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System-based Integration of Electric Vehicles in an Electricity System

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The support of alternative propulsion technologies like electric vehicles being integrated into transport and electricity systems must be based on efficient and economically reasonable implementation concepts. A successful integration of electric vehicles into an electricity system is affected by adequate business cases. The realisation of the mobility needs of vehicle users must be defined as a main constraint for each target function. The approach within this paper is based on systematic analysis of various charging (direction of electric current from grid to vehicle) and discharging (direction of electric current from vehicle to grid) concepts for electric vehicles, which are subdivided into: uncontrolled, controlled and intelligent charging and discharging strategies. The considered concepts are allocated to the controlled one. In all analysed applications, the discharging of batteries (in case of LiFePO4 batteries) cannot achieve sufficient revenues. This makes an economical realisation of such concepts unfeasible. The main reasons are high battery capacity losses due to discharging and the associated battery degradation costs. Therefore, the calculated revenues of discharging concepts are not able to cover inverter costs and the investments needed for the communication and control infrastructure. In terms of economic analysis and the impact of a high penetration level of electric vehicles on low voltage grids, a system-relevant integration of EVs is subdivided into two different implementation stages.

Die Förderung von alternativen Antriebstechnologien wie z. B. Elektrofahrzeugen, die in das Verkehrs- und Stromsystem integriert werden, muss auf effizienten und wirtschaftlich sinnvollen Umsetzungskonzepten basieren. Eine erfolgreiche Eingliederung von Elektrofahrzeugen in ein Stromsystem wird von geeigneten „Business Cases" beeinflusst. Die Umsetzung der

Mobilitätsbedürfnisse der Fahrzeugnutzer muss als Hauptbedingung jeder Zielfunktion definiert werden. Der Ansatz in diesem Beitrag basiert auf der systematischen Auswertung verschiedener Konzepte zum Auf- (Richtung des elektrischen Stroms vom Netz zum Fahrzeug) und Entladen (Richtung des elektrischen Stroms vom Fahrzeug zum Netz) von Elektrofahrzeugen, die wie folgt unterteilt sind: unkontrollierte, kontrollierte und intelligente Auf- und Entladestrategien. Die betrachteten Konzepte gehören alle zu den kontrollierten Strategien. In allen untersuchten Anwendungen konnten für das Entladen von Batterien (im Fall von LiFePO4-Batterien) keine zufriedenstellenden Ergebnisse erzielt werden. Somit ist eine wirtschaftliche Umsetzung solcher Konzepte nicht möglich. Die Hauptgründe hierfür sind der hohe Kapazitätsverlust der Batterie durch das Entladen und die damit verbundenen Degradationskosten. Daher reichen die voraussichtlichen Einnahmen, die mit den Entladungskonzepten erzielt werden können, nicht aus, um die Kosten für Wechselrichter und die erforderlichen Investitionen für Kommunikations- und Kontrollinfrastruktur zu decken. Was die wirtschaftliche Analyse und den Einfluss der hohen Durchdringungsrate von Elektrofahrzeugen auf Niederspannungsnetze angeht, so ist eine systemrelevante Integration von Elektrofahrzeugen in zwei verschiedene Implementierungsstufen unterteilt.

1 Introduction

The propulsion systems of passenger vehicles are nowadays generally based on internal combustion engines. This technological structure in combination with the estimated development of the existing vehicle stock (World Energy Council 2007) will intensify environmental damage. The European Union has recognized the mentioned aspects in conjunction with the development of transportation and tries to mitigate these problems with targeted regulatory schemes and guidelines (EU 2011).

The support of an alternative propulsion technology being integrated into the transport and electricity system must be based on efficient and economically reasonable implementation strategies. A successful integration of electric vehicles (EV) is affected by adequate business models which fulfil diverse target functions. The realisation of the mobility needs of vehicle users must be defined as a main constraint for each target function. Following the idea of Timm/Vierbauch (2011), the business models for e-mobility need to show a so-called multidimensionality that consists of target groups, products and services.

Regarding to a system based integration of electric vehicles in an electricity system, relevant discharging (V2G) and charging (G2V) strategies must be defined. Vehicle-to-grid (V2G) depicts a system in which the vehicles communicate with the frequency reserves or energy markets to sell demand response services by returning electricity into the grid. Grid-to-Vehicle (G2V) sell demand response services to the mentioned markets (a communication system is needed) by charging the batteries of vehicles.

This paper is organised as follows: The selected methodology is presented in section 2. The following two sections describe the main data base used in this paper and its outcomes. The conclusion is given in section 5. A suggestion for an efficient integration of EVs into an electricity system will be drawn in the last section.

2 Methodology

The objective of this paper is implemented by defining related business cases for EVs with associated use cases and descriptions of the main influencing factors. The methodological approach to assigning various business cases is given in this section and comprises the following applications (controlled charging and discharging strategies):

- Market-based charging/discharging strategy: Participation in frequency reserve markets (STR 1)
- Generation-based charging/discharging strategy: Electric vehicles and balancing model (STR 2)
- Generation- and load-based charging/discharging strategy (STR 3)

2.1 Market-based Charging/Discharging Strategy: Participation in Frequency Reserve Markets (STR 1)

Generation and consumption in an electricity system must be equal at each instant. Due to the deviation between the forecasted and actual electricity generation and consumption at any point in time, there is a need for a balancing mechanism matching generation and consumption, and thus a need for maintenance of the electricity supply system. This balancing mechanism is organized and operated by the transmission system operator (TSO). The balancing energy (deviation between generation and consumption of electricity at any point in time) will be realized with the activation of capacity reserves of power plants being contracted by the TSO (Galus et al. 2010). According to ENTSO-E (2012), the capacity reserves comprise the following:

- Frequency containment reserves (FCR), which are activated automatically and limit frequency deviation. The reserves are also called “primary reserves”. Primary energy is exchanged between the control zones.
- Frequency restoration reserves (FRR), which are activated automatically and manually. They aim at the restoration of the value of frequency after its limitation due to the activation of containment reserves. In literature, the automatic frequency reserves are also called “secondary reserves” and the manual reserves are known as “tertiary reserves”.

A deviation in system frequency (50 Hz +/- 20 mHz) leads to an activation of frequency containment reserves (primary reserves), which, within seconds, attempt to stabilize the system. A further deviation of 180 mHz leads to the activation of the whole containment reserve. The automatic restoration reserve will be activated – at a minimum, within seconds, and at a maximum, within 15 minutes – to restore the frequency to its original value before the deviation. This also frees the containment reserve for possible further irregularity (ENTSO-E 2009) and re-establishes the planned cross-border power flows (Galus et al. 2010). If the frequency deviation in the control zone continues, the manual restoration reserve will be activated. It releases the automatic restoration reserves and restores the frequency value before the incident.

As an example, a higher electricity generation or a lower consumption level causes an increase in system frequency. Thus, the system can be stabilized with counteractions like decreasing/increasing the electricity generation/demand.

The ensuring of required frequency reserves for the provision of balancing energy is organised by the transmission system operator (TSO) through bilateral contracts with capacity reserve bidders, which take part in a weekly or daily bidding process.

Each one of the daily activated frequency reserve capacities (automatic/manual, negative/positive) differs itself apart in terms of the amount of activated reserve capacity and the number of activations. Hence, an exact assessment of the economic potential due to the participation of EVs in the frequency reserve markets is not possible. Therefore, the calculation of a feasible economic spread as a consequence of the participation of EVs in frequency reserve markets enables a targeted assessment of the described economic potential. As a result, a modelling of the daily activated frequency reserves is conducted, whereby the statistical analysis of frequency reserves occurred from 2006 to 2010 build up the database. The modelling prepares different scenarios. The scenarios differ in the amount of activated reserve capacities and the number of activations during a day.

2.2 Generation-based Charging/Discharging Strategy: Electric Vehicles and Balancing Model (STR 2)

The possibility of consumers having the free choice of supplier results from the implementation of the so-called balancing group model in an electricity system which allows a distinction between physical delivery of electricity and accounting of electricity and delivering businesses. Each market player must therefore participate in a commercial balancing group. Each balancing group has to be balanced at any points in time in terms of electricity generation/procurement and also during electricity consumption/delivery. Each balancing group is represented by a balancing group representative who takes over both the interaction of their own balancing group with other stakeholders and the financial risks of the balancing group according to the management of balancing energy. The analysis of the implementation of electric vehicles in a balancing group is based on the creation of a fictional balancing group. The fictional balancing group depicts a single demand profile mainly comprising households. The household profiles are derived from one-week measurements (one winter and one summer week) conducted within a project (ADRES 2011). The total amount of generated electricity is the same as the consumed electricity during a week. The fictional balancing group is supplied by different power generation portfolios. The considered generation structures for supplying the balancing group are given in Table 1.

Table 1: Analysed Generation Portfolios of a Fictional Balancing Group with 100 % Renewable Electricity Generation

Generation structures	*Biogas (%)*	*Wind (%)*	*PV (%)*
1	60	20	20
2	50	50	0
3	0	50	50
4	50	0	50
5	100	0	0
6	0	100	0
7	0	0	100

Source: Own compilation

The delta of the balancing group ($\Delta_{BG,i}$) at any point in time (i) is determined by calculating the difference between electricity consumption and generation. Referring to the responsibilities of the balancing group representative, a balance between electricity generation and consumption ($\Delta_{BG,i} = 0$) is attained. The balancing group representative can utilize EVs for reaching this purpose. The basic principle this strategy consists of is charging EVs in times of electricity surplus (, electricity consumption < generation) and discharging them in the inreverse case.

2.2.1 Combined Charging and Discharging Concepts for the Implemented EVs within the Balancing Group

The weekly delta curve (difference between electricity consumption and generation) of the balancing group, in this case, is considered in the optimization approach instead of forecasted day-ahead wholesale electricity prices.

The aim of the optimization is to minimise the weekly delta of the balancing group. EVs are generally defined as stationary storages, including the definition of their availability (vehicle is used by a driver or not). One assumption is made: EVs are always connected to the grid during non-driving times.

2.2.2 Charging Concept for the Implemented EVs within the Balancing Group Only

This concept is relevant only for charging EVs in times of surplus electricity in the balancing group ($\Delta_{BG} < 0$, consumption < generation). The EV can be charged at any location equipped with a charging station. The vehicles will be separately integrated into the balancing group. Each integrated vehicle changes the trend of for the whole analysed week. The actual state of the balancing group is given by the new trend. The assessment of the charging strategy of the next vehicle is aligned with the new trend of Δ_{BG}.

2.3 Generation- and Load-based Charging/Discharging Strategy (STR 3)

Generally, PV and EV technologies are connected to the low voltage grids (LV grids). With the implementation of a high share of these technologies, the distribution system operators (DSOs) must be able to manage the resulting extreme grid situations. These extreme cases are the following:

- A high level of PV generation feeding into the grid (typical for summer days) in combination with a low number of available EVs (low load level in the LV grid).
- A low level of PV generation feeding into the grid (typical for winter days) with a

high number of EVs that need to be charged during the day.

The interaction between renewable electricity generation (here: PV) and EVs can be coordinated locally with generation- and load-based charging/discharging concepts.

The charging strategy is based on the usage of PV electricity generation at home for charging EVs, mainly in times of high generation levels. Charging can be conducted if the vehicles are available at home. As such, the concept tries to reduce the impact of PV generation peaks on the low voltage grids.

The described generation-based charging strategy is enhanced by two other grid-based aspects.

1. If the vehicle user's desire for specific battery states at defined times cannot be covered due to charging from PV generation, a second G2V concept is activated. Charging occurs in such cases in times from 00:00 to 6:00 hours, overcoming the deficit between the set and current battery state.
2. The charging concepts are complemented by a V2G concept (load-based discharging of battery between 07:00 p.m. and 09:00 p.m.). The aim of the V2G strategy is to reduce the physical load of the linked LV grid in the mentioned timeframe.

The economic analysis of the use case is based on the assessment of the V2G concept at home, where the maximum possible revenues of discharging are evaluated without consideration of the charging cost. The assessment does not take into account the cost of the required control communication system.

3 Main Database

3.1 Energy and Capacity Prices of Automatic FRR (Secondary Control) for 2020

The assumed average electricity price on the day-ahead market (a market where power is traded for delivery during the next day) is 80.82 €/MWh (a fixed value) for 2020. The balancing energy prices for positive frequency reserve restoration (FRR) products are forecasted for 2020 based on the proportion between the offered balancing energy prices on FFR markets and average electricity price on the day-ahead market. It is assumed that the capacity prices in FRR markets will double until 2020 (base year = 2010), which describes an optimistic scenario. In spite of the mentioned assumptions, the average capacity price for automatic FRR (secondary control) is 26 €/MW/h and energy price 117 €/MWh.

3.2 Degradation of Li-ion Batteries

The influence on the lifetime of Li-ion batteries due to the realization of various V2G concepts is considered in the economic calculation and assessment of the V2G use cases. Peterson et al. (2009) analyse the impact of the combination of discharging due to driving and additional discharging because of V2G utilization on capacity losses of LiFePO4 batteries. The outcomes depict that the capacity loss strongly depends on the kind of discharge. It is lower for V2G than driving support application (per cent capacity lost per normalized Wh or Ah; Peterson et al. 2009):

- −6.0×10−3% for driving support (dynamic discharging)
- −2.70×10−3% for V2G application (constant discharging)

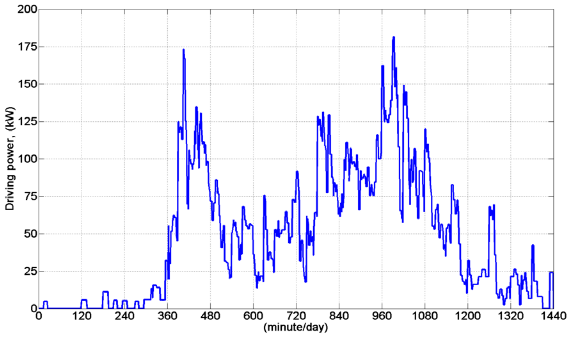
According to Peterson et al. (2009), it can be calculated that 1 % capacity losses from a Li-ion battery (LiFePO4) with 16 kWh entire capacity are conducted by around 6,000 kWh discharging energy due to V2G utilization or 2,700 kWh energy used for driving. These values are considered in the economic calculation and assessment of discharging and reusing use cases.

EV batteries are utilized at between 10 % and 90 % of their entire capacity bearing the impact of deep discharging and full charging on the capacity losses. In the case of plug-in hybrid electric vehicles (PHEV), the spread is between 20 % and 80 % of the entire battery capacity.

3.3 Driving Patterns and Alternative Propulsion Technologies

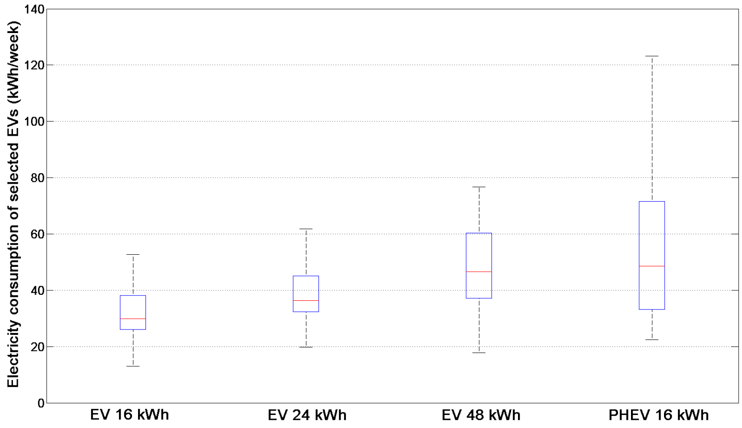
The evaluation of charging or discharging profiles for analysed EVs is based on the assignment of driving patterns, which are derived from the statistic data sets of a mobility survey conducted in Salzburg city (see Herry 2005). Litzlbauer (2012) gathers information on motorized individual transport from the existing data set and extracts 2,606 anonymous distance and time curse profiles of interviewees. The adaption of the mentioned survey data set to the electric vehicles with different battery capacities (16, 24 and 48 kWh) results in the evaluation of appropriate electricity consumption profiles with minute resolution (Litzlbauer 2012).

Fig. 1: Sum of Driving Power of all Existing Vehicles (200 EVs) for a Chosen Day



Source: Litzlbauer (2012), own depiction

Fig. 2: Consumed Electricity for Driving of Different EV Categories



Each Boxplot shows from bottom to top the minimum value, lower quartil, median, upper quartil and maximum value for energy consumption of different EV categories.

Source: Litzlbauer (2012), own depiction

Figure 1 depicts the sum load profile of required electrical power (kW) for the driving of 200 EVs a working day. The considered alternative propulsion technologies show different driving activities (duration of driving time) because of differences in the utilized technology (EV, PHEV) and installed battery capacity (16, 24 and 48 kWh) (Fig. 2).

4 Results

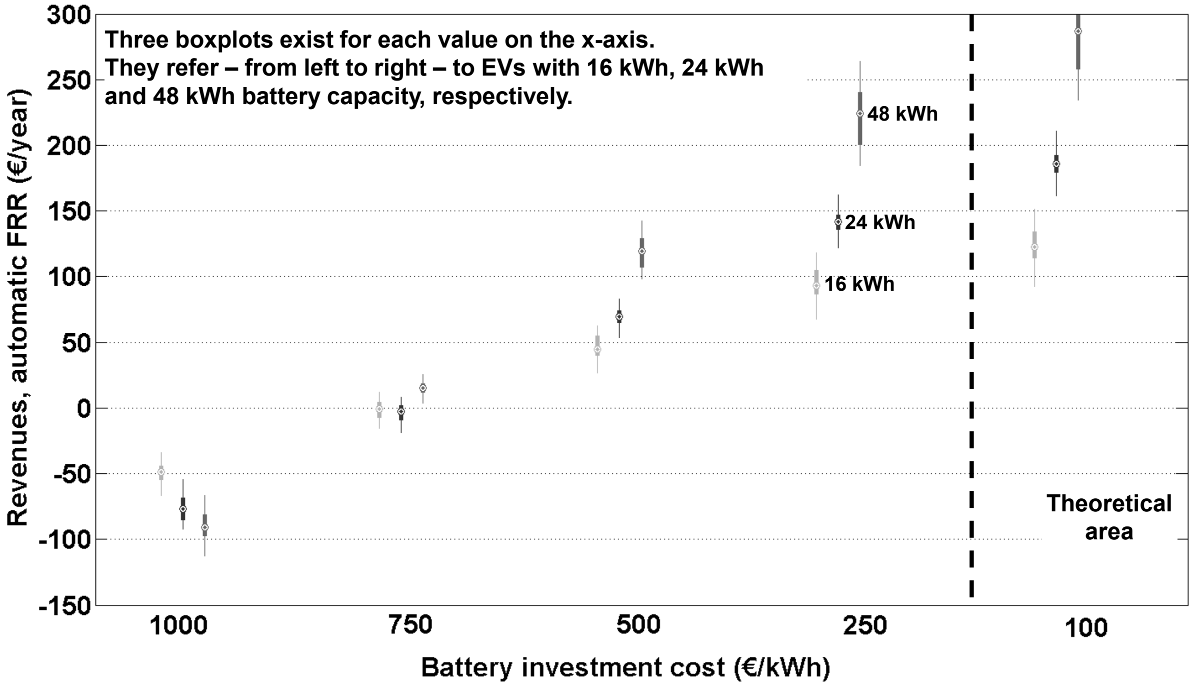
4.1 Market-based Charging/Discharging Strategy: Participation in Frequency Reserve Markets (STR 1)

The calculation reveals that the participation of EVs in positive automatic FRR markets results in positive revenues if battery investment costs are less than or equal to 500 €/kWh. The consideration of the evaluated dispatch probability of reserved capacity in the range of 17 % obtains revenues between 45 € and 119 € per vehicle and year due to the participation of EVs in the automatic FRR market. The battery investment costs are 500 €/kWh (Fig. 3).

The presented results (maximum possible revenues) do not consider competition with other market participators, like generators, and other storage technologies. The consideration of the competition situation of EVs with other providers of positive FRR reserves prevents or reduces to a high degree the realisation of the mentioned revenues. The following reasons are given in this context:

1. The offered balancing energy price must cover at least the marginal generation cost of a supplier. Figure 4 depicts the marginal generation cost of Li-ion (degradation costs without consideration of the cost for communication and charging/discharging control) in the case of discharging in comparison to pumped hydro energy storages and other bulk energy storages. Pumped hydro energy storages

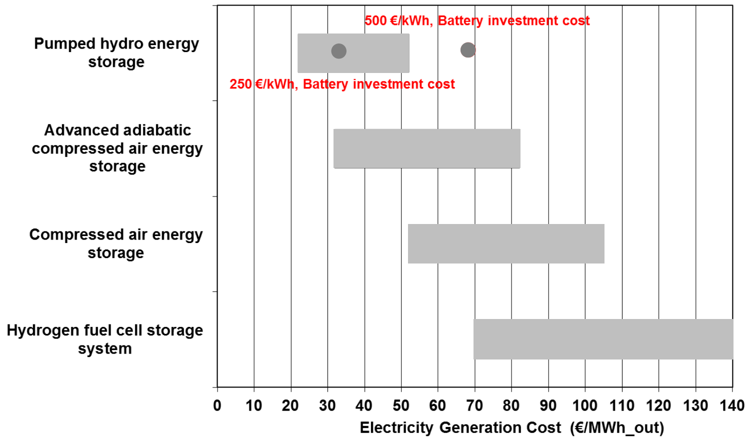
Fig. 3: EV Revenues Due to Their Participation in Automatic FRR Market



Source: Own depiction

provide a major portion of the activated automatic FRR reserves in Austria and can be seen as significant competitors to EVs. The degradation costs of the Li-ion battery with investment costs of 500 €/kWh are clearly higher than the marginal costs of pumped hydro energy storages. A reduction of the battery degradation costs of 33.75 €/MWh (battery investment costs of 250 €/kWh) which describe a very low level of degradation costs, does not express beneficial competition of EVs versus pumped hydro energy storages.

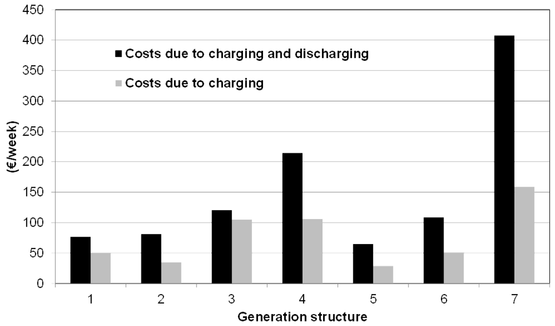
Fig. 4: Comparison Between the Electricity Generation Costs of Difference Bulk Storage Systems (Zach et al. 2012) and the Degradation Costs of Li-ion Batteries



Source: Own depiction

2. Changes and adaption of the FRR market rules can encourage EVs to participate in FRR markets. An adaption like reduction of minimum bid size results in increased competition in the FRR markets because other small suppliers (for example pooling of diesel generator sets, small storage systems, heat pumps, etc.) are able to provide restoration reserves. The higher the number of suppliers, the greater the competition, which results in a reduction of offered capacity and balancing energy prices. The described situation results in the decline of possible revenues for EVs and increases the challenge to cover the V2G costs (degradation, communication and control costs including the investment costs for the V2G inverter)

Fig. 5: Comparison of the Costs Incurred by a Combined Charging/Discharging Strategy (Without Consideration of Communication and DC/AC Inverter costs) to the Charging-only Approach of Vehicles Within a Balancing Group



Source: Own calculation and depiction

4.2 Generation-based Charging/Discharging Strategy: Electric Vehicles and Balancing Model (STR 3)

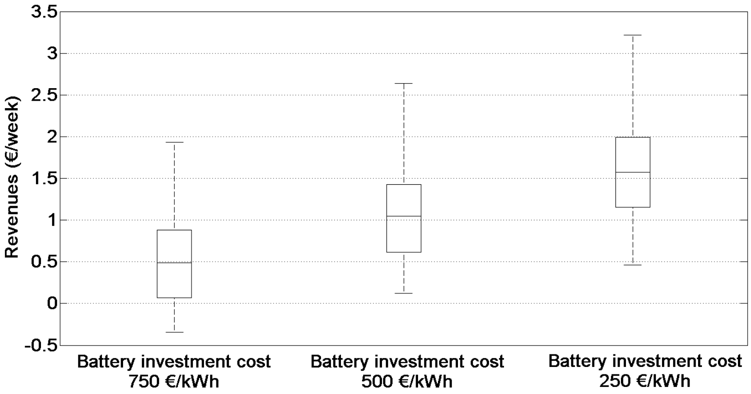
Figure 5 compares the costs incurred (median values) by charging and combined charging/discharging strategies based on day-ahead electricity prices in 2010, considering different forms of electricity generation (see Table 1). The determination of depicted costs for combined charging and discharging consists of charging costs, revenues from discharging and the associated degradation costs (the assumed battery investment cost is 500 €/kWh). Due to the existing battery (Li-ion) degradation costs, the total costs of a combined charging and discharging strategy – independent of the concerned generation structure – are significantly higher than those for the strategy which only includes the charging of EVs. The balancing group responsible acts against own short-term deviation by participation in day-ahead or intra-day electricity markets, respectively. This means that for the provision of balances within its own balancing group, a balancing group representative considers the short-term deviation and can save the balancing costs incurred (ex-post) with appropriate management of controllable EVs (defining charging times).

However, the charging of EVs for the balancing or reduction of the scheduled deviation of the balancing group demonstrates an efficient system-based integration of EVs. In this case, on the one hand the charging costs (determination of charged electricity with electricity prices on day-ahead or intra-day markets) are covered by vehicle users. On the other hand, this results in cost saving due to non-consumed balancing energy. The saved balancing costs can be seen as a compensation for the investment in control infrastructure needed for charging EVs.

4.3 Generation- and Load-based Charging/Discharging Strategy (STR 3)

Figure 6 depicts potential revenues of the V2G concept associated with assumed battery investment costs and mentioned electricity prices. Positive revenues can be achieved for any cases (driving patterns, household profile, availability at home and strength of solar radiation) from battery investment costs of 500 €/kWh downwards. Median revenues in the range of about

Fig. 6: Revenues Due to Discharging EVs from 07:00 pm to 09:00 pm for Different Battery Investment Costs

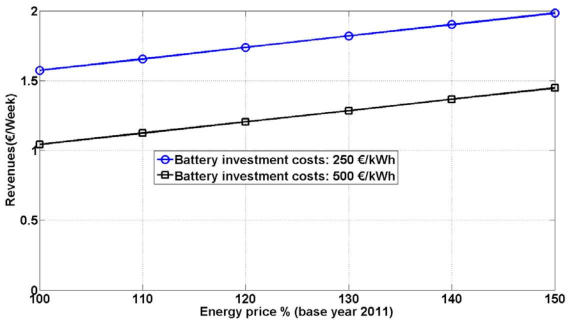


Each Boxplot shows from bottom to top the minimum value, lower quartil, median, upper quartil and maximum value for gained revenues due to selling electric energy by discharging EV battery.

Source: Own depiction and calculation

50 €/yr can be reached per vehicle and with a battery investment cost of 500 €/kWh. Due to a successful realization of the V2G concept, the achieved revenues must be able to cover the linked costs of this concept, such as the additional costs for the charging station, control communication system and required DC/AC converter.

Fig. 7: Discharging Revenues Based on Variation of Battery Investment Costs and Average Day-ahead Electricity Prices



Source: EXAA 2012; own depiction and calculation

Figure 7 depicts the relation between the revenues, battery investment costs and average electricity prices on the day-ahead market. Increasing electricity prices in the range of 50 % results in a rise of revenues in the range of roughly 39 % (case: battery investment cost is about 500 €/kWh).

5 Conclusions

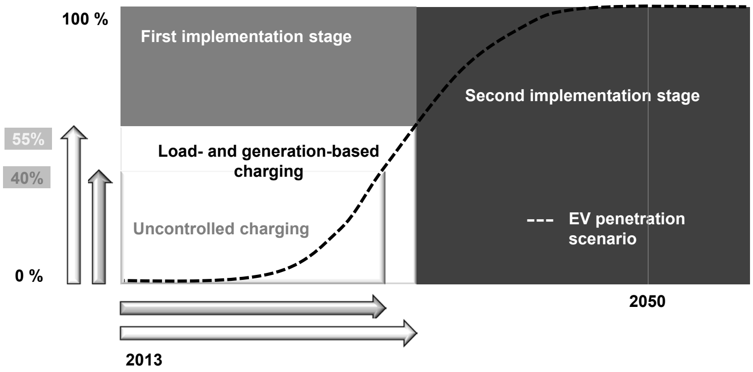
V2G is always seen as a promising technology option for the storage of fluctuating generated electricity. But the various analysed discharging strategies seem to be unrealisable because of capacity losses due to discharging and the resulting high degradation costs. The calculated revenues might be too low to cover the associated system costs (DC/AC inverter, investment for communication and control system). The potential future reduction of battery investment cost at a low range of about 250 €/kWh does not change this statement. A successful economic realisation of the V2G concept could be reached in conjunction with a considerable reduction of capacity losses in battery technology, also by increasing cycle stability of battery cells. Therefore, an efficient integration of EVs in an electricity system must be based on the implementation of a sufficient charging strategy. The results of various analysed charging concepts show that a system-relevant implementation of EVs can be conducted by their integration into the existing balancing groups.

6 Outlook and Suggestion for an Efficient Integration of EVs in an Electricity System

The impact of a high penetration rate of EVs on eight different LV grids (located in rural and urban areas) is analysed in Prueggler et al. (2013). The technical assignment shows that LV grids are able to integrate the resulting number of EVs derived from a 40 % penetration rate even if the implemented EVs are charged based on an uncontrolled approach. An introduction of controlled charging concepts will increase the mentioned penetration rate of EVs in LV grids from 40 % to 55 %. This signifies that controlled charging with a lower coincidence factor than in uncontrolled charging results in the integration of a higher number of EVs in LV grids without comprehensive reinforcement activities within LV grids. Therefore, depending on the chosen charging concept, a comprehensive reinforcement of LV grids is needed beyond a penetration rate of 40 % or 55 %, respectively.

In conjunction with the explanation of the relation between the chosen charging concept and its impact on LV grids, integration of EVs in the Austrian electricity system can be subdivided into two implementation stages (Fig. 8). The first stage is linked to a moderate penetration of EVs in LV grids, whereby a reinforcement of grids is not needed. The second implementation stage is defined by the comprehensive reinforcement of LV grids due to the continuation of uncontrolled or controlled charging concepts. In addition, the second implementation stage can be characterised by the introduction of intelligent charging concepts which determine

Fig. 8: Implementation Stages for E-mobility in the Austrian Electricity System from the Market Point of View and Based on an Analysis of the Impact of EVs on Selected LV Grids



Source: Prueggler et al. 2013; own adaptation and depiction

real-time charging strategies based on market information and current status in LV grids.

Based on the results of the economic assessment for various charging/discharging strategies, an efficient integration of EVs in both implementation stages can be discussed as follows:

- *First implementation stage: Integration of EVs in existing balancing group – current electricity market architecture*. A balancing group representative can deploy/use flexible equipment among other operation modes in times of deviation between electricity generation and consumption within the balancing group. This results in a reduction of the deviation of the balancing group and linked balancing energy costs. Therefore, a new task for a balancing group representative can be the determination of EV charging strategies fitting to the own requirements, whereby the desire of the vehicle users for specific battery states at defined times must be considered. Furthermore, vehicle users take over the charging costs incurred and the balancing group representative can spend the saved imbalance costs on a required energy management system and associated communication infrastructure for EV charging.
- *Second implementation stage: a new stakeholder*. This implementation stage of EVs begins as a result of a high integration rate of EVs in the transportation sector and the possible existence of mature smart grid applications in an electricity system. For this stage, many studies mention the introduction of a new stakeholder in the electricity market model, which is mostly called the “aggregator”. The duties of the aggregator are to provide mobility-derived services. The aggregator has the ability to charge and discharge EVs according to different target functions, which are based on its know-how of existing electricity services in the electricity sector (see Clement-Nyns et al. 2010; Galus et al. 2010; Kristoffersen et al. 2010 and EU-Smart Grids 2011). It can be stated that an aggregator represents EVs in the electricity market and takes over all needed interaction with other existing stakeholders. The aggregator determines charging and discharging concepts after own requirements with consideration of driving patterns and the mobility needs of electric vehicles.

A comparison between the roles of a balancing group representative and the tasks of an aggregator shows an obvious similarity between them. Due to the assumed existence of mature smart grid applications in this second stage, distribution system operators are informed about the actual status in their own grids. Once an enhanced form of the balancing group representative is defined in the electricity system, coordination between times of controlled charging and local grid status (mainly LV grid) must be conducted (intelligent charging). This is the main distinction from the first implementation stage and represents an enhanced form of a balancing group representative.

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