MARKET POTENTIAL ANALYSIS FOR THE PROVISION OF BALANCING RESERVE WITH A FLEET OF ELECTRIC VEHICLES

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ABSTRACT

This paper analyses the economic and technical potential of the electric vehicle park for the provision of balancing reserve in the German energy market. Each individual electric vehicle is modelled separately considering all relevant techno-economic restrictions by means of a bottom up mixed integer linear optimisation algorithm. The objective is to maximize the electric vehicles' contribution margin in the context of Multi Market Operation considering the Day Ahead, the Intraday and the Balancing Reserve Markets at the same time. The economic benefits obtained with this approach significantly exceed the margin calculated in earlier top-down aggregation models. The value of different strategies and markets is assessed to identify the most beneficial options for electric vehicles. The findings presented suggest the possibility of favourable economics for balancing reserve services based on electric vehicles, which could create a positive momentum for electric vehicle uptake in Germany.

INTRODUCTION

Several studies [1, 2] aim to assess the economic potential of a novel electric vehicle (EV) embedded ancillary service concept, particularly balancing reserve for frequency control in energy markets.
This paper - which is the outcome of a joint research project of E.ON and RWTH Aachen University - considers for the first time a bottom up optimisation approach to model a fleet consisting of up to 1000 individual electric vehicles, taking into account representative driver profiles, grid connection power, battery size and customer behaviour/preferences. The ancillary service concept researched is not constraint to single market operation but operates the EV vehicle park in the context of simultaneous multi market coordinated services in the German market.
The scenario of an aggregator, taking into account wholesale market prices at EPEX Spot Market (Day Ahead and Intraday) and the German Balancing Reserve Markets for Primary (PR), Secondary (SR) and Tertiary Reserve (TR), is examined in this investigation. To identify the monetary value of Multi Market Operation the pure procurement of the required driving energy for the EV at EPEX Day Ahead Market (reference case) is put in contrast to all other marketing options. Retail prices including tax, grid charges etc. are neglected within this investigation.

MARKET OPERATION STRATEGIES

Within the project several strategies have been developed to maximize the economic benefit for EV fleets. Starting with a simple "Day Ahead Market Only" strategy successively more and more markets are included into the optimisation routine. In particular the three Balancing Reserve Markets (Primary, Secondary and Tertiary Reserve) and also the exploitation of flexible Intraday Trading are considered.

Basic Day Ahead Market Operation

This first strategy primarily foresees the pure procurement of driving energy for all EV in the fleet (reference case) at the Day Ahead Market.
In the case of vehicles with bi-directional V2G capability a planned re-selling of electricity into the Day Ahead Market is also possible. Thereby first revenues through arbitrage can be achieved compared to the reference case.

Vehicle to Grid 1.0

In addition to Basic Day Ahead Market Operation the uni- and bi-directional allocation of balancing reserve is foreseen within the strategy V2G 1.0.
Provision of reserve always implies uncertainty regarding the batteries' State of Charge (SoC) due to the stochastic nature of balancing energy demand. Thus the planning of market operation needs to consider a range of possible

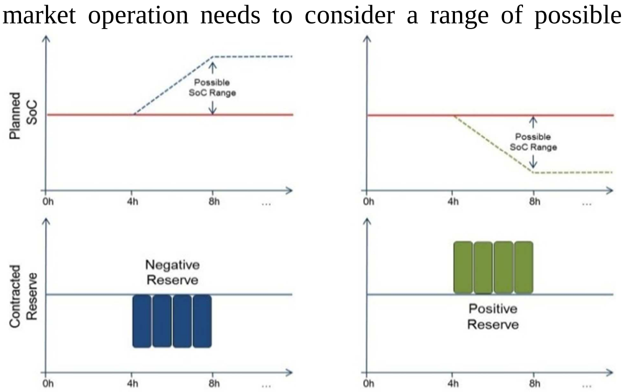

Figure 1: Uncertain SoC caused by uncertain reserve demand with V2G 1.0 Strategy

SoC levels (Fig.1). However, in order to guarantee the fleets' capability of providing the contracted reserve at any time step, all possible SoCs need to be covered. Hence, the provision of balancing reserve in this basic V2G 1.0 Strategy always leads to a blocked part of the vehicle's battery. This is due to the fact, that during the planning phase the actual balancing energy demand is uncertain.

As a result of the uncertainties in SoC the number of reserve contracts to participate in is significantly limited by the storage size. The following Vehicle to Grid 2.0 strategies have been developed in order to solve this problem and to allow an extensive Balancing Reserve Market participation by the EV fleet.

Vehicle to Grid (V2G) 2.0

The enhanced V2G 2.0 strategies additionally use the flexibility of Intraday Market transactions. This makes it possible to guarantee a certain SoC within the optimisation (planning stage) even when providing balancing reserve with uncertain balancing energy demand. Exemplarily the V2G 2.0 strategy "Charging with Reserve Energy" will be presented. The goal of this strategy is to charge the battery as far as possible through provision of reserve, whilst filling up the gap on Intraday Market. The strategy can be conducted either with uni-directional and bi-directional connected EVs. Figure 2 illustrates the basic idea behind the strategy.

Provision of Negative Reserve

In case the EV provides negative reserve and the corresponding balancing energy is not demanded, the battery is not charged with balancing energy. To ensure a certain SoC within the optimisation, an "Optional Intraday Market Buy In" is added to the reserve contract. In contrast, if the balancing energy is demanded within the fulfilment period, there is no need to actually place the "Intraday Market Buy In", because the battery gets charged with balancing energy. In both cases there is a definitely reached SoC at a certain following period that can be anticipated within the optimisation model.

To provide a certain amount of positive balancing reserve

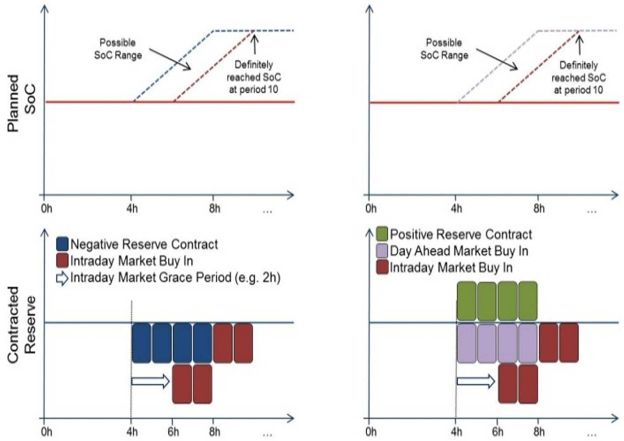

Figure 2: Guaranteed SoC by Intraday Trading Provision of Positive Reserve

with the strategy "Charging with Reserve Energy", the maximum amount of possibly demanded balancing energy needs to be bought at the Day Ahead Market in advance. In case of a positive balancing energy demand the vehicle abstains from charging at the Day Ahead Market in order to provide the requested balancing energy. Again an "Optional Intraday Market Buy In" is placed behind the reserve contract in order to "recharge" the EV and to guarantee a certain SoC within the planning stage. The real decision to place or not to place the "Intraday Market Buy In" will be made during the fulfilment period depending on the actual reserve demand.

OPTIMISATION MODEL

Embedding a fleet of electric vehicles into the German energy market needs to comply with multiple constraints, both from the vehicle perspective as well as from the market perspective. To manage this complex challenge, a linear mixed integer optimisation model has been developed, considering every car as individual with its specific constraints.

Modelling of Electric Vehicles

For each EV the following techno-economic characteristics are considered within the model:

- Driving patterns (cycles) – obtained from a survey [3]
- Grid Connection
  - Power (3,7 kW / 11 kW / 30 kW)
  - Uni- / Bi-directional Charging
- Battery
  - Size [kWh]
  - Costs for Battery Wear [€/kWh]
  - Battery Efficiency [%]
- Owner's Preferences (share of Battery to be used for Multi Market Operation)

Each EV is therefore modelled by a set of decision variables $p_{k,i,t}$ defined as follows:

$p_{k,i,t}$	Power [kW] procured by Vehicle k in Market/Product i at Time Step t

Market/Product Index i Breakdown:

1	*Day Ahead Market Buy In*
2	*Day Ahead Market Sells*
3	*Tertiary Reserve Positive*
4	*Tertiary Reserve Negative*
5	*Secondary Reserve Positive*
6	*Secondary Reserve Negative*
7	*Primary Reserve*
8	*Intraday Market Buy In*

In addition the EV model needs some input data represented by a set of constants:

p_k^{out}	Maximum discharging power of Vehicle k
p_k^{in}	Maximum charging power of Vehicle k
W_k^{max}	Battery capacity of Vehicle k
W_k^{min}	Minimum accepted SoC of Vehicle k
η_k^{out}	Battery discharging efficiency of Vehicle k

η_k^{in}	Battery charging efficiency of Vehicle k
c_k^{bat}	Battery costs per kWh discharged energy of Vehicle k
$d_{k,t}$	Driving energy of Vehicle k at time step t
τ_{intra}	Intraday Market Grace Period

Lower Storage Limit
The battery of an EV must not be discharged below a lower bound W_k^{min}. Therefore all certain energy inputs less energy sells on the Day Ahead Market and driving losses are summed up for each time step:

$$W_k^{min} \leq \sum_{\pi=1}^{t} \left(\eta_k^{in} \sum_{i=1,8} p_{k,i,\pi} - \frac{p_{k,2,\pi}}{\eta_k^{out}} - d_{k,\pi} \right) \quad \forall\, k,t$$

The constant W_k^{min} can be set to zero, but also to a customer specific value above in order to indicate the customer's willingness to provide reserve. In case of a $W_k^{min} > 0$ the SoC can only fall below this value caused by driving and not by market operation (discharging).

Upper Storage Limit
Analogously the maximum battery capacity also may not be exceeded through market operation.

$$\sum_{\pi=1}^{t} \left(\eta_k^{in} \sum_{i=1,4,6,7} p_{k,i,\pi} - \frac{p_{k,2,\pi}}{\eta_k^{out}} - d_{k,\pi} \right) \leq W_k^{max} \quad \forall\, k,t$$

Power Limits – Charging and Discharging
Charging and discharging summarised over all markets is limited to the maximum connection power.

$$\sum_{i=1,4,6,7,8} p_{k,i,t} \leq p_k^{in} \qquad \forall\, k,t$$

$$\sum_{i=2,3,5} p_{k,i,t} \leq p_k^{out} \qquad \forall\, k,t$$

Coupling of Positive Reserve and Day Ahead Market
As illustrated in Figure 2, the V2G 2.0 strategy "Charging with Reserve" provides positive reserve via simultaneous Day Ahead Market Buy In and an abdication of charging in case of reserve call. This is modelled as follows:

$$\sum_{i=3,5,7} p_{k,i,t} \leq p_{k,1,t} \qquad \forall\, k,t$$

Intraday Market Adjustment – Positive Reserve
When providing positive reserve, an "Optional Intraday Market Buy In" is placed behind the reserve contract with a time offset of Intraday Market Grace Period.

$$\sum_{i=3,5,7} p_{k,i,t} = p_{k,8,t+\tau_{intra}} \qquad \forall\, k,t$$

Intraday Market Adjustment – Negative Reserve
Analogously after negative reserve contracts an "Optional Intraday Market Buy In" is added.

$$\sum_{i=4,6,7} p_{k,i,t} = p_{k,8,t+\tau_{intra}} \qquad \forall\, k,t$$

Unavailability of EV when Driving
When an EV is driving, it cannot operate on any market.

$$p_{k,i,t} = 0 \;\; if \;\; d_{k,t} \neq 0 \qquad \forall\, k,i,t$$

Modelling of Markets

As markets are already represented in every single EV Model through the variables $p_{k,i,t}$, it is only necessary to add one set of market variables for each market, representing the total fleet's market operation as the sum over all single vehicles.

$M_{i,t}$	Market Contract [MW] for Market/Product i at Time Step t

On these market variables additional market specific constraints can be imposed in order to model time slices, offer increments and minimum bid sizes stipulated by the single markets.

Summation of Power Procurement
For each market M_i the market contract volume comes up to the sum of all vehicles' market contribution divided by 1000 to consider the market contracts unit [MW].

$$\frac{\sum_k p_{k,i,t}}{1000} = M_{i,t} \qquad \forall\, i,t$$

Minimum Bid Sizes and Offer Increments
For each market a certain minimum bid size $\underline{P_i}$ is stipulated. The Day Ahead Spot Market for instance requires a minimal bid size of 1 MW. The reserve markets require 1 MW (PR) up to 5 MW (SR + TR) at present. This can be expressed as:

$$\underline{P_i} \leq M_{i,t} \;\vee\; M_{i,t} = 0 \quad \forall\, i,t \quad ; \qquad M_{i,t} \in \mathbb{Z}$$

Market contracts are standard products with certain increments of typically 1 MW. Therefore the market variables $M_{i,t}$ are defined as integer variables within the optimisation.[1]

Time Slices
Not all markets permit hourly changes in contract volume but stipulate time slices of up to 168 hours (e.g. PR) with a constant contract volume. This can be modeled by a time coupling equality constraint for all hourly product variables of the certain product.

Objective Function

The model's objective is to maximize the expected contribution margin (= Revenue – Variable Costs) through Multi Market Operation of the whole EV fleet. Within the linear objective function the variables $p_{k,i,t}$

[1] Hence, the class of problems switches from an LP (Linear Programming Problem) to a MILP (Mixed Integer Linear Problem).

are therefore multiplied by the appropriate market prices in order to incentivise market operation. Discharging in terms of selling energy back into the Day Ahead Market leads to revenues in the amount of Day Ahead Market prices, but also to variable costs caused by battery wear c_k^{bat}.

EXEMPLARY RESULTS

Scenario Assumptions

- Optimisation Period: 1 week, $T = 168\,hours$ Average weekly prices 2011 in hourly resolution (Perfect Information and Price Taker Model)
- Reserve Market Prices only include Mean Capacity Prices, no Balancing Energy Price considered
- Neglect of Minimum Bid Sizes and Increments
- Fleet of 100 EV, Type "Medium Dist. Commuter" with $p_k^{in} = p_k^{out} = 3.7\,kW$ (bi-directional)
- Driving patterns perfectly known by algorithm
- Battery Capacity 18 kWh; Discharge Costs (Battery Wear): 1ct/kWh; Battery Efficiency 90% (In & Out); $W_k^{min} = 20\%$

The historical Spot- and Reserve Market prices are illustrated in Figure 3 in an hourly resolution.

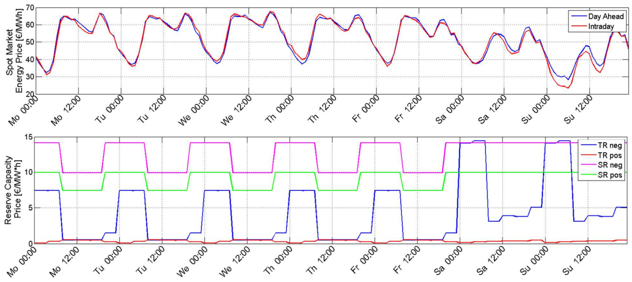

Figure 3: Assumed Market Prices (Year 2011)

Results: Basic Spot Market Operation

The fleet of 100 EV collectively consumes 3800 kWh for driving in the considered week. The average weekly distance per EV is around 200 km (≙30…40 kWh/week). Without selling energy back into the Day Ahead Market this leads to average costs of 1.59 € per EV. With additional discharging in peak periods (see Fig. 4) the

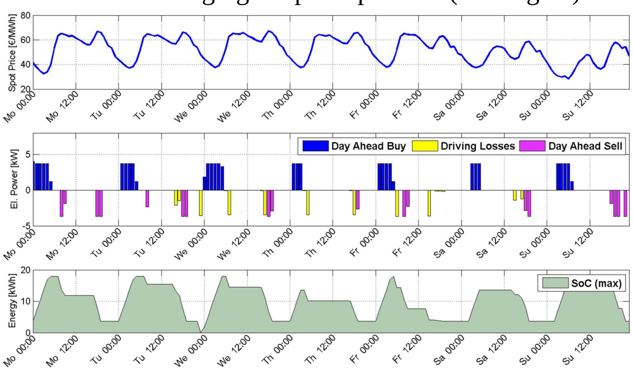

Figure 4: Schedule for EV1 with Basic Spot Market Operation and discharging enabled

fleet can reduce costs to 1.26 € per car by doing some arbitrage. Of course this value highly depends on the chosen discharge costs of only 1 ct/kWh in this example.

Results: Vehicle to Grid 1.0

The uncertainty of SoC leads to outmost conservative Reserve Market participation with the V2G 1. 0 strategy. Only within the last two days (weekend) the EV provides negative Tertiary Reserve (Fig. 5, green bars), leading to an uncertain SoC, represented by the green surface in the SoC plot of Fig. 5. The associated costs are 1.14 € per EV and week.

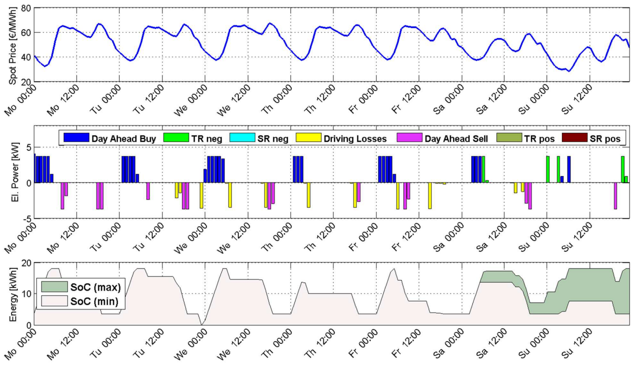

Figure 5: Schedule for EV1 with V2G 1.0 strategy

Results: Vehicle to Grid 2.0

With the enhanced V2G 2.0 strategy "Charging with Reserve" the cost amounts to -1.09 € per vehicle and week. This means, the EV is not only driving for free but earning money on top. The total margin compared to the reference case therefore is 2.68 € per vehicle and week.
This is due to extensive Reserve Market participation (Fig. 6) including Secondary and Tertiary Reserve. Primary Reserve is neglected by the optimisation because of its high exigencies regarding the 168 h time slice in the German market. Intraday Market operation leads to a dynamic storage usage with mostly two cycles per day. The difference between minimum and maximum SoC is limited through the Intraday transactions (green surface in SoC subplot).

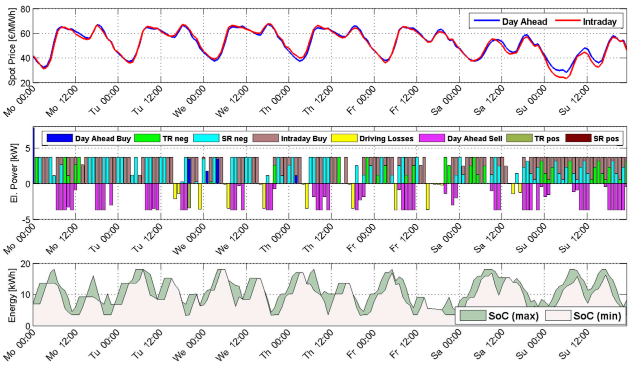

Figure 6: Schedule for EV1 with V2G 2.0 strategy "Charging with Reserve"

The calculation only takes into account revenues through reserve capacity price. Including the additional reserve energy revenues through reserve charging would lead to even higher revenues caused by savings in energy procurement.

CONCLUSION AND OUTLOOK

It can be concluded, that Multi Market Operation, in particular Intraday Market integration is the key for successful novel V2G business concepts in Germany. According to the results achieved, an annual profit between 100 and 150 € is possible for each EV only through the capacity margin. The integration of energy prices into the calculation will increase benefits significantly up to 500 € per year and vehicle as further investigations show. A higher installed electrical rating of e.g. 11 kW or even 33 kW or batteries with higher capacity would also increase revenues. Using the developed optimisation model makes it possible to assess all different constellations in order to identify best suited vehicle configurations, customers and market strategies.
Of course uncertainties regarding e.g. market prices and driving patterns will complicate the planning process and will therefore have negative impact on revenues in reality. This topic as well as the requirements for practise application will be discussed in a further research project.

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