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Vehicle-to-grid regulation based on a dynamic simulation of mobility behavior

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Abstract

This study establishes a new approach to analyzing the economic impacts of vehicle-to-grid (V2G) regulation by simulating the restrictions arising from unpredictable mobility requests by vehicle users. A case study for Germany using average daily values (in the following also called the ‘static’ approach) and a dynamic simulation including different mobility use patterns are presented. Comparing the dynamic approach with the static approach reveals a significant difference in the power a vehicle can offer for regulation and provides insights into the necessary size of vehicle pools and the possible adaptations required in the regulation market to render V2G feasible.

In a first step, the regulation of primary, secondary and tertiary control is analyzed based on previous static methods used to investigate V2G and data from the four German regulation areas. It is shown that negative secondary control is economically the most beneficial for electric vehicles because it offers the highest potential for charging with “low-priced” energy from negative regulation. In a second step, a new method based on a Monte Carlo simulation using stochastic mobility behavior is applied to look at the negative secondary control market in more detail. Our simulation indicates that taking dynamic driving behavior into account results in a 40% reduction of the power available for regulation. Because of the high value of power in the regulation market this finding has a strong impact on the resulting revenues. Further, we demonstrate that, for the data used, a pool size of 10,000 vehicles seems reasonable to balance the variation in driving behavior of each individual. In the case of the German regulation market, which uses monthly bids, a daily or hourly bid period is recommended. This adaptation would be necessary to provide individual regulation assuming that the vehicles are primarily used for mobility reasons and cannot deliver the same amount of power every hour of the week.

Table of Contents

1 Introduction

Grid connected-battery electric vehicles[1] (GC-BEVs) are regarded as a promising option for balancing power in the electricity system and providing ancillary services (Kempton, Tomić et al. 2001). Evidence is accumulating that batteries combined with power electronics can react as very fast regulation units. In a first pilot test, GC-EVs are being used to provide frequency control (Kempton/Victor et al. 2009). Vehicle-to-grid (V2G) (including demand-side management and back-feeding electricity from the battery storage) therefore seems to be a technically feasible option to balance electricity in the future. Economic aspects of V2G services have been analyzed in a number of previous studies (Kempton/Tomić et al. 2001; Williams/Kurani 2007; Kempton/Tomić 2007; Andersson/Elofsson et al. 2010.). Most studies identify benefits for V2G vehicle owners in the range of a few to several hundred dollars per month. Using 2008 German market data, our study shows similar results for negative control. Positive control and feeding back electricity are not found to be promising options due to the costs in terms of battery degradation and for the bidirectional power electronics. In terms of mobility behavior, existing studies only take average values into account, e.g. the vehicle being parked for 23 hours a day. It is obvious, however, that the available battery capacity varies during different hours and days of the week depending on mobility behavior. For instance, the driving behavior at weekends is very different to that on weekdays. If only negative control - as the most feasible V2G option - is taken into account, the kilometers travelled during different periods of the day become more important. This is because only consumed energy can be used as negative regulation. The main purpose of this study, therefore, is to investigate the impacts of driving behavior on the value of V2G in more detail. To do so, the stochastics of mobility behavior will be analyzed using a dynamic Monte Carlo simulation approach. The study starts with an overview of the German markets for ancillary services and describes the assumptions made for infrastructure, vehicles and mobility behavior. A static analysis made with average mobility behavior following Kempton/Tomić (2005) is used to find the most profitable ancillary service in Germany. Finally, a dynamic simulation demonstrates the impact of mobility behavior on V2G services.

1 For example Plug-in Hybrid Vehicles (PHEVs) or purely electric vehicles (EVs).

2 Data basis

2.1 German markets for ancillary services

Markets and products for ancillary services are not standardized worldwide. One example for differences are those between Germany and California, but even within the European Union the markets are not standardized. The California Independent System Operator (CAISO) requests and remunerates through market mechanisms the following ancillary services related to load-frequency control: regulation reserves and contingency operating as well as reserves: spinning and non-spinning reserves, whereas the European Network of Transmission System Operators for Electricity (ENTSOE-E) distinguishes between primary control[2], secondary control[3] and tertiary control[4]. Products for ancillary services differ in terms of pre-qualification and control methods from region to region. Prices for similar services are affected by the types of power plants installed in the different service areas.

The ENTSOE-E is responsible for frequency control in Central Europe. Control is performed in a series of three independent control steps. *Primary control* starts only seconds after a frequency deviation as a joint action of all the thermal power plants. This type of regulation capacity is mainly supplied by conventional power stations which are operated slightly below their maximum capacity. Primary balancing power has to be deployed within 30 seconds and provided for up to 15 minutes. *Secondary control* replaces primary control and restores the frequency to its nominal level. Adjustments of secondary control are realized in the time-frame of seconds up to 15 minutes after an incident. The Transmission System Operator (TSO) in the control area is responsible for the activation of secondary control if there is an imbalance between generation and load. Secondary control is based on continuous Automatic Generation Control. If necessary, *Tertiary control* is activated by the responsible TSO. *Tertiary control* reserves are activated manually in the framework of 15 minutes to one or two hours. These are primarily used to free up the secondary reserve in a balance

2 Dr. Tomás Gómez San Román: “In California this service exists as a mandatory reliability standard for generators but its procurement is not remunerated.”

3 Dr. Tomás Gómez San Román: “Secondary control is similar to Regulation reserves used by CAISO.”

4 Dr. Tomás Gómez San Román: “Tertiary control is similar to the Contingency Operating reserves in California.”

situation and as a supplement to the other reserves in case of large incidents (for detailed information see ENTSOE-E 2009).

A very sensible parameter for V2G services is the dispatch time (operating availability) that must be provided to pre-qualify as a regulation service supplier. The power a GC-BEV or a pool of vehicles can provide is heavily influenced by the dispatch time required for pre-qualification and the mobility behavior of the vehicle users. The price for regulation energy is another important factor influencing the economic efficiency of V2G. Our calculations used the average 2008 market prices from the four German TSOs[5]. Table 2-1 summarizes the market capacities, capacity and energy prices as well as the monthly dispatch and the dispatch probability (dispatch to contract ratio) for the three German ancillary service markets. In all three markets, an actor offers an exclusive bid for a specific capacity. Furthermore, for secondary and tertiary control, a distinction is made between positive and negative control as well as between prime (Hauptzeit: HZ) and secondary time (Nebenzeit: NZ). Prime time is defined as the time period between 8 a.m. and 8 p.m. on weekdays. Secondary time covers the remaining time on weekdays and the whole day at weekends. Simultaneous bids for positive and negative control are possible but are not part of this study. Beside the capacity price, a price for positive and negative energy is paid in case of secondary and tertiary control. The dispatch probability describes how often capacity is retrieved and therefore the energy an actor has to provide or reduce in a certain time period. The operating availability is defined as the time a specific capacity has to be provided by a control unit (maximal energy an actor has to provide) to pre-qualify and is therefore essential for the bidding capacity of GC-BEVs. Since there are no standards for battery storage, it is assumed that the operating availability in the secondary regulation and tertiary markets equals four hours. This corresponds to the rules for pump storage power stations. The operating availability for conventional power plants is 12 hours. For the dispatch probability, the values from 2008 are used. Since no published figures are available on the dispatched regulation for primary balancing power capacity, the dispatch probability is taken from Kempton/Tomić 2007, p. 461.

5 50 Hertz Transmission GmbH (E.ON), Amprion GmbH (RWE), Transpower Stromuebertragungs GmbH (Vattenfall) and EnBW Transportnetze AG.

Table 2-1: Average market prices in 2008 for different ancillary services of the four German TSO areas

			Capacity [MW]	Normalized capacity price p_{cap} [€/MW·h]	Dispatch [MWh/month]	Energy price p_{el} [€/MWh]	Operating availability t_{disp} [h]	Dispatch probability $R_{d\text{-}c}$ [%]
Primary control			667	20.51	-	-	0.25	n.s.
Secondary control	**Prime time**	**Positive**	3,081	22.05	120.163	111.6	4	14.9
		Negative	2,451	4.04	106.521	1	4	16.6
	Secondary time	**Positive**	3,050	7.41	116.29	69.1	4	8.1
		Negative	2,413	8.23	270.227	0.1	4	23.8
Tertiary control	**Prime time**	**Positive**	3,263	10.4	9.332	214.3	4	1.1
		Negative	1,949	0.31	11.681	0.4	4	2.3
	Secondary time	**Positive**	3,205	2.73	3.181	167.3	4	0.2
		Negative	1,919	3.92	18.77	0	4	2.1

Prime time (Hauptzeit); secondary time (Nebenzeit); data basis: German Transmission System Operators 2009. [6]

The maximum power limit (P_{Max}) is set by the electricity connection. Three-phase 400 V and a maximum charging current of 63 A is presumed. The maximum power is 43.6 kW, which is equivalent to a new domestic power line in Germany.[7] This capacity seems to be very high and difficult to manage with current battery technology. The following evaluation shows that this maximum power is never achieved in the calculations and does not represent a binding restriction under the assumed values. In the static approach no distinction determination between prime time and secondary time is analyzed. Average values are used for prime time and secondary time (ratio NT 9: HT 5). The current electricity price for private customers is taken as the power price (c_{ps}) for conventional charging. In Germany, this end-user price is in the range of 21 cent/kWh.

2.2 Vehicle and infrastructure

The vehicle data are taken from Biere/Dallinger et al. 2009. Since the study revealed that only PHEVs and so-called 'CityBEVs' (BEVs with small batteries

6 Dispatch probability for primary control is not specified (n.s.). For the calculation a value of 10% is taken.

7 The dimensioning of the three-pin plug varies between 50 A in the low-voltage grid of the German utility EnBW and 100 A in Vattenfall's network.

and limited range) will be economical in 2020, this analysis focuses on these two types of cars.[8]

Table 2-1: Technical and economic electric vehicle parameters

			PHEV	City-BEV
Maximum depth of discharge	DoD_{max}		80 %	80 %
Charging/discharging efficiency	η_{inv}		92 %	92 %
Charging and discharging efficiency	η_{conv}		85 %	85 %
Interest rate	d		5 %	5 %
Battery lifespan	n	[years]	12	12
Battery price per kWh[9]	$p_{Batt,kWh}$	[€/kWh]	337	286
Battery capacity	E_s	[kWh]	14	25
Total battery price	p_{Batt}		4714 €	7152 €
Energy consumption	c_{Fzg}	[kWh/km]	0.16	0.13
Electric driving share	R_{el}		60 %	100 %

The cost data for the infrastructure are taken from a study which modeled vehicles providing regulation energy in the US[10]. The V2G hardware comprises a meter for invoicing (29 €), the communication system with the transmission network operator (71 €) and, in the case of supplying positive regulation energy, bidirectional electronics/charger (power inverter, buck-boost converter and grid monitoring) for charging and delivering power back into the grid. Since these have to be sized to match the maximum capacity, a capacity-dependent price is assumed in contrast to the above mentioned model (Tomić/Kempton 2007). The prices of power inverters used in photovoltaic systems can be taken as a guideline.

- The study assumes 286 € for an American grid connection with 12 kW or 0.024 € per kWh.[11]

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8 See p.11 and Biere/Dallinger et al. 2009.

9 (Kalhammer/Kopf et al. 2007). The value represents the best-case cost reduction for batteries.

10 (Tomić/Kempton 2007). The assumed exchange rate is $ 1.40 = 1 €.

11 240 V · 50 A = 12 kW

- According to an examination of the costs for photovoltaic electricity generation, the prices for power inverters dropped by 70% down to 0.36 €/W between 1991 and 2007. It is assumed that by 2020 the price can be reduced further to 0.15 – 0.20 €/W due to economies of scale.[12]

Evaluating the data in the model shows that the vehicles can provide regulation capacity of 1.8 – 2.6 kW based on the demanded operating availability. Assuming that the price drops to 0.15 €/W, the investment in the bidirectional electronics would be in the range between 270 and 390 €. The assumed prices are shown in Table 2-2.

Table 2-2: Necessary investments in the infrastructure

	Negative regulation	**Positive regulation**
Meter for invoicing	29 €	29 €
Communication system	71 €	71 €
Bidirectional electronics	-	0.15 €/W

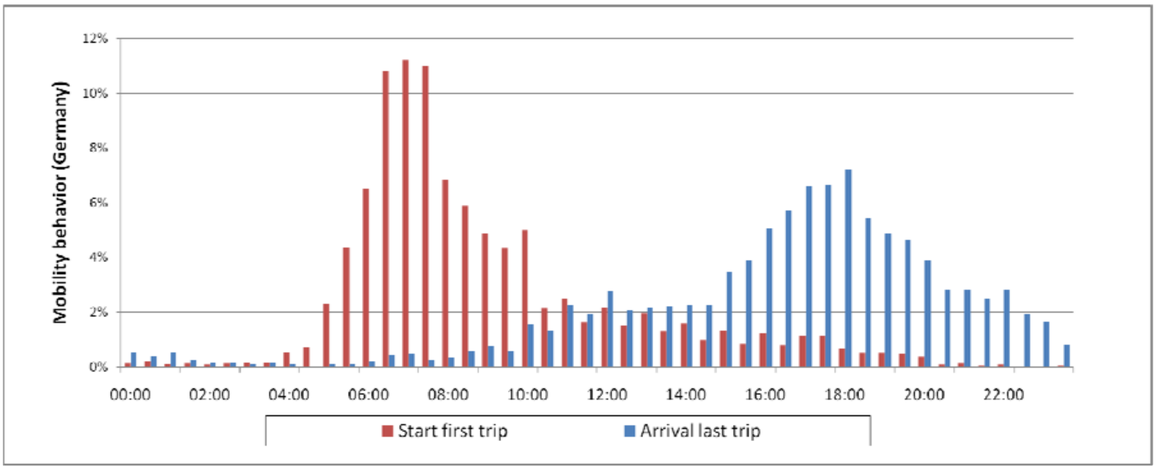
To calculate the annuities, an interest rate (d) of 5 % and a lifespan (n) of 12 years are assumed for the electronics and the battery. The costs of creating a pool or providing a control signal to the vehicles participating in the pool are unclear so far and therefore not taken into account in this study.

2.3 Driving behavior

The relevant data sets of the 2002 mobility study are filtered out for this study using the selection criteria from Biere/Dallinger et al. 2009. These criteria comprise values affecting the return on investment such as the driving distance per day or the ratio of inner-city driving and the values of basic needs such as, for example, a private parking lot with an available power connection to charge the vehicle. The dynamic simulation of driving behavior uses probability distributions for when the first trip of the day starts and when the last trip of the day finishes. Figure 2-1 illustrates the probability for journeys in Germany on a typical Monday for full-time employees.

12 Meinhardt/Burger et al. 2007.

Figure 2-1: Mobility behavior of German full-time employees on a Monday



Data basis: MiD 2002

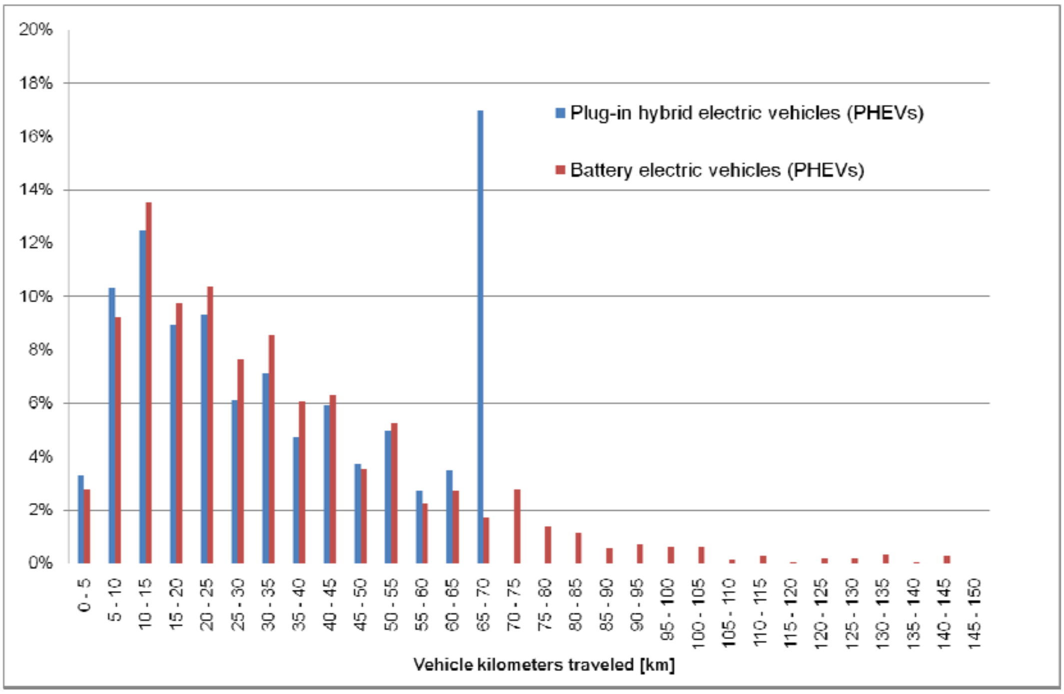
It is obvious that most first routes start before 8 a.m. and last routes end around 6 p.m. The average standing time during the day is in the range of 6 hours for full time employees. The average standing time during the night is 16 h. Assuming a charging time of 1.4 hours[13] plus 0.6 hours driving results in an available load-shifting time of 4 hours during the day and 14 hours during the night. The standing time of other user segments is lower. For a more detailed analysis, see Dallinger/Nestle et al. 2009.

The probabilities for the kilometers travelled differ slightly between the segments of PHEVs and BEVs (Figure 2-2). Differences in the 65 to 70 km class arise from the fact that all trips longer than 65 km are collected in this class. Thus, a maximum purely electric range of 70 km is presumed for PHEVs[14].

13 Average route: 20 km; energy consumption: 0.2 kWh/km; grid connection 3.6 kW.

14 For a PHEV, we assume that a 14 kWh battery is used. The DoD is 80% and the power consumption 0.16 kWh/km. Therefore the maximum electric range of a PHEV is 70 km. A blended driving mode is not taken into account.

Figure 2-2: Probability for different route ranges. Data for BEVs and PHEVs is filtered out using the selection criteria from Biere/Dallinger et al. 2009



Data basis: MiD 2002

In the static approach, the standing time between the final and the first trip, and the number of daily kilometers represent the average values of the users of a respective class of vehicle. A PHEV does not need a range buffer since its mobility is guaranteed by the additional combustion engine. For City-BEVs, the 90% quantile of the individual recorded trips is calculated and taken as a buffer. In the unlikely event that the battery is completely discharged due to the supply of positive regulation energy, this ensures that the user could still use his car for 90% of all trips. The data on driving behavior are given in Table 2-3

Table 2-3: Data on driving behavior used for the calculations

			PHEV	City-BEV
Standing time between last – first trip	$t_{plug,day}$	[h]	16.0	15.9
Daily kilometers	d_d	[km]	44.2	33.16
Range buffer	d_{rb}	[km]	0	74

Data basis: MiD 2002

3 Static approach: value of vehicle-to-grid power for regulation

3.1 Energy for Vehicle-to-Grid Services (V2G)

The share of car batteries which can be used either for driving or for V2G purposes depends on the battery capacity (E_S) and the permissible depth of discharge (DoD). At the end of the day, the power discharged by the battery corresponds to the number of kilometers driven that day (d_d). In order to not restrict the mobility of the users of electric drive vehicles, there always has to be sufficient energy available for a longer trip. For this reason, an additional range buffer (d_{rb}) is taken into account. Other parameters are the electric share of driving (R_{el} – 100% for BEV, 60% for PHEV), the energy consumption per kilometer driven (c_{Veh}) and the charging/discharging efficiency (η_{Inv}). The energy per vehicle which is available for delivery back into the grid (positive energy[15]) is calculated as follows:

$$W_{pos} = (E_S \cdot DoD - (d_d + d_{rb}) \cdot R_{el} \cdot c_{Veh}) \cdot \eta_{Inv} \tag{3-1}$$

The energy which can be delivered to the battery during controlled charging (negative energy) depends mainly on the daily kilometers driven – it is only possible to replace what has been consumed over the course of the day.

$$W_{neg} = \frac{d_d \cdot R_{el} \cdot c_{Veh}}{\eta_{Inv}} \tag{3-2}$$

3.2 Possible regulation capacity

While the energy per vehicle which can be made available for V2G services is independent of the type of regulation performed, there are additional restrictions on the regulation capacity per vehicle which have to be considered. A fixed period of operating availability (t_{dtsy}) has to be guaranteed for the regulation capacity offered. In addition, it is possible that capacity may be dispatched from one vehicle for several system balancing processes over the bidding period. In the positive regulation energy markets, it is assumed that the time between two

15 In Germany, the term “Regelenergie” is used to describe the energy used to balance power supply and demand. Positive regulation is when power is withdrawn from the vehicle battery into the grid; negative regulation is when power is charged into the battery in a controlled manner at specific times. In this way, V2G services can help to balance the load and the generation in the power system.

dispatch events is sufficient to recharge the energy withdrawn. Where negative regulation energy is concerned, the dispatch probability is taken into account additionally (R_{d-c} - Dispatch to contract ratio). Another restriction is the capacity limit set by the domestic power connection or the charging infrastructure (P_{Max}).

Primary control capacity has to be available at the same time for both positive and negative regulation.

$$P_{Veh,PR} = min\left\{\frac{min\{W_{pos}, W_{neg}\}}{max\{t_{disp}, 24 \cdot R_{d-c}\}}, P_{Max}\right\} \tag{3-3}$$

For positive secondary control capacity and tertiary control, only energy and operating availability are considered.

$$P_{Veh,Pos} = \left\{\frac{W_{pos}}{t_{disp}}, P_{Max}\right\} \tag{3-4}$$

For negative secondary regulation capacity and spinning reserves, the dispatch probability is additionally taken into account in order to avoid the battery being fully charged after the first dispatch call and then unable to provide any more regulation energy.

$$P_{Veh,Neg} = \left\{\frac{W_{pos}}{max\{t_{disp}, 24 \cdot R_{d-c}\}}, P_{Max}\right\} \tag{3-5}$$

3.3 Dispatched energy per year

To calculate the dispatched regulation energy for secondary and tertiary control, first of all, the time a vehicle spends connected to the grid each year is regarded. 250 days per year and an average standing time between the last and the first journey on a week day are assumed.

$$t_{plug} = 250 \cdot t_{plug,day} \tag{3-6}$$

The dispatched regulation energy can be calculated from the standing time, the dispatch probability and the possible regulation capacity of a vehicle.

$$E_{disp} = P_{Veh} \cdot R_{d-c} \cdot t_{plug} \tag{3-7}$$

3.4 Calculating the income per year

The income (r_{reg}) is made up of the income due to providing regulation capacity (r_{cap}) and the income from supplying regulation energy (r_{el}). The price for regulation capacity (p_{cap}) is based on a different period depending on the length of time (bidding period) the type of regulation energy is offered. Standardized capacity prices for one day are used for the calculations.

$$r_{cap} = \frac{p_{cap}}{24} \cdot P_{Veh} \cdot t_{plug} \quad (3\text{-}8)$$

For positive balancing (secondary and tertiary control), the price for energy (p_{el}) shows how much money the provider receives for the dispatched electricity.

$$r_{el,Pos} = p_{el} \cdot E_{disp} \quad (3\text{-}9)$$

For negative regulation, the provider has to pay an amount for the energy withdrawn. At the same time, however, the opportunity costs for conventional charging (c_{pe}) also have to be taken into account. The provider gets relatively cheap energy from negative regulation and saves money because he only has to charge his vehicle manually to some extent.

$$r_{el,Neg} = \left(c_{pe} - p_{el}\right) \cdot E_{disp} \quad (3\text{-}10)$$

For primary regulation, only the income from supplying regulation capacity is considered. The saving from providing negative regulation energy is not calculated because it is assumed that the positive and negative dispatches balance each other out.

$$r_{reg,PR} = r_{cap} \quad (3\text{-}11)$$

For all other types of regulation energy, the income results from providing capacity and energy for ancillary services.

$$r_{reg,SR\ und\ MR} = r_{cap} + r_{el} \quad (3\text{-}12)$$

3.5 Calculating the annual cost

Infrastructure investments

In order to make it possible to control charging or to deliver power back into the grid, first of all, investments in the infrastructure have to be made. Independent of the type of regulation energy and capacity, it is necessary to have a meter for billing and a communications system with the transmission network operator. In addition, bidirectional charging electronics are necessary to deliver power back into the grid when supplying positive regulation energy. It is assumed that the price increases in proportion to the capacity offered.

Fixed costs

Fixed costs (c_{fix}) result whether energy is withdrawn or charged (i.e. for both positive and negative regulation) in the form of depreciation and capital costs which are calculated from the investment sum (c_c). The annual costs can be calculated depending on the rate of interest (d) and the lifespan (n) using the annuity formula.

$$c_{fix} = c_c \cdot \frac{d}{1-(1+d)^{-n}} \tag{3-13}$$

Variable costs

The battery is discharged when providing positive regulation energy. Variable costs (c_{var}) result due to battery degradation (c_d) and energy withdrawal (c_{en}).

$$c_{var,pos} = (c_d + c_{en}) \cdot \mathrm{E}_{disp} \tag{3-14}$$

Since the battery is not discharged when negative regulation energy is concerned, no variable costs[16] result and the annual costs (c_{reg}) are comprised solely of the fixed costs.

$$c_{reg,neg} = c_{fix} \tag{3-15}$$

$$c_{reg,pos} = c_{fix} + c_{var} \tag{3-16}$$

The costs for withdrawing energy are calculated using the electricity price and the losses when charging and then discharging the battery (η_{conv}).

$$c_{en} = \frac{c_{pe}}{\eta_{conv}} \tag{3-17}$$

3.6 Evaluating battery degradation

To evaluate battery degradation in monetary terms, it has to be estimated how much the battery's lifespan is shortened by providing positive regulation energy.

In the first step, the depth of discharge due to V2G services (DoD_{V2G}) is calculated. It is assumed that the vehicle is fully charged before every dispatch. Information available about the length of a discharge cycle is not available yet.

16 Note: The regulation energy price for withdrawing negative regulation energy was already considered in the income $i_{,eg}$.

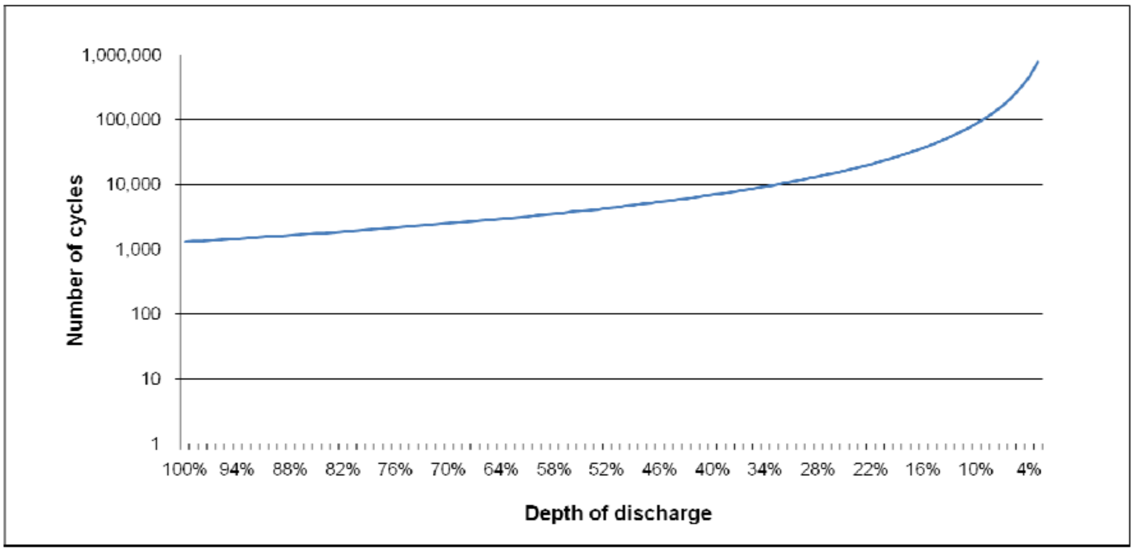
However, it can never be longer than the average total dispatch period per day or the fixed operating availability.

$$DoD_{V2G} = \frac{P_{Fzg} \cdot min\{t_{Disp}; 24 \cdot R_{G-t}\}}{E_S} \tag{3-18}$$

In the second step, the number of cycles over the entire lifespan of the battery (C_{life}) is calculated using the approach of Rosenkranz and the Fraunhofer ISI's model.[17] The number of cycles is reduced disproportionately to the depth of discharge. If the battery depth of discharge during a cycle is always relatively shallow, a greater energy delivery rate can be achieved over the entire lifespan of the battery than at a deeper discharge rate. The parameters of a Li-Ion battery produced by the company Saft were used for the calculation.

$$C_{life} = 1331 \cdot DoD^{-1{,}8248} \tag{3-19}$$

Figure 3-1: Correlation between DoD and cycle lifespan[18]



In the third step, the energy delivery rate of the battery (L_{ET}) is calculated over the entire lifespan.

$$L_{ET} = C_{life} \cdot E_S \cdot DoD_{V2G} \tag{3-20}$$

17 Wietschel/Dallinger et al. 2008, p.119.

18 According to Rosenkranz 2003 and Wietschel/Dallinger et al. 2008, p. 120.

The cost of battery degradation is assumed to be the same as the value which would result if the battery were used exclusively for V2G services.

$$c_d = \frac{p_{Batt}}{L_{ET}} \qquad (3\text{-}21)$$

3.7 Results of the static approach

The findings on the economic efficiency of participating in regulation markets are the same for PHEVs and City-BEVs. The only difference is that the profits and losses are more marked for PHEVs. The reason for this is that PHEVs have a smaller battery but are still able to provide greater capacity on the energy markets because the additional combustion engine guarantees mobility even at deeper battery discharges.

Results of the calculations

Table 3-1: Economic efficiency of PHEV participation in regulation markets

PHEV		Primary regulation	Positive secondary regulation	Negative secondary regulation	Positive spinning reserves	Negative spinning reserves
Capacity provided	P_{Fzg}[kW]	1.92	2.58	1.15	2.58	1.15
Depth of discharge V2G	DoD_{V2G}	3 %	47 %	-	2 %	-
Income from regulation capacity	r_{cap}	191.95 €	130.19 €	31.02 €	56.38 €	12.12 €
Income from regulation energy	r_{el}	-	98.63 €	195.20 €	10.18 €	20.18 €
Total income	r_{reg}	**191.95 €**	**228.82 €**	**226.22 €**	**66.56 €**	**32.30 €**
Fixed costs	c_{fix}	43.80 €	54.88 €	11.28 €	54.88 €	11.28 €
Variable costs	c_{var}	12.03 €	402.66 €	-	13.65 €	-
Total costs	c_{reg}	**55.83 €**	**457.54 €**	**11.28 €**	**68.53 €**	**11.28 €**
Profit/loss		**136.12 €**	**- 228.72 €**	**214.94 €**	**- 1.97 €**	**21.02 €**

Table 3-2: Economic efficiency of City-BEV participation in regulation markets

City-BEVs		Primary regulation	Positive secondary regulation	Negative secondary regulation	Positive spinning reserves	Negative spinning reserves
Capacity provided	P_{Fzg}[kW]	1.65	1.81	0.99	1.81	0.99
Depth of discharge V2G	DoD_{V2G}	2 %	23 %	-	1 %	-
Income from regulation capacity	r_{cap}	163.81 €	90.70 €	26.47 €	39.28 €	10.34 €
Income from regulation energy	r_{el}	-	68.71 €	166.58 €	7.09 €	17.22 €
Total income	r_{reg}	**163.81 €**	**159.41 €**	**193.05 €**	**46.37 €**	**27.56 €**
Fixed costs	c_{fix}	39.24 €	41.88 €	11.28 €	41.88 €	11.28 €
Variable costs	c_{var}	5.74 €	226.61 €	-	9.27 €	-
Total costs	c_{reg}	**44.98 €**	**268.49 €**	**11.28 €**	**51.15 €**	**11.28 €**
Profit/loss		**118.83 €**	**- 109.08 €**	**181.77 €**	**- 4.78 €**	**16.28 €**

Providing positive regulation capacity

Providing positive regulation capacity does not seem to make economic sense. In the market for positive secondary regulation capacity, the high dispatch probability results in very high variable costs. Approximately one third of these costs comprise those for battery degradation and two thirds those for energy costs. In the market for positive spinning reserves, dispatches are so seldom that the income from providing regulation capacity and the fixed costs are decisive. The capacity price is too low and the rare dispatch occurrences result in it not being economical to make the relatively high investment in the bidirectional power electronics.

The only profitable way to feed energy back into the grid is to participate in the primary control market. The profits are still relatively small at today's prices for regulation energy, but this option could become more relevant considering the strong price increase in the past[19] and the presumed upwards trend in demand due to the expansion of renewable energies. At the moment participation seems to be ruled out by the regulatory requirements. Batteries can indeed react very quickly unlike gas turbines and therefore appear to be suitable in general, but

19 Compare German Transmission System Operators (2009).

the prequalification requirements are very high and since they do not allow for pooling resources, each generation unit has to be able to provide at least 10 MW capacity. The bidding period does not distinguish between peak and off-peak times and, based on driving behavior, it seems to make more sense for electric cars to differentiate the capacity offered between these times (see section 4). During the day more drivers are on the road and fewer vehicles are plugged into the grid. If the frame conditions changed over the next few years, this option might become an interesting way to support primary regulation.

Positive and negative controls were analyzed separately to reduce the complexity and reveal the different secondary and tertiary markets. In general, either negative or positive regulation is needed within one regulating zone. Therefore it is possible to bid for positive and negative control at the same time. Especially in the secondary market, it seems promising to realize further benefits by providing negative control after loading the battery with positive control services. Moreover, pooling vehicles provides new options for advanced bidding strategies. A vehicle pool can provide positive control simply due to the reduction of the load. Hence the pool can participate on the positive control market without bidirectional grid connection. Overall, this could result in an economic benefit since there are no costs for battery degradation or the bidirectional grid connection.

Providing negative regulation capacity

The results illustrate that the biggest profits can be made in the market for negative secondary regulation capacity. The relatively high dispatch probability means that the energy costs of conventional charging can be avoided. In this way, drivers are able to draw some of their power practically free of charge. The technical effort and the investments in the infrastructure are relatively small. Battery degradation does not occur since the batteries are not additionally discharged. The tertiary control market is less attractive. The necessary investments are identical, but less money can be earned due to the lower dispatch probability.

Summary

Providing negative secondary regulation capacity is the best way to participate in the regulation markets under present conditions in Germany. Primary regulation could be a possible option if frame conditions were altered. Alongside the economic advantages, the prequalification requirements already plan for pooling generation units to provide secondary regulation capacity[20] in contrast to those for providing primary regulation. Since this type of regulation energy is mainly called for at night, it matches the typical behavior pattern of vehicle drivers, who tend to re-charge their vehicle after the final trip of the day. Against the background of expanding renewable energies in Germany and the greater difficulties associated with predicting and planning this energy supply, electric cars could make an important contribution to integrating renewable energies.

Through its simplified way of looking at things, the static model offers the possibility to compare several options with each other and to identify a target market. Since many factors of the model (standing vehicles, prices, load curves) change dynamically over the course of the day, the obvious thing to do would be to examine the most promising options in more detail in a dynamic simulation.

3.8 V2G market volume

In the case of significant market penetration, the question of the market volume for ancillary services will become more relevant. The volume of the German control markets estimated by the German Transmission System Operators German Transmission System Operators, 2009 for capacity C_{market} and energy E_{market} is shown in Table 2-1.[21]

In order to estimate the maximum number of vehicles participating in the control market, a 100% market share is assumed. In the previous computation, P denotes the power that one vehicle can provide for ancillary services. The computation already considers two constraints.

1. The vehicle needs to be able to guarantee the power for a certain period of time (dispatch time t_{disp}).
2. Since there may be multiple demands per day for ancillary services, the contract-to-dispatch ratio also needs to be considered ($R_{d\text{-}c}$).

A cross-check whether the vehicles can provide the energy E_{market} is therefore not required and the number of vehicles V_{market} necessary to provide capacity and energy can be computed based on C_{market} as denoted in Eq. (3-22.

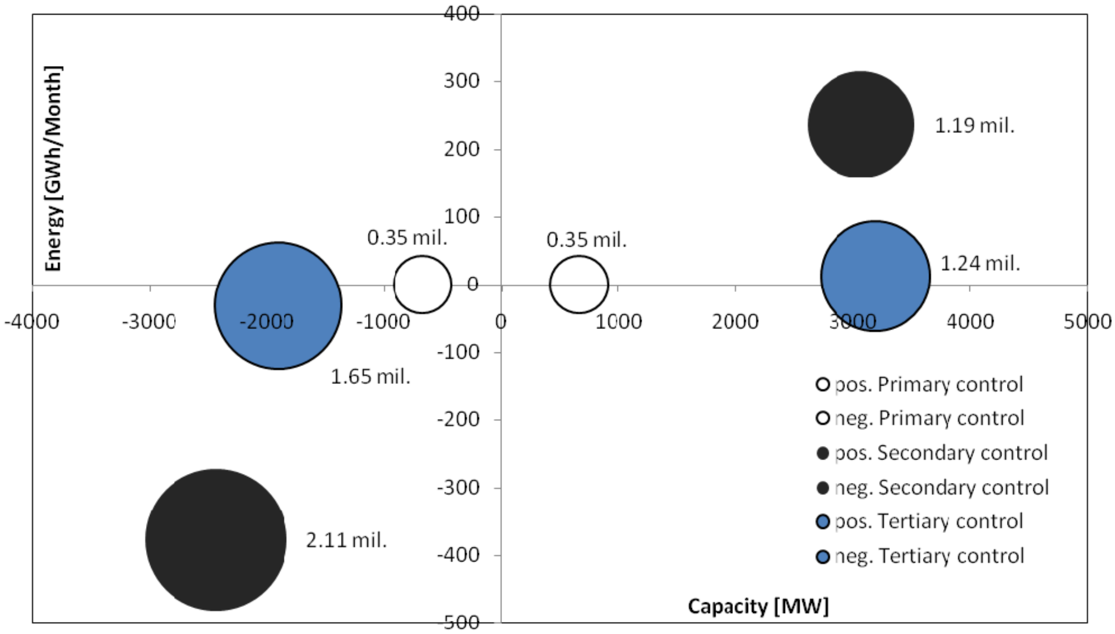
$$V_{market} = \frac{C_{market}}{P} \qquad (3\text{-}22)$$

20 Compare German Transmission System Operators (2009).

21 Primary control $t_{dis} = 0.25\ h$, secondary control $t_{dis} = 1\ h$ and tertiary control $t_{dis} = 4\ h$

The results of the market volume analysis for vehicles with a PHEV battery[22] are summarized in Figure 3-1. The most profitable markets (secondary and positive primary control) have a low volume. In total, theoretically, approximately 2.46 million vehicles or 5% of German passenger vehicles could participate in the primary and negative secondary control market. This result indicates the limitation for the most profitable V2G-markets, especially if competition with other actors is assumed.

Figure 3-1: Control market volume for PHEV (14 kWh) in Germany



Own calculations based on data from German Transmission System Operators (2009). Number at the bubble indicates the maximal number of vehicles in the market.

The tertiary control market has a high market volume, but lower investment returns. The calculated total volume of all German control markets is 6.54 million or about 15% of all passenger vehicles.

22 A battery size of 14 kWh is assumed for PHEV.

4 Dynamic simulation approach: Value of vehicle-to-grid power for regulation

4.1 Methodology

The static model was extended in order to consider driving behavior across the week in the analysis of the V2G benefits. Instead of using average daily values for driving and idle times, the power that one vehicle can provide for ancillary services is computed in a dynamic simulation. Furthermore, the target group for electric vehicles, which has been studied previously (Biere/Dallinger et al. 2009), is used to determine driving behavior. This group is significantly different to the group of average users.

We use a Monte Carlo simulation approach, simulating a pool of vehicles on a certain weekday and repeating this experiment 500 times in order to get an insight into the variance of the results.

For the one-day simulation, the approach can be divided into two steps:

- First, the driving behavior of BEV and PHEV users is simulated. The vehicles enter the system after their last trip of the day and they leave it with the first trip on the next day. The battery of each vehicle and its state of charge are combined in a virtual pool battery. The simulation result is the energy that could be charged to the pool battery at each point in time on that specific day (regulation down).
- Second, the power that could be offered by the vehicle pool that day is computed. The bid is subject to the regulations for the providers of ancillary services.

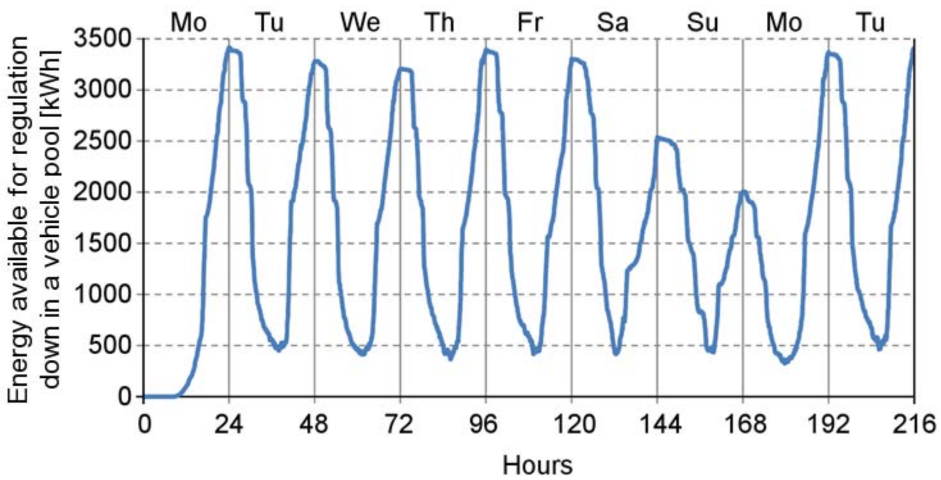
The one-day simulation is repeated 500 times.

Step 1: Simulation output

Changing the simulation time from one day to nine days gives an overview of the characteristics of each weekday. Figure 4-1 shows the result of the first step in a long-term simulation. The large variation in the pool battery across the nine days indicates that considering the characteristics of the different weekdays and the variation throughout the day yields significantly different results compared to a static, average value approach.

In order to avoid the initialization bias in the one-day simulation, the starting point is set 48 hours before the actually simulated day and the data of the first 48 hours is truncated.

Figure 4-1: State of charge in a vehicle pool battery of 1000 vehicles. Vehicle pool consists of 10% City-BEVs (20 kWh) and 90% PHEVs (16 kWh)



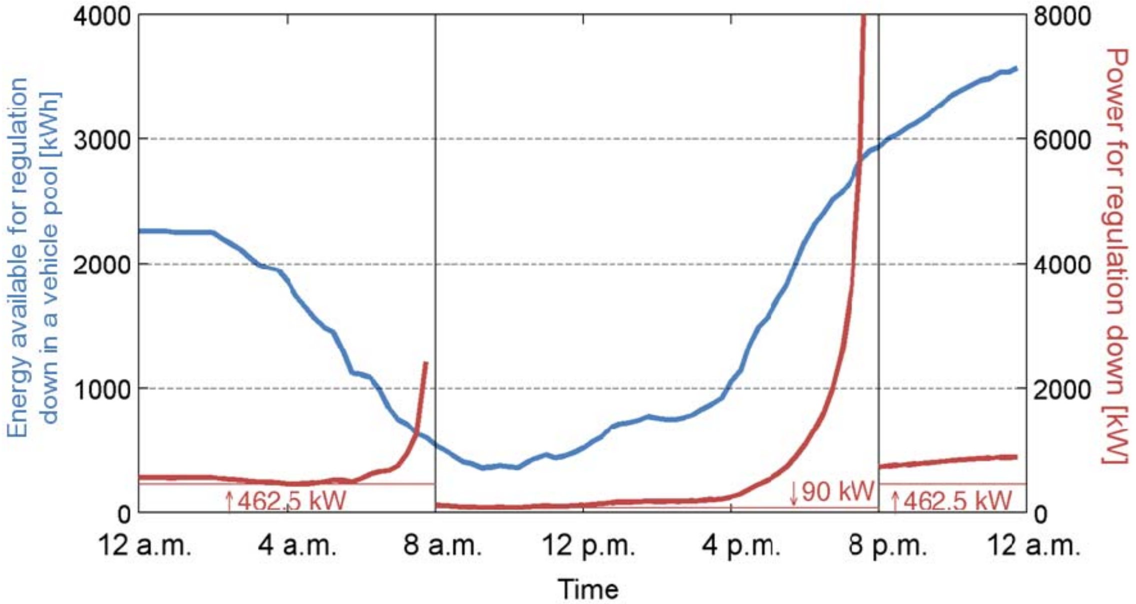
Assumptions about driving behavior based on Biere/Dallinger et al. 2009 and MiD 2002

Step 2: Computation of the power for regulation

The power for regulation can be computed using the results from step one. The required dispatch time for supplying power t_{disp} is assumed to be four hours as in the static approach (secondary and tertiary market). For each point in time throughout the day it is assumed that the energy is constant and the possible power for ancillary services is computed. Weekdays are divided into a prime time period (Hauptzeit) (from 8 a.m. to 8 p.m.) and secondary time period (Nebenzeit) (from 8 p.m. to 8 a.m.). A bid is valid for one of the two time periods. The computation assumes that the pool only needs to provide power until the end of the time period although t_{disp} may be larger. Therefore the power increases at 8 a.m. and 8 p.m. in the example shown in Figure 4-2. Formula (4-1) describes this interrelation.

$$Power_t = \frac{Energy_t}{min\{4h, t_{end} - t\}} \tag{4-1}$$

Figure 4-2: Available regulation power and energy for a vehicle pool with 1000 vehicles on a Monday



Assumptions about behavior based on Biere/Dallinger et al. 2009 and MiD 2002

Since the bid is valid for the whole time period, the minimum power available throughout the period determines the amount of regulation power that could be offered by the pool on that specific day. The example in Figure 4-2 results in 90 kW in the prime time and 462.5 kW in the secondary time period. As most vehicles are used throughout the day and are not able to provide V2G services, we focus on the secondary time for providing regulation power.

4.2 Results of the dynamic approach

In order to get an insight into the variance of the results, the one-day simulation was repeated 500 times and the results evaluated statistically.

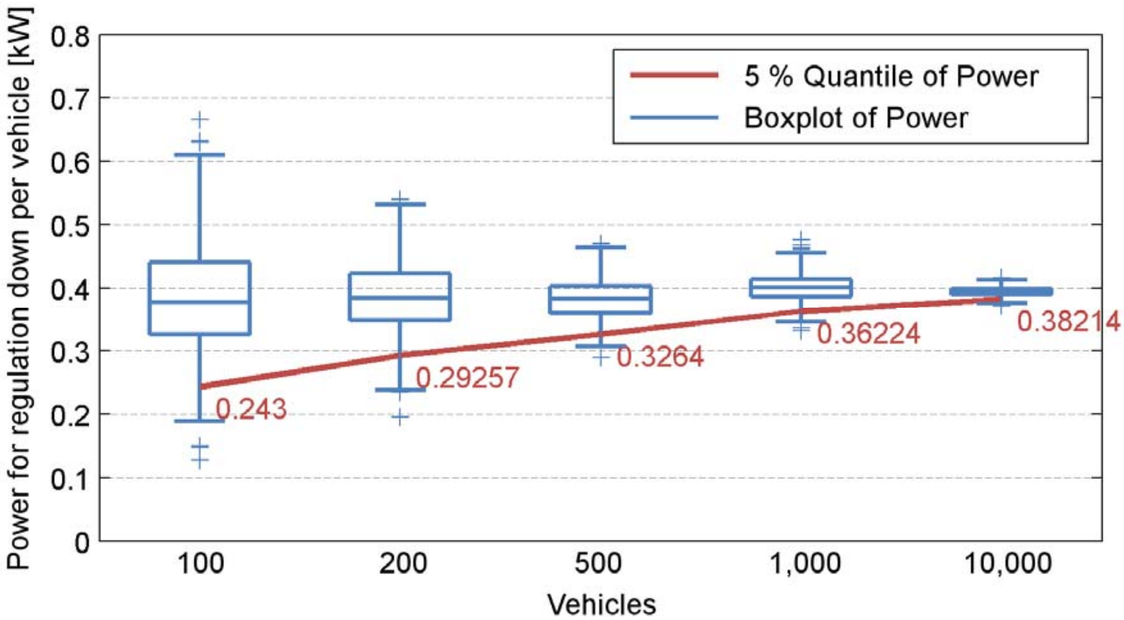
Impact of the pool size

Figure 4-3 shows the variation in regulation power (across the 500 iterations) that a pool of a certain size could provide per vehicle. It can be observed that the power converges towards a fixed value with increasing pool size. A large number of vehicles can even out the variation in the driving behavior of each individual and therefore provide more regulation power per vehicle.

It is postulated that the pool needs to be able to provide the offered regulation power for 95% of all days (iterations). This provides additional security since it is unlikely that ancillary power would be demanded at the weakest point in time on one of the 5% uncertain days. Therefore the capacity that a pool of a certain size could offer is assumed to be the 5% quantile of the sample.

A pool with 10,000 vehicles can already determine the power per vehicle with a high degree of certainty.

Figure 4-3: Regulation power for one vehicle on a Monday in the secondary operation time



Assumptions about behavior based on Biere/Dallinger et al. 2009 and MiD 2002

Impact of the duration of an offer

According to the current requirements for the providers of ancillary power, an offer placed in the secondary control market is valid for the prime or secondary time period of one month. Since driving behavior depends mainly on the weekday concerned, this requirement is a strong restriction and leads to an inefficient usage of the pool's capabilities.

Table 4-1 shows the high correlation between weekday and regulation power per vehicle. The offer for one month is limited by the relatively low power available at the weekend. For example, a pool of 100 cars could only offer 34 W per vehicle at the weekend, although it would be able to provide more than ten times this amount from Tuesday till Friday. Changing the requirements would enable the pool operator to make more efficient use of the pool's capabilities.

Table 4-1: Regulation power per vehicle for the secondary time depending on the pool size and weekday using a dispatch time of four hours

Pool size	Mo	Tu - Th	Fr	Sa	Su	Minimum of all weekdays
[Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]
100	243	508.8	501.7	34	64	34
1,000	362.2	629	612.1	77.9	112.1	77.9
10,000	382.1	663.2	644.7	100	135.9	100

If the offers could be differentiated depending on the weekday, the average power across the week could be increased by between 360 and 900%. Smaller pools would profit from a weekday-dependent offer more than large ones.

Table 4-2: Increase of power for the secondary time after differentiation of the offers depending on the weekday

Pool size	[Veh.]	100	1,000	10,000
Original regulation power	[W/Veh.]	34	77.9	100
Average regulation power after differentiation of weekday	[W/Veh.]	338.4	435.9	464.6
Increase of power		895 %	460 %	365 %

Impact of the required dispatch time

Calculating the power for regulation in step 2 is based on the currently required dispatch time of four hours. Reducing the dispatch time for a vehicle pool could increase the regulation power and facilitate participation in the regulation markets.

A decrease of the dispatch time t_{disp} by factor $a, a \in (0,1)$ yields higher power. The relation between the dispatch time and the power is not reciprocally proportional as might be expected. The increase in power depends on the location of the old and new minimum power across the time period. For instance, decreasing the dispatch time from four to two hours ($a = 0.5$) does not necessarily result in doubling the power. Formula (4-2) shows the relation between power and dispatch time.

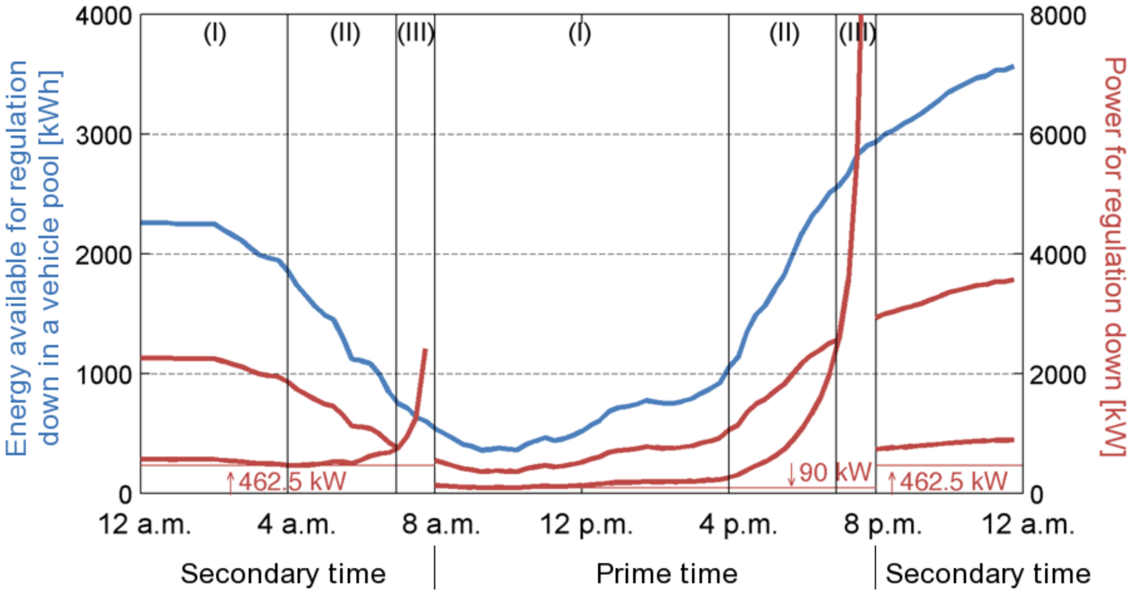
(I)

(II) (4-2)

(III)

Figure 4-4 illustrates the effect of decreasing the dispatch time from four hours to one hour ($a = ¼$).

Figure 4-4: Increase in power for a pool of 1000 vehicles by reducing the dispatch time on a Monday



The lower red line represents the power for a dispatch time of 4 hours and the upper red line the power for a dispatch time of 1 hour.

In the secondary time period, the minimum power is located in section (II) after the decrease in the dispatch time. In section (II) the difference in power for regulation is not reciprocally proportional. Therefore, the power increase is smaller than four times the previous power. In the prime time period, the minimum before and after the decrease is located in section (I). In this section, the power difference is reciprocally proportional and is therefore four times higher than with a dispatch time of 4 hours.

Table 4-3 shows the power per vehicle for each weekday after reducing the dispatch time to one hour. The relative increase compared to Table 4-1 which shows the results based on four hours is given in brackets.

Table 4-3: Regulation power per vehicle for the secondary time period depending on the pool size and weekday using a dispatch time of one hour

Pool size	Mo	Tu - Th	Fr	Sa	Su	Minimum of all weekdays
[Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]	[W/Veh.]
100	312 (28 %)	696 (37 %)	752 (50 %)	136 (300 %)	256 (300 %)	136 (300 %)
1,000	555.2 (53 %)	965.6 (54 %)	1017.2 (66 %)	311.6 (300 %)	448.4 (300 %)	311.6 (300 %)
10,000	626.2 (64 %)	1110.6 (67 %)	1169.6 (81 %)	400 (300 %)	543.7 (300 %)	400 (300 %)

On Saturdays and Sundays, the minimum capacity providing regulation down is located in section (I) and the power could be increased by 300%. The weekend is the limiting period for the entire monthly offer. If the offers were not distinguished by weekdays, the pool could provide four times the power. If both changes were realized at the same time, i.e. differentiation by weekday and decrease in the dispatch time, the average capacity per offer would increase but by less than four times because the minimum power on weekdays is in section (II).

Value of vehicle-to-grid power for regulation (negative secondary control market in the secondary operation time)

The value of vehicle-to-grid power supplied by a vehicle pool strongly depends on the pool size and the requirements on the markets for ancillary power.

Table 4-4 shows the potential profit per vehicle and year excluding the administration costs of the pool operator under different conditions and pool sizes. It is assumed that a pool consists of 90% PHEV and 10% BEV.[23] The impact of the vehicle technology is relatively low because the maximum range is rarely exceeded. The result shows that it is not economical to provide ancillary power from electric vehicles under today's circumstances.[24]

Table 4-4: Potential power and value of V2G per vehicle and year under different conditions and pool sizes

		Differentiation of offers depending on the weekday			
		No		Yes	
		100 Veh.	10,000 Veh.	100 Veh.	10,000 Veh.
Decrease of the required dispatch time from 4 to 1 hour.	No	- 4.25 € (34 W)	9.40 € (100 W)	58.62 € (338.4 W)	84.88 € (464.6 W)
	Yes	16.85 € (136 W)	71.44 € (400 W)	93.36 € (506.3 W)	168.01 € (867.3 W)

Color codes indicate profitability:
Red: not profitable, yellow: may be profitable in the future, green: profitable.

If the user already has a contract for his vehicle with an energy supplier who installs a smart meter and provides the monthly accounting anyway, the additional costs for providing V2G services may be negligible. In this case or if energy prices increase significantly (and "free charging" via regulation down becomes very attractive), participating in the markets for regulation could already become economical, even if the suggested requirement changes were not fully implemented. The corresponding scenarios are marked in yellow in Table 4-4.

Generally, it is favorable to integrate many vehicles in one pool in order to even out the stochastic behavior of the individuals and thus allow for better forecasts of the possible regulation power.

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23 Wietschel/Dallinger et al. (2008): The Fraunhofer ISI evaluated different scenarios on the diffusion of electric vehicles in Germany. The "ISI Dominance Scenario" postulates that 98% of the electric vehicles in the year 2020 will be PHEV. This fraction will decrease to 86% in the year 2030.
Biere/Dallinger et al. (2009): A different study of the first users of electric vehicles assumes that the fraction of PHEV will be between 64 and 86% in 2020. Since there is a large uncertainty about which technology will dominate in the future, this study assumes a fraction of 90% PHEV and 10% BEV.

24 No differentiation of weekdays and a required dispatch time of four hours.

If the suggested changes of decreasing the dispatch time and integrating a weekday-based differentiation of the offers were implemented, a large vehicle pool could already be economical even at today's energy prices.

4.3 Comparison of the results to the static approach

The results in Table 4-1 show that the power is highly overestimated using the static approach. In the market for negative secondary control, the model estimates that a BEV could provide 0.99 kW and a PHEV 1.15kW (Table 3 1 and Table 3 2).

There are two reasons for the different results:

1. *Dynamic change of the system*
   The static model uses the daily maximum power for the calculations. The power $(P_{Fzg,Neg})$ results from the state of charge after the last trip of the day and the required dispatch time (3-5). Considering the state of charge at 12 a.m. when most of the vehicles have not started charging yet, the simulation model provides similar values to the static model. Figure 4-5 shows a maximum of 3500 kWh for a pool of 1000 vehicles, which corresponds to 3.5 kWh per vehicle. Using a required dispatch time of four hours at this point in time results in a power of

   $$P = \frac{3{,}5\ kW}{4} = 0{,}875\ kW$$

   The figure also indicates the power that could be guaranteed across the whole day. Applying this dynamic view yields a smaller power of 0.462 kW.

2. *Random system variation*
   A larger pool can compensate stochastic variations and ensure a larger regulation power per vehicle. The static model uses deterministic inputs and delivers the same results for small and large pools. The simulation takes this variation into account and therefore shows smaller results than is the static model based on average values.

The static model is a reasonable way to identify the most suitable market for the participation of electric vehicles. Since electric vehicles have a variable availability, they are not comparable to conventional energy storage systems. Therefore the dynamic driving behavior should be included in the computation of possible regulation power and the evaluation of the potential profits.

5 Conclusion

The analysis of V2G services of electric vehicles reveals that incomes can be generated in the German electricity market, especially in the negative secondary control market. In contrast to the US studies, the delivery of electricity to the grid is not economic in the German case and under today's conditions. This is mainly because of the higher dispatch time (operating availability), which is necessary to pre-qualify as a regulation service supplier, and the reduced power a vehicle can therefore provide for regulation. When real-life driving patterns are taken into account for a certain time period, the potential income from participating on the regulation markets is significantly reduced in comparison to approaches based on average values. The conclusions in detail are:

- *A dynamic approach is required since driving behavior has a strong impact on the participation in the regulation markets.*
  For acceptance reasons, the vehicle owner's mobility should not be constrained when offering V2G services. This is an essential difference to the current technologies for ancillary power. Pump storage systems and gas turbines are stationary systems, whose major purpose is to generate electrical power. Electric vehicles primarily provide mobility and, only as a by-product, V2G services. Considering the dynamic driving behavior when estimating the V2G value leads to significantly different results compared to a static approach which focuses on average values.

- *The potential regulation power offered varies across the day. A large vehicle pool can compensate the stochastic variation of the individual drivers.*
  The power offered by a vehicle pool has to be guaranteed for a certain time period (dispatch time) and the energy has to be available at each point in time during the specific bidding period. The supply of regulation power is therefore computed as the minimum of the potential offers across the day. A larger pool compensates for stochastic variations and guarantees a larger regulation power per vehicle. This provides an essential advantage for larger pools up to a certain size. For a pool of 10,000 vehicles, these variations are already very low and further increases in pool size do not deliver any more significant improvements in the amount of regulation power per vehicle.

- *The market for negative secondary control in the secondary time period offers the best potential for electric vehicles.*
  The static approach reveals that the market for negative secondary control offers electric vehicles the most advantages. The simulation provides evidence that a pool can offer more ancillary power in the secondary than in the prime time period because most cars are connected to the grid at night. Furthermore, the demand for regulation down is larger during this secondary period, which offers the highest potential for "free charging". A combined offer in both prime and secondary periods would not necessarily improve the results since energy that was charged during the day cannot be charged during the secondary time period and the possible regulation power offered would decrease. Therefore participation should be limited to the secondary time period.

- The market volume for regulation is limited. Assuming a 100% market share of GC-BEVs in the promising control markets (primary regulation and negative secondary control[25]) results in a volume of only 2 million vehicles when using average driving behavior. The actually achievable market share is probably much lower. The argument that a higher share of intermittent renewable supply will increase the required control capacity in the future is well founded. However, because of the increasing accuracy in the forecast for intermittent generation and intraday electricity markets, the volume of this increase is probably not significant (Holttinen/Meibom et al. 2008).

- *For conventional providers of ancillary power, integrating a vehicle pool in their portfolio could create synergies.*
  The providers could establish a priority ranking during the regulation process that favors the use of the vehicle pool and only makes use of conventional installations if the power provided by the electric vehicles is not sufficient. It could, for instance, be of advantage to charge the vehicle pool first before reducing the power of a generating plant. The electric vehicles should be charged before their first trip of the next day either by regulation or conventional charging. It is beneficial to shift the charging process to a point in time with excess power where regulation down is triggered. Reducing the power of a generating plant as an alternative way to balance the supply usually leads to a reduction in efficiency since the power plant is then no longer operated at its optimal power output. In addition, the feed-in location can be

25 See results of static approach.

controlled very precisely. These synergies that result from linking the control of electric vehicles and conventional generating plants are not captured in the calculated V2G value and would create additional benefits.

- *Flexible requirements for the suppliers of regulation power could greatly facilitate the integration of electric vehicles in the markets for ancillary power.*
  The requirements are defined in the Transmission Code of the German Transmission System Operators (VDE Association for Electrical, Electronic & Information Technologies 2007). They were drawn up for stationary systems, whose primary purpose is to generate electrical power. In order to capitalize on the full potential of electric vehicles for V2G, the requirements would have to be adjusted to account for the time- and weekday-dependent behavior of the vehicle owners. If requirements were adapted, 2.8 million cars would be sufficient to provide the entire demand for negative secondary control in the secondary operation time. This figure corresponds to the expected number of GC-BEVs in Germany between the years 2022 and 2030 (Wietschel/ Dallinger et al. 2008).

This study has shown that electric vehicles have a substantial potential for V2G services. The increase in the amount of energy from renewable sources reduces the ability to balance the energy markets from the supply side and creates a greater demand for regulating power. Electric vehicles can be used to support control of the grid through demand side management. Modern information and communication technology, which is being increasingly integrated into the grid infrastructure, enables the coordination of distributed energy producers and consumers. These new technologies are the foundation for integrating electric vehicles. The vehicle owners have the possibility to reduce their energy costs without limiting their mobility and without degradation of the battery. Thus, V2G services can facilitate the diffusion of electric vehicles and improve their economic efficiency in comparison to conventional vehicles.

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