Vehicle-to-Grid Regulation Reserves Based on a Dynamic Simulation of Mobility Behavior

David Dallinger, Daniel Krampe, and Martin Wietschel

Abstract—This study establishes a new approach to analyzing the economic impacts of vehicle-to-grid (V2G) regulation reserves 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 ancillary services and provides insights into the necessary size of vehicle pools and possible adaptations required in the regulation market to render V2G feasible. In the static approach 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 reserves. A Monte Carlo simulation using stochastic mobility behavior results in a 40% reduction of the power available for regulation compared to the static approach. 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 each individual’s driving behavior. 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.

Index Terms—Ancillary services, demand side management, electric vehicles, regulation reserves, vehicle-to-grid.

NOMENCLATURE

- $c_{\text{cap}}$: Capital costs
- $c_{\text{var}}$: Variable costs due to battery degradation
- $c_{\text{en}}$: Variable costs from energy withdrawal
- $c_{\text{fix}}$: Fixed costs
- $C_{\text{life}}$: Cycle life (battery)
- $C_{\text{market}}$: Market volume capacity
- $c_{\text{elec}}$: Electricity costs for private customers
- $c_{\text{reg}}$: Annual costs regulation
- $c_{\text{var}}$: Variable costs
- $c_{\text{Veh}}$: Energy consumption per vehicle
- $d$: Interest rate
- $d_{\text{d}}$: Daily distance
- $\text{DoD}$: Depth of discharge
- $\text{DoD}_{\text{max}}$: Maximum depth of discharge
- $d_{\text{fb}}$: Range buffer
- $E_{\text{disp}}$: Energy dispatched for regulation
- $E_{\text{market}}$: Market volume energy
- $E_{\text{store}}$: Energy storage (battery)
- $E_{\text{life}}$: Lifetime energy throughput (battery)
- $n$: Battery lifespan in years
- $p_{\text{Batt}}$: Battery price
- $p_{\text{Batt.kWh}}$: Battery price per kWh
- $p_{\text{cap}}$: Price for regulation capacity
- $p_{\text{elec}}$: Price for regulation energy
- $P$: Power
- $P_{\text{max}}$: Maximum power limit
- $P_{\text{Veh.Neg}}$: Power per vehicle providing negative regulation
- $P_{\text{Veh.Pc}}$: Power per vehicle providing primary control
- $P_{\text{Veh.Pos}}$: Power per vehicle providing positive regulation
- $r_{\text{cap}}$: Revenue from regulation capacity per year
- $R_d$: Dispatch to contract ratio
- $R_{\text{elec}}$: Electric driving share
- $r_{\text{elec}}$: Revenue from regulation energy per year
- $r_{\text{elec.Neg}}$: Revenue from negative regulation energy per year
- $r_{\text{elec.Pos}}$: Revenue from positive regulation energy per year
- $r_{\text{reg}}$: Revenue from regulation per year
- $r_{\text{reg.Pc}}$: Revenue from regulation primary control per year
- $r_{\text{reg.sec}}$: Revenue from regulation secondary control per year

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I. INTRODUCTION

The enormous growth of intermittent renewable energy sources (RES) in countries like Spain, Germany, and Denmark and the further expected increase in RES necessitates new thinking in terms of smarter energy systems. The regulation capacity needed for a reliable energy supply increases with a higher share of intermittent RES. The opposite situation—a very low operating capacity of conventional power plants which can react within seconds to power failures will also become more likely in the future. Grid-connected battery electric vehicles (GC-BEVs) are regarded as a promising option for balancing power in the electricity system and providing ancillary services [1]. Further, these novel players in the regulation market can create more competition and improve the efficiency of regulation. Evidence is accumulating that batteries combined with power electronics can react as very fast regulation units. In a first pilot test, GC-BEVs are being used to provide frequency control [2].

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 [1]–[5]. 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 regulation. 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., assume the vehicle is parked for 23 h a day. It is obvious, however, that the available battery capacity varies over different hours and days of the week depending on mobility behavior. For instance, 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, exclusively 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 [6] is used to find the most profitable ancillary service in Germany. Finally, a dynamic simulation demonstrates the impact of mobility behavior on V2G services.

II. DATA BASIS

A. German Markets for Ancillary Services

The European Network of Transmission System Operators for Electricity (ENTSO-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 power system 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 s and provided for up to 15 min. 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 min after an incident. The transmission system operator (TSO) in the control area is responsible for frequency 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 min to 1 or 2 h. These are primarily used to free up the secondary reserve in a balance situation and as a supplement to the other reserves in case of large incidents (for detailed information see [7]).

Our calculations used the average 2008 market prices from the four German TSOs. Table I 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, dispatch probability for primary control is not specified (n.s.). For the calculation a value of 10% is taken.

### TABLE I

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary control</td>
<td>400</td>
<td>22.02</td>
<td>1.00</td>
<td>0.01</td>
<td>0.66</td>
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<tr>
<td>Secondary control</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Tertiary control</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

1For example, plug-in hybrid vehicles (PHEVs) or purely electric vehicles (EVs).

250 Hertz Transmission GmbH (E.ON), Amprion GmbH (RWE), Transpower Stromübertragungs GmbH (Vattenfall), and EnBW Transportnetze AG.

3Dispatch probability for primary control is not specified (n.s.). For the calculation a value of 10% is taken.
a distinction is made between positive and negative control as well as 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 the 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 prequalify and is therefore essential for the bidding capacity of GC-BEVs. Since there are no defined requirements for battery storage, it is assumed that the operating availability in the secondary regulation and tertiary markets equals 4 h. This corresponds to the rules for pump storage power stations. The operating availability for conventional power plants is 12 h. 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 [4].

The maximum power limit 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. In the static approach no distinction 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 German electricity price of 21 cents/kWh for private customers is taken as the power price for conventional charging.

### B. Vehicle and Infrastructure

The vehicle data are taken from [8]. Since the study revealed that only PHEVs and so-called “City-BEVs” (BEVs with small batteries and limited range) will be economical in 2020, this analysis focuses on these two types of cars [8].

The cost data for the infrastructure (meter and communication system) are taken from [4]. For the bidirectional power electronics (power inverter, buck-boost converter and grid monitoring), the prices of power inverters used in photovoltaic systems can be taken as a guideline. 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 a price of 0.15 euros/W, the investment in the bidirectional electronics would be in the range between 270 and 390 euros. The assumed prices are shown in Table III.

### C. Driving Behavior

The relevant data sets of the 2002 mobility study [11] are filtered out for this study using the selection criteria from [8]. 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. Fig. 1 illustrates the probability for journeys in Germany on a typical Monday for full-time employees.

For a more detailed analysis, see [12].

The probabilities for the kilometers travelled differ slightly between the segments of PHEVs and BEVs (Fig. 2). The probabilities for the kilometers travelled differ slightly between the segments of PHEVs and BEVs (Fig. 2).

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To calculate the annuities, an interest rate (r) 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 still unclear and therefore not taken into account in this study.

### TABLE II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PHEV</th>
<th>City-BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum depth of discharge</td>
<td>DoDₘₜₜₓ</td>
<td>80%</td>
</tr>
<tr>
<td>Charging/discharging efficiency</td>
<td>φₜₛᵥ</td>
<td>92%</td>
</tr>
<tr>
<td>Charging and discharging efficiency</td>
<td>φₜₜₜₜ</td>
<td>85%</td>
</tr>
<tr>
<td>Interest rate</td>
<td>d</td>
<td>5%</td>
</tr>
<tr>
<td>Battery lifespan</td>
<td>n</td>
<td>12</td>
</tr>
<tr>
<td>Battery price per kWh</td>
<td>pₕₙₜₜₜₜ</td>
<td>337</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>Eₙ</td>
<td>14</td>
</tr>
<tr>
<td>Total battery price</td>
<td>pₙₚₜₜₜₜ</td>
<td>4714 €</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>cₜₚₜₜₜₜ</td>
<td>0.16</td>
</tr>
<tr>
<td>Electric driving share**</td>
<td>Rₙₚₜₜₜₜ</td>
<td>60%</td>
</tr>
</tbody>
</table>

* [9] The value represents the best-case cost reduction for batteries. ** Fraction of vehicle km traveled on electricity.
Fig. 2. Probability for different route ranges. Data for BEVs and PHEVs is filtered out using the selection criteria from [8]. Data basis: [11].

TABLE IV
DATA ON DRIVING BEHAVIOR

<table>
<thead>
<tr>
<th>Data on driving behavior</th>
<th>PHEV</th>
<th>City-BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing time between last–first trip $t_{plug, day}$ [h]</td>
<td>16.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Daily kilometers $d_d$ [km]</td>
<td>44.2</td>
<td>33.16</td>
</tr>
<tr>
<td>Range buffer $d_{rb}$ [km]</td>
<td>0</td>
<td>74</td>
</tr>
</tbody>
</table>

Source: Own calculation, data basis: [11]

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.\(^7\)

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. For City-BEVs, the 90% quantile of the individual recorded trips is calculated and taken as a range buffer ($d_{rb}$). 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 IV.

III. STATIC APPROACH: VALUE OF VEHICLE-TO-GRID POWER FOR REGULATION

Section III follows [6].

A. 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 ($d_d$). 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 ($\eta_{ch,v}$). The energy per vehicle which is available for delivery back into the grid (positive energy)\(^8\) is calculated as follows:

$$W_{pos} = (E_s \cdot DoD - (d_d + d_{rb}) \cdot R_{el} \cdot c_{veh}) \cdot \eta_{ch,v}.$$  \hspace{1cm} (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.

$$W_{neg} = \frac{d_d \cdot R_{el} \cdot c_{veh}}{\eta_{ch,v}}.$$  \hspace{1cm} (2)

B. 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 ($t_{disp}$) 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 dispatch events is sufficient to recharge the energy withdrawn. Where negative regulation energy is concerned, the dispatch probability is taken into account additionally ($R_{disp-e}$—Dispatch to contract ratio [6]). 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

$$P_{Veh, Pr} = \min \left\{ \frac{\min \{W_{pos}, W_{neg}\}}{\max \{t_{disp}, t_{plug, day} \cdot R_{el} \cdot c\}}, P_{Max} \right\}. \hspace{1cm} (3)$$

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

$$P_{Veh, Pr, pos} = \left\{ \frac{W_{pos}}{E_{plug}} \right\} \cdot P_{Max}. \hspace{1cm} (4)$$

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

$$P_{Veh, Ne, neg} = \left\{ \frac{W_{neg}}{\max \{t_{disp}, t_{plug, day} \cdot R_{el} \}}, P_{Max} \right\}. \hspace{1cm} (5)$$

C. 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. Two hundred fifty\(^9\) days

\(^7\)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.

\(^8\)In German, 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 generation in the power system.

\(^9\)This value represents the working days per year for Germany.
per year and an average standing time between the last and the first journey on a week day are assumed

$$t_{\text{plug}} = 250 \cdot t_{\text{plug\ day}}.$$  \hfill (6)

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

$$E_{\text{disp}} = P_{\text{Veh}} \cdot R_{d-e} \cdot t_{\text{plug}}.$$  \hfill (7)

D. Calculating the Income per Year

The income \(r_{\text{reg}}\) is made up of the income due to providing regulation capacity \(r_{\text{cap}}\) and the income from supplying regulation energy \(r_{\text{ele}}\). The price for regulation capacity \(p_{\text{cap}}\) 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

$$r_{\text{cap}} = \frac{p_{\text{cap}}}{24} \cdot P_{\text{Veh}} \cdot t_{\text{plug}}.$$  \hfill (8)

For positive balancing (secondary and tertiary control), the price for energy \(p_{\text{ele}}\) shows the amount the provider receives for the dispatched electricity

$$r_{\text{ele, pos}} = p_{\text{ele}} \cdot E_{\text{disp}}.$$  \hfill (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 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

$$r_{\text{ele, neg}} = (c_{\text{pne}} - p_{\text{ele}}) \cdot E_{\text{disp}}.$$  \hfill (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

$$r_{\text{reg, PC}} = r_{\text{cap}}.$$  \hfill (11)

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

$$r_{\text{reg, SC and MC}} = r_{\text{cap}} + r_{\text{ele}}.$$  \hfill (12)

E. 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 \(c_{\text{fix}}\) 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 \(c_{\text{cap}}\). The annual costs can be calculated depending on the rate of interest \(d\) and the lifespan \(n\) using the annuity formula

$$c_{\text{fix}} = c_{\text{cap}} \cdot \frac{d}{1 - (1 + d)^{-n}}.$$  \hfill (13)

Variable Costs: The battery is discharged when providing positive regulation energy. Variable costs \(c_{\text{var, pos}}\) result due to battery degradation \(c_{\text{d}}\) and energy withdrawal \(c_{\text{en}}\)

$$c_{\text{var, pos}} = c_{\text{d}} + c_{\text{en}} \cdot E_{\text{disp}}.$$  \hfill (14)

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

$$c_{\text{reg, PC}} = c_{\text{fix}}.$$  \hfill (15)

$$c_{\text{reg, pos}} = c_{\text{fix}} + c_{\text{var}}.$$  \hfill (16)

The costs for withdrawing energy are calculated using the electricity price and the losses when charging and then discharging the battery \(\eta_{\text{ele, conv}}\)

$$c_{\text{en}} = \frac{c_{\text{pne}}}{\eta_{\text{ele, conv}}}.$$  \hfill (17)

F. 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 \(\text{DoD}_{\text{V2G}}\) is calculated. It is assumed that the vehicle is fully charged before every dispatch. Information about the length of a discharge cycle is not yet available. However, it can never be longer than the average total dispatch period per day or the fixed operating availability

$$\text{DoD}_{\text{V2G}} = \frac{P_{\text{Veh}} \cdot \min\{t_{\text{disp}} : 24 \cdot R_{d-e}\}}{E_{\text{a}}}.$$  \hfill (18)

In the second step, the number of cycles over the entire lifespan of the battery \(C_{\text{life}}\) is calculated using the approach of Rosenkranz [13] with a degradation according to [14]

$$C_{\text{life}} = 1331 \cdot \text{DoD}_{\text{V2G}}^{-1}.$$  \hfill (19)

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

$$L_{\text{ET}} = C_{\text{life}} \cdot E_{\text{a}} \cdot \text{DoD}_{\text{V2G}}.$$  \hfill (20)

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

$$d_{\text{d}} = \frac{P_{\text{stat}}}{L_{\text{ET}}}.$$  \hfill (21)

10The regulation energy price for withdrawing negative regulation energy was already considered in the income \(r_{\text{ele, neg}}\).
TABLE V
ECONOMIC EFFICIENCY OF PHEV PARTICIPATION IN REGULATION MARKETS

<table>
<thead>
<tr>
<th>PHEV</th>
<th>Primary control</th>
<th>Positive secondary control</th>
<th>Negative secondary control</th>
<th>Positive tertiary control</th>
<th>Negative tertiary control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity provided $P_{\text{min}}$ [kW]</td>
<td>2.88</td>
<td>2.58</td>
<td>1.15</td>
<td>2.58</td>
<td>1.15</td>
</tr>
<tr>
<td>Depth of discharge V2G $\text{DoD}_{\text{V2G}}$ [%]</td>
<td>5</td>
<td>47</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Income from regulation capacity $r_{\text{om}}$ [€/a]</td>
<td>288.23</td>
<td>130.19</td>
<td>31.02</td>
<td>56.38</td>
<td>12.12</td>
</tr>
<tr>
<td>Income from regulation energy $r_{\text{e}}$ [€/a]</td>
<td>-</td>
<td>98.63</td>
<td>195.20</td>
<td>10.18</td>
<td>20.18</td>
</tr>
<tr>
<td>Total income $r_{\text{om}}$ [€/a]</td>
<td>288.23</td>
<td>228.82</td>
<td>226.22</td>
<td>66.56</td>
<td>32.30</td>
</tr>
<tr>
<td>Fixed costs $c_{\text{f}}$ [€/a]</td>
<td>60.06</td>
<td>54.88</td>
<td>11.28</td>
<td>54.88</td>
<td>11.28</td>
</tr>
<tr>
<td>Variable costs $c_{\text{v}}$ [€/a]</td>
<td>25.25</td>
<td>402.66</td>
<td>-</td>
<td>13.65</td>
<td>-</td>
</tr>
<tr>
<td>Total costs $c_{\text{om}}$ [€/a]</td>
<td>85.31</td>
<td>457.54</td>
<td>11.28</td>
<td>68.53</td>
<td>11.28</td>
</tr>
<tr>
<td>Profit/loss [€/a]</td>
<td>202.92</td>
<td>-228.72</td>
<td>214.94</td>
<td>-1.97</td>
<td>21.02</td>
</tr>
</tbody>
</table>

TABLE VI
ECONOMIC EFFICIENCY OF CITY-BEV PARTICIPATION IN REGULATION MARKETS

<table>
<thead>
<tr>
<th>City-BEVs</th>
<th>Primary control</th>
<th>Positive secondary control</th>
<th>Negative secondary control</th>
<th>Positive tertiary control</th>
<th>Negative tertiary control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity provided $P_{\text{min}}$ [kW]</td>
<td>2.50</td>
<td>1.81</td>
<td>0.99</td>
<td>1.81</td>
<td>0.99</td>
</tr>
<tr>
<td>Depth of discharge V2G $\text{DoD}_{\text{V2G}}$ [%]</td>
<td>3</td>
<td>23</td>
<td>-</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Income from regulation capacity $r_{\text{om}}$ [€/a]</td>
<td>247.78</td>
<td>90.70</td>
<td>26.47</td>
<td>39.28</td>
<td>10.34</td>
</tr>
<tr>
<td>Income from regulation energy $r_{\text{e}}$ [€/a]</td>
<td>-</td>
<td>68.71</td>
<td>166.58</td>
<td>7.09</td>
<td>17.22</td>
</tr>
<tr>
<td>Total income $r_{\text{om}}$ [€/a]</td>
<td>247.78</td>
<td>159.41</td>
<td>193.05</td>
<td>46.37</td>
<td>27.56</td>
</tr>
<tr>
<td>Fixed costs $c_{\text{f}}$ [€/a]</td>
<td>53.57</td>
<td>41.88</td>
<td>11.28</td>
<td>41.88</td>
<td>11.28</td>
</tr>
<tr>
<td>Variable costs $c_{\text{v}}$ [€/a]</td>
<td>12.21</td>
<td>226.61</td>
<td>-</td>
<td>9.27</td>
<td>-</td>
</tr>
<tr>
<td>Total costs $c_{\text{om}}$ [€/a]</td>
<td>65.78</td>
<td>268.49</td>
<td>11.28</td>
<td>51.15</td>
<td>11.28</td>
</tr>
<tr>
<td>Profit/loss [€/a]</td>
<td>182.00</td>
<td>-109.08</td>
<td>181.77</td>
<td>-4.78</td>
<td>16.28</td>
</tr>
</tbody>
</table>

G. 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: Results of the calculations are shown in Tables V and VI.

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 (compare [15]) 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. Because 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.

Positive and negative control 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 positive control after loading the battery with negative 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 a 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 income 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. Alongside the economic advantages, the prequalification requirements already plan for pooling generation units to provide secondary regulation capacity (compare [15]) 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 recharge their vehicle after the final trip of the day.

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. However, since many factors of the model (standing vehicles, prices, load curves) actually change dynamically over the course of the day, we examine the most promising options in more detail in a dynamic simulation (Section III).
Fig. 3. Control market volume for PHEV (14 kWh) in Germany. Own calculations based on data from [15]. Number at the bubble (million vehicles) indicates the maximal number of vehicles in the market.

H. 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 Chapter IV.\textsuperscript{11}

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 ($R_{d-c}$).

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 (22)

$$V_{market} = \frac{C_{market}}{P}.$$  \textbf{(22)}

The results of the market volume analysis for vehicles with a PHEV battery\textsuperscript{12} are summarized in Fig. 3. 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.

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.

\textsuperscript{11}Primary control $t_{dis} = 0.25$ h, secondary control $t_{dis} = 1$ h, and tertiary control $t_{dis} = 4$ h.

\textsuperscript{12}A battery size of 14 kWh is assumed for PHEV.

IV. DYNAMIC SIMULATION APPROACH: VALUE OF VEHICLE-TO-GRID POWER FOR REGULATION

A. Methodology

The static model was extended 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 [8], 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 insights into the variance of the results.

For the one-day simulation, the approach is based on two steps.

1. 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 (negative regulation).

2. 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. The results of the simulation time from one day to nine days gives an overview of the characteristics of each weekday. Fig. 4 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 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 h before the actually simulated day and the data of the first 48 h is truncated.

Step 1: Simulation Output: Changing the simulation time from one day to nine days gives an overview of the characteristics of each weekday. Fig. 4 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 different weekdays and the variation throughout the day yields significantly different results compared to a static, average value approach.

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 4 h 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 \( t_{\text{disp}} \) may be larger. Therefore, the power increases at 8 a.m. and 8 p.m. in the example shown in Fig. 5. Formula (23) describes this interrelation

\[
\text{Power}_t = \frac{\text{Energy}_t}{\min\{4h, t_{\text{end}} - t_1\}}. \tag{23}
\]

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 Fig. 5 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.

**B. 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:** Fig. 6 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.

**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 VII 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 to Friday. Changing the requirements would enable the pool operator to make more efficient use of the pool’s capabilities.

If the offers could be differentiated by 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.

**Impact of the Required Dispatch Time:** Calculating the power for regulation in step 2 is based on the currently required dispatch time of 4 h. 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 \( t_{\text{disp}} \) by factor \( a, a \in (0.1) \) yields higher power. The relation between the dispatch time and 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 4 to 2 h \( (a = 1/2) \) does not necessarily double the power. Equation (24), at the bottom of the page, shows the relation between dispatch time and power.

Fig. 7 illustrates the effect of decreasing the dispatch time from 4 h to 1 h \( (a = 1/4) \). In the secondary time period, the minimum power is located in section (II) of Fig. 7 after the decrease in the dispatch time. In section (II) of Fig. 7 the difference in power for regulation is not reciprocally proportional. Therefore, the power increase is four times smaller than the previous power. In the prime time period, the minimum before and after the decrease is located in section (I) of Fig. 7. In this section, the power difference is reciprocally proportional and is therefore four times higher than for a dispatch time of 4 h.

Table IX shows the power per vehicle for each weekday after reducing the dispatch time to one hour. The relative increase compared to Table VII, which shows the results based on 4 h, is given in brackets.

On Saturdays and Sundays, the minimum capacity providing negative regulation reserves is located in section (I) of Fig. 7 and the power could be increased by 300%. The weekend is the limiting period for the entire monthly offer. If the offers were distinguished by weekdays, the pool could provide four times the amount of 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 still increase, but by less than four times because the minimum power on weekdays is in section (II) of Fig. 7.

**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 X 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. 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.14

If the user already had a contract for his vehicle with an energy supplier prepared to install a smart meter and provide the monthly accounting, the additional costs for providing V2G services may be negligible. In this case, or if energy prices increase significantly (and “free charging” via negative regulation becomes very attractive), participating in the markets for regulation could already be economical, even if the suggested requirement changes were not fully implemented. The corresponding scenarios are marked yellow in Table X.

---

**Table IX**

<table>
<thead>
<tr>
<th>Pool size</th>
<th>Mo</th>
<th>Tu - Th</th>
<th>Fr</th>
<th>Sa</th>
<th>Su</th>
<th>Minimum of all weekdays</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>312 (28%)</td>
<td>696 (37%)</td>
<td>752 (50%)</td>
<td>136 (300%)</td>
<td>256 (30%)</td>
<td>136 (300%)</td>
</tr>
<tr>
<td>1,000</td>
<td>555.2 (53%)</td>
<td>965.6 (54%)</td>
<td>1,017.2 (66%)</td>
<td>311.6 (300%)</td>
<td>448.4 (30%)</td>
<td>311.6 (300%)</td>
</tr>
<tr>
<td>10,000</td>
<td>626.2 (64%)</td>
<td>1,110.6 (67%)</td>
<td>1,169.6 (81%)</td>
<td>400 (300%)</td>
<td>543.7 (30%)</td>
<td>400 (300%)</td>
</tr>
</tbody>
</table>

---

**Equation (24)**

\[
\begin{align*}
\text{Power}_{t_{\text{end}} - t_{\text{disp}}} &= \begin{cases} \\
\frac{\text{Energy}_{t_{\text{end}} - t_{\text{disp}}}}{\text{Power}_{t_{\text{end}} - t_{\text{disp}}}} & t_{\text{disp}} < t_{\text{end}} - t \\ \frac{\text{Energy}_{t_{\text{end}} - t_{\text{disp}}}}{\text{Power}_{t_{\text{end}} - t_{\text{disp}}}} & t_{\text{disp}} < t_{\text{end}} - t \leq t_{\text{disp}} \\ \frac{\text{Energy}_{t_{\text{end}} - t}}{\text{Power}_{t_{\text{end}} - t}} & t_{\text{end}} - t \leq t_{\text{disp}} \cdot a \end{cases} \\
\text{[I]} \text{ [see Fig. 7]} & \text{[II]} \text{ [see Fig. 7]} & \text{[III]} \text{ [see Fig. 7]}
\end{align*}
\]
DALLINGER et al.: VEHICLE-TO-GRID REGULATION RESERVES BASED ON A DYNAMIC SIMULATION OF MOBILITY BEHAVIOR

<table>
<thead>
<tr>
<th>TABLE X</th>
</tr>
</thead>
<tbody>
<tr>
<td>POTENTIAL POWER AND VALUE OF V2G PER VEHICLE AND YEAR</td>
</tr>
<tr>
<td>UNDER DIFFERENT CONDITIONS AND POOL SIZES</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Differentiation of offers depending on the weekday</th>
<th>No</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Veh.</td>
<td>10,000 Veh.</td>
<td>100 Veh.</td>
</tr>
<tr>
<td>Decrease of the required dispatch time from 4 to 1 hour</td>
<td>No</td>
<td>(34 W)</td>
</tr>
<tr>
<td>Yes</td>
<td>(136 W)</td>
<td>(400 W)</td>
</tr>
</tbody>
</table>

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

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 yields smaller results than 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 varying availability, they are not comparable to conventional energy storage systems. Therefore, the dynamic driving behavior should be included in any computation of possible regulation power or evaluation of potential profits.

V. CONCLUSION

The analysis of V2G services of electric vehicles reveals that income can be generated in the German electricity market, especially in the negative secondary control market. In contrast to the U.S. studies, the delivery of electricity to the grid is not economic in the German case under today’s conditions. This is mainly because of the higher dispatch time (operating availability) necessary to prequalify 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 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 V2G services only as a by-product. 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 frequency 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 represents an essential advantage for larger pools up to a certain size. For a pool of 10000 vehicles, these variations are already very low and further increases in pool size do not deliver any other significant improvements in the amount of regulation reserve power per vehicle. Negative effects of controlling large pools may occur but were not considered in this paper.

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

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. A differentiation between weekday and weekend is also a reasonable improvement for GC-BEVs.

C. Critical Review

Possible drawbacks of changed requirements in the German regulation market have not been analyzed. Daily offers would probably lead to a higher effort for market clearing and other organizational issues. Further, decreasing the required dispatch time for secondary control could have effects on the dispatch of tertiary control and the reliability of the entire regulation market. A detailed power flow analysis and/or a field test is necessary to evaluate the exact technical effects of vehicles providing regulation.

D. Comparison of the Results to the Static Approach

The results in Table VII show that 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 1.15 kW (Tables V and VI). 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 \( P_{\text{V2G, N,R}} \) results from the state of charge after the last trip of the day and the required dispatch time (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. Fig. 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 4 h at this point in time results in a power of

\[
P = \frac{3.5 \text{ kW}}{4} = 0.875 \text{ kW},
\]

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) Organizational Issues: The results in Table VII show that 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 1.15 kW (Tables V and VI). There are two reasons for the different results:

- The potential offers vary significantly across the day. A large vehicle pool can compensate the stochastic variation of the individual drivers.
- The potential regulation power offered across the day. A large vehicle pool can compensate the stochastic variation of the individual drivers.
• **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 negative regulation reserves 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 reserve power offered would decrease. Therefore, participation should be focused on the secondary time period.

• **The market volume for ancillary services is limited.** Assuming a 100% market share of GC-BEVs in the promising control markets (primary control and negative secondary control) 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 [16].

• **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 reserves or conventional charging. It is beneficial to shift the charging process to a point in time with excess power where negative frequency regulation is triggered. Reducing the power of a generating plant as an alternative way to balance 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 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 [17]. 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 [14].

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 on the supply side and creates a greater demand for regulating power. Electric vehicles can help to control the grid using 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 form the basis for integrating electric vehicles. The vehicle owners have the possibility to reduce their energy costs without limiting their mobility or 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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