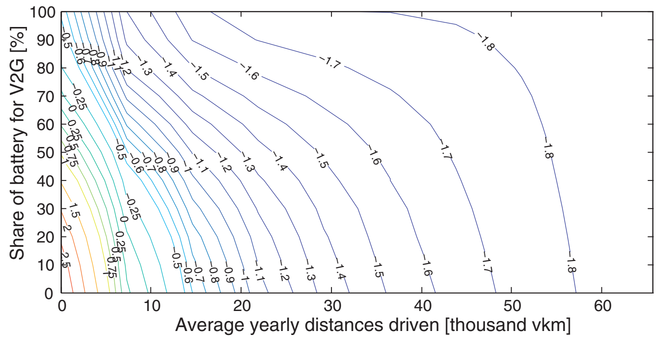

Fig. 8. Differential costs per kilometer of the electric vehicle minus conventional diesel without battery degradation.

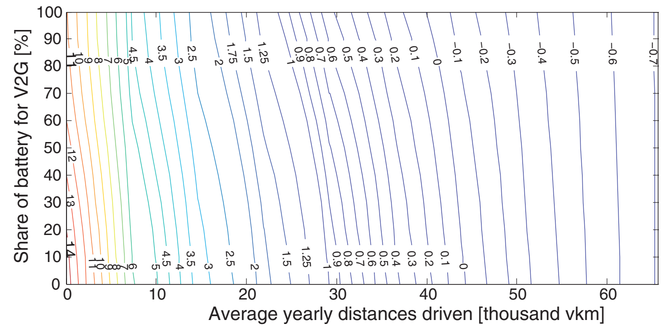

Fig. 10. Differential costs per kilometer of the electric vehicle minus conventional diesel (high battery cost of 434 EUR_{2009} kWh^{-1}).

ential costs in EUR_{2009} vkm^{-1} of an electric vehicle minus those of a conventional diesel vehicle with the settings described in Table 2 is shown. If the differential costs are zero, the yearly costs of the EV equal those of the conventional diesel. The battery degradation is hereby included as described in Section 2.3.

It can be seen, that with no V2G service, the vehicle should be driven at least about 10.000 vkm in 1 year to compensate the higher investment cost of the EV compared to the conventional diesel. For higher yearly driven distances, the advantage of the low operation costs of the EV result in lower costs per vkm of the EV than those of the conventional diesel. An additional usage of the storage for V2G service results for low shares of the battery (less than 20%) in a small reduction of the differential vkm costs. However, due to the increased storage use, the impact of the higher battery degradation is noticeable if the share of battery for V2G service increases over 20%. The higher battery degradation hereby equals out the benefit of using the storage for V2G service. The main impact on the cost per vkm are the battery costs and the assumptions on battery degradation.

In Fig. 8 the differential costs are shown without considering the impact of the battery degradation. Especially for small yearly distances driven and high share of the battery for V2G service, the advantage of using the amount of energy, which is not used for driving, for trading energy at the stock exchange can be noticed. For example, if about 60% of the idle battery capacity is used for V2G service (yearly driven distance 10.000 vkm), the differential costs per vkm drop about 1 $EURct_{2009}$. The assumed cost of the battery (217 EUR_{2009} kWh^{-1}) is the goal in Germany for the year 2030. Battery costs are varied to a higher level (at 434 EUR_{2009} kWh^{-1}) to see its effect on the results if this goal is not reached (with battery degradation in Fig. 9 and without battery degradation in Fig. 10).

The difference in battery cost of 217 and 434 EUR_{2009} kWh^{-1} results in a shifting of the equalized differential costs to higher yearly distances driven. On the one hand, to reach lower costs of the EV the yearly distances driven have to be almost 45,000 km. Also as can be seen in Fig. 10, the lack of battery degradation does not have a significant impact on the differential costs as for lower battery costs.

To conclude, it can be seen, that for low battery costs of 217 EUR_{2009} kWh^{-1} the electric vehicle displays lower costs, if the yearly distances driven is high. The battery degradation has a large impact on the differential costs, which results even in higher costs per vkm of the EV than those of the conventional diesel, if a large fraction of the battery is used for V2G service. Due to uncertainties related to battery degradation the results are also shown without any battery degradation. Hereby the positive impact of V2G service on the costs of the EV is noticeable. However, it must be said that the impact is low and largely depending on the assumptions about the battery size and connection to the grid.

High battery costs (e.g. 434 EUR_{2009} kWh^{-1}) results in high costs of the EV, which can only be equalized to those of the conventional diesel for yearly distances driven over 45,000 vkm. On the other hand, the favorable effects of trading energy at the stock exchange are reduced to almost zero, even without a battery degradation.

4. Conclusion

Due to the high plug-in availability of passenger cars in Germany with the introduction of electric vehicles, a large storage potential at any instance can be achieved. However to reach a high overall storage power and capacity the supply of electricity (e.g. at stores or at work) has to be secured. Therefore, the need for investments into supply facilities is needed in advance to reach the high plug-in availability. The charging of the electric vehicles can have positive as well as negative effects on the grid. Without any charging strategy the fluctuations of the grid can increase immensely, which requires a charging strategy. Using the vehicle to trade energy at the stock exchange has positive impacts on the costs per kilometer, which however are low. An important issue, which has to be analyzed in detail is the battery degradation. Hereby open questions remain such as how the charging of the vehicles and the usage of the battery for V2G services effect the battery degradation. Future research also needs to be accomplished in benefit models for V2G services for example about benefits of a vehicle, which is used to secure the system stability.

To conclude, there are numerous options to use vehicles when they are plug-in available. In this paper the V2G option to trade energy at the stock exchange was examined. The results showed that there can be favorable impacts on the economic performance of an electric vehicle. However, the impact is very low. But the results also showed, that it is mandatory to reach low battery costs. Also the German grid is not ready to adequately assess the benefit which can result out of the integration of electric vehicle into the grid. To promote the adoption of electric vehicles, the assets and drawbacks,

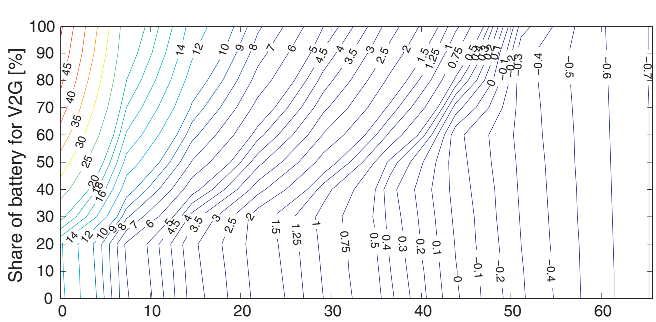

Fig. 9. Differential costs per kilometer of the electric vehicle minus conventional diesel (high battery cost of 434 EUR_{2009} kWh^{-1}, including battery degradation).

which results out of the integration of the EVs, have to be examined in detail.

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References

[1] BMU – Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit: Nationaler Entwicklungsplan Elektromobilätät der Bundesregierung, August 2009.
[2] BMVBS – Bundesministerium für Verkehr, Bau und Stadtentwicklung: Modellregionen Elektromobilität, April 2009.
[3] P. Albertus, J. Couts, V. Srinivasan, J. Newman, Journal of Power Sources 183 (September 2) (2008) 771–782.
[4] M. Fischer, M. Werber, P.V. Schwartz, Energy Policy 37 (July 7) (2009) 2639–2641.
[5] S.A.H. Ali, A.K. Arof, Journal of Alloys and Compounds 449 (2008) 292–295.
[6] K.S. Ng, C.-S. Moo, Y.-P. Chen, Y.-C. Hsieh, Applied Energy 86 (2009) 1506–1511.
[7] T.E. Lipman, M.A. Delucchi, Hybrid-Electric Vehicle Design Retail and Lifecycle Cost Analysis/Analysis and Report Prepared for the Energy Foundation, 2003.
[8] G. Passier, F.V. Conte, S. Smets, F. Badin, A. Brouwer, S.M. Alaküla, D. Santini, Status Overview of Hybrid and Electric Vehicle technology (2007)/IEA – International Energy Agency, 2007.
[9] W. Kempton, S. Letendere, Transportation Research D 2 (3) (1997) 157–175.
[10] W. Kempton, J. Tomic, Journal of Power Sources 144 (1) (June 2005) 268–279.
[11] C. Guille, G. Gross, Proc. IEEE Energy 2030 Conference ENERGY, 2008, pp. 1–3.
[12] S. Letendre, W. Kempton, in: Public Utilities Fortnightly, February 15, 2002, pp. 16–26.
[13] H. Lund, W. Kempton, Energy Policy 36 (9) (September 2008) 3578–3587.
[14] W. Kempton, J. Tomic, S. Letendre, A. Brooks, T. Lipman, Vehicle-to-Grid Power: Battery, Hybrid, and Fuel Cell Vehicles as Resources for Distributed Electric Power in California/California Air Resources Board and the California Environmental Protection Agency (under contract ARB00-612, Feasibility of Electric Drive Vehicles as Distributed Power Generation Assets in California), and Los Angeles Department of Water and Power, Electric Transportation Program, 2001.
[15] J. Tomic, in: Seattle V2G Technical Symposium, 6 June 2005.
[16] J. Tomic, W. Kempton, Journal of Power Sources 168 (2) (June 2007) 459–468.
[17] European Energy Exchange, EEX: Intraday Spot market prices. http://www.eex.com (accessed on 10.10.09).
[18] ADAC, Allgemeiner Deutscher Automobil Club, Statistiken. www.adac.de (accessed on 24.11.09).
[19] Infas, Institut für angewandte Sozialwissenschaft GmbH und Deutsches Institut für Wirtschaftsforschung (DIW) Ergebnisbericht, 2004. www.kontiv2002.de (accessed on 20.11.08).
[20] Shell Pkw-Szenarien bis 2030 – Flexibilitaet bestimmt Motorisierung, Shell Deutschland Oil. http://www.shell.de (accessed on 19.03.10).
[21] B. Kennedy, D. Patterson, S. Camilleri, Journal of Power Sources 90 (October 2) (2000) 156–162.
[22] S. Campanari, G. Manzolini, F. de la Iglesia, Journal of Power Sources 186 (January 2) (2009) 464–477.
[23] C.-S. Shiau, C. Samaras, R. Hauffe, J.J. Michalek, Energy Policy 37 (July 7) (2009) 2653–2663.
[24] C.E. Thomas, International Journal of Hydrogen Energy 34 (August 15) (2009) 6005–6020.
[25] Kraftfahrt-Bundesamtes (KBA), Statistik des Kraftfahrt-Bundesamtes. http://www.kba.de (accessed on 19.03.10).
[26] VDE-Studie, Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger – Bedeutung, Stand der Technik, Handlungsbedarf, VDE-Studie, December 2008.
[27] Y. Zhang, C.-Y. Wang, Journal of Electrochemical Society 156 (7) (2009) A527–A535.
[28] E. Tomi, Unter 120 Gramm? Sonnenenergie, September-October 2008.
[29] EPRI Electric Power Research Institute, Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume 1: Nationwide Greenhouse Gas Emissions, Final Report, July 2007.
[30] HBEFA, Handbuch Emissionsfaktoren des Strassenverkehrs, Version 2.1,April 2004. Dokumentation zur Version Deutschland erarbeitet durch INFRAS AG Bern/Schweiz in Zusammenarbeit mit IFEU Heidelberg, Hrsg., Umweltbundesamt, Berlin. http://www.hbefa.net/.
[31] IER, RWI, ZEW: Die Entwicklung der Energiemärkte bis 2030 – Energieprognose 2009. Schlussbericht. Institut für Energiewirtschaft und Rationelle Energieanwendung der Universität Stuttgart, Rheinisch-Westfälisches Institut für Wirtschaftsforschung Essen, Zentrum für Europäische Wirtschaftsforschung Mannheim, Stuttgart, Essen, Mannheim, 2009.
[32] Concawe, EUCAR, JRC: Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Well-to-Tank Report, Version 2c, March 2008.
[33] International Energy Agency: Prospects for Hydrogen and Fuel Cells, IEA, Paris, 2005.
[34] R. Graham, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, USA, 2001.
[35] IPTS, Hybrids for Road Transport, IPTS/IE, 2005.
[36] International Energy Agency: Energy Technology Perspectives, IEA, Paris, 2008.
[37] N. Hartmann, E.D. Özdemir, P.H. Goyns, L. Eltrop, in: 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Stavanger, May 13–16, 2009.
[38] N. Hartmann, E.D. Özdemir, in: Proceedings of ASME 2010 4th International Conference on Energy Sustainability, ES2010, May 17–22, 2010, Phoenix, Arizona, USA.
[39] Bundesregierung Deutschland, Eine Million Elektroautos bis, 2020. http://www.bundesregierung.de (accessed on 16.02.10).