DISSERTATION

Integration of Electric Vehicles in the Austrian Electricity System

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To my mother

Abstract

The attainment of settled Austrian climate and energy targets requires a coordinated framework and contribution from all existing economic sectors. In this conjunction, the electricity supply industry and transportation sector can support this aim by taking accurate targets that can be based on electricity generation from renewable energy sources and deployment of more efficient propulsion systems for passenger vehicles.

The support of alternative propulsion technologies like electric vehicles being integrated into the transportation and electricity system must be based on efficient and economically reasonable implementation concepts. A successful integration of EVs is affected by adequate business cases, 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.

This thesis tries to recommend an efficient way to implement electric vehicles in the electricity sector. This work answers the following questions:

- What kind of system-relevant V2G and G2V concepts can be designed?
- What are the impacts of framework conditions in an electricity market with regard to the economic performances of analysed charging/discharging strategies (business models) and their use cases?
- How do cost-benefit effects influence involved stakeholders (consumers, producers, retailers, mobility providers, vehicle owners, system operators, etc.)?
- What kind of charging/discharging concept or use case could efficiently support a system-relevant integration of EVs in an electricity system?

The selected approach within this work is based on systematic analysis of various charging and discharging concepts, which are subdivided into: uncontrolled, controlled and intelligent charging and discharging strategies. The considered concepts are allocated to the controlled one. They are subdivided into the following: market-based charging/discharging strategies (participation of electric vehicles in frequency reserve markets in the Austrian control zone), load-based charging/discharging strategies and generation-based charging/discharging concepts. In this conjunction, participation of electric vehicles in frequency reserves markets in the Austrian control zone and also their integration in a fictional balancing group with different generation structures are analysed. A combination of generation-based charging (charging from PV generated electricity at home), load-based charging from 00:00 a.m. to 06:00 a.m. and discharging (in times with high household electricity demand) describes the last determined application.

In all analysed applications, discharging of batteries (LiFePO4- batteries) cannot achieve sufficient revenues. This makes an economical realisation of such concepts unfeasible. The main reason is high battery capacity loses 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 particular, the estimated revenues due to participation of electric vehicles in frequency restoration reserve markets in the Austrian control zone cannot be realised because of existing competitors: pumped hydro energy storage (major provider of restoration reserve) have lower electricity generation costs than the degradation costs of batteries. So, discharging concepts are classified as non-realisable strategies. Therefore, the discussion

about efficient implementation of electric vehicles in the Austrian electricity system is based on allocation of system-relevant charging concepts.

In terms of economic analysis and also the impact of a high penetration level of electric vehicles on low voltage grids (LV-grids), a system-relevant integration of EVs is subdivided into two various implementation stages. The first stage is linked to a moderate penetration of EVs in LV-grids, whereby a reinforcement of grids due to integration of EVs is not needed. The second stage is characterised by a high number of EVs in the Austrian electricity system and assumes the existence of a mature smart grids infrastructure, which allows the realisation of intelligent charging and consideration of the actual grid situation in determining charging strategies.

An efficient integration of electric vehicles in the Austrian electricity system within both implementation stages is given by the integration of electric vehicles in existing balancing groups, whereby balancing group representatives (enhanced form in the second stage) set charging concepts according to their own requirements. The desire of the vehicle users for specific battery states at defined times must also be considered (fulfilment of mobility needs).

The charging of EVs by a balancing group representative (or enhanced form of it in the second implementation stage) according to own requirements (e.g. reduction of needed balancing energy) and generation/consumption portfolio also supports an effective integration of renewable technologies in the Austrian electricity system. In this conjunction, vehicles can be charged in times of existing renewable surplus energy (depending on the generation portfolio of the balancing group). Enhanced balancing group representatives in the second implementation stage have a more advanced collaboration with distribution system operators compared to the current relationships in the electricity market. The balancing group representatives consider the grid status in the determination of an intelligent charging strategy, whereby the relevant grid data are published by the distribution system operators in order to guarantee a non-discriminatory access for involved stakeholders.

Kurzfassung

Um österreichische Klima- und Energieziele erreichen zu können, wird die Festlegung einer koordinierten Rahmenbedingung und gemeinsamen Beteiligung aller Wirtschaftszweige benötigt. Der Elektrizitäts- und Verkehrssektor können mittels Einsatz erneuerbarer Technologien und Integration emissionsarmen Antriebstechnologien im Personenverkehr einen essentiellen Beitrag zur Erreichung dieser Ziele leisten.

Die Integration von Elektrofahrzeuge in die Elektrizitätsstruktur soll basierend auf eine wirtschaftliche und systemrelevante Implementierung erfolgen. Eine erfolgreiche Integration von Elektrofahrzeuge wird von adäquaten Lade- und Entladestrategien beeinflusst, welche unterschiedliche Zielfunktionen erfüllen. Dabei soll die Erfüllung von Mobilitätsbedürfnissen der Fahrzeugnutzer als eine wichtige Rahmenbedingung der Zielfunktionen berücksichtigt werden.

In dieser Arbeit werden Empfehlungen im Zusammenhang mit relevanten Implementierungsmöglichen von Elektrofahrzeuge in die Elektrizitätsstruktur abgegeben, dabei werden folgenden Forschungsfragen adressiert:

- Welche systembezogenen G2V (Grid-to-Vehicle)- und V2G (Vehicle-to-Grid)-Konzepte können konzipiert werden?
- Welchen Einfluss haben veränderte Rahmenbedingungen im Energiemarkt auf die wirtschaftliche Bewertung der Geschäftsmodelle?
- Welche Kosten-/Nutzeneffekte sind für die involvierten Marktteilnehmer in den Geschäftsmodellen gegeben?
- Mit welchen Lade- bzw. Entladestrategie kann die Durchdringung der E-Fahrzeuge in der Elektrizitätswirtschaft unterstützt und auf eine effiziente Weise ermöglicht werden?

Zur Beantwortung dieser Fragen wird eine systematische energiewirtschaftliche Analyse von unterschiedlichen Lade- und Entladestrategien verfolgt. Diese werden unterteilt in: ungesteuerte, gesteuerte und intelligenten Strategien/Konzepte. Die hier bewerteten Konzepte beziehen sich zur Gänze auf gesteuerten Strategien, die aus folgenden Applikationen bestehen: Marktorientiert gesteuertes Laden/Entladen, erzeugungsorientiert und lastorientiert gesteuertes Laden/Entladen.

In diesem Zusammenhang wird die Teilnahme der Elektrofahrzeuge an den Regelenergiemärkten in der APG (Austrian Power Grid) Regelzone sowie deren Integration in einer fiktiven Bilanzgruppe (virtueller Zusammenschluss von Verbrauchern und Erzeugern) untersucht. Eine kombinierte Strategie bestehend aus erzeugungsorientiert gesteuertem Laden (aus PV-Erzeugung), lastorientiert gesteuertem Laden (in den Nachtstunden) und Entladen (in Zeiten mit tendenziell hohen Lasten) der Elektrofahrzeuge bildet den letzten untersuchten Anwendungsfall.

In allen untersuchten Anwendungsfällen kann die Energierückspeisung aus den Batterien (LiFePO4- Batterien) aufgrund des niedrigen Niveaus der Erlöse derzeit als nicht realisierbar eingestuft werden. Die Gründe liegen in den hohen Kapazitätsverlusten und den daraus resultierenden Degradationskosten der Batterien. Damit ist es unwahrscheinlich, dass die berechneten Erlöse die Kosten für Wechselrichter (DC/AC), Kommunikationsinfrastruktur und Entladesteuerung übersteigen. Vor allem sind die Erlöse der Elektrofahrzeuge bei Teilnahme an den Regelenergiemärkten als nicht realisierbar einzuschätzen, da

konkurrierende Anbieter wie z.B. Pumpspeicherkraftwerke geringere Stromspeicherungskosten im Vergleich zu den Degradationskosten der Batterien aufweisen. Daher ist eine Einbindung der Elektrofahrzeuge ins Energiesystem lediglich durch gezielte Ladestrategien als effizient zu erachten. In Bezug auf energiewirtschaftlichen Analysen und Auswirkung einer hohen Durchdringungsrate der Elektrofahrzeuge auf Niederspannungsnetze, ist die effiziente Implementierung der Elektromobilität in Elektrizitätswirtschaft in zwei Phasen unterteilt worden. Die erste Implementierungsphase ist durch eine moderate Durchdringung von Elektrofahrzeugen gekennzeichnet, wobei die Integration dieser Anzahl an Elektrofahrzeugen im Niederspannungsbereich keine Netzengpässen hervorruft. Die zweite Implementierungsstufe ist charakterisiert durch eine hohe Durchdringung von Elektrofahrzeuge unter Einsatz technisch ausgereifter Smart-Grids Anwendungen/Algorithmen die eine Realisierung von intelligentem Laden unter Berücksichtigung der Netzzustände in den Ladestrategien ermöglicht.

Eine systembezogene und effiziente Integration der Elektrofahrzeuge in die Elektrizitätsstruktur kann in beiden Implementierungsphasen durch Integration in bestehenden Bilanzgruppen erfolgen. Dabei kann das Laden der Fahrzeuge unteranderem im Sinne des Ausgleichs der bestehenden Bilanzgruppen bewerkstellig werden. Die Ladestrategie wird seitens der Bilanzgruppenverantwortlichen (oder einer erweiterten Form von diesem Marktteilnehmer in der zweiten Implementierungsstufe) an eigenen Bedürfnisse (Erzeugungs- und Verbrauchsprofil) angepasst. Eine Ökobilanzgruppe kann hier zusätzlich in Zeiten mit Fahrplanabweichungen (erneuerbare Elektrizitätserzeugung > Verbrauch der Bilanzgruppe) das Laden der Fahrzeuge vornehmen und somit eine effizientere Integration von erneuerbaren Erzeugungstechnologien in elektrische Versorgungsstruktur vorantreiben. Dabei soll die Erfüllung der Mobilitätsbedürfnisse der Fahrzeugnutzer nicht außer Acht gelassen werden. Der Vorteil dieser Strategie liegt darin, dass einerseits die verursachten Ladekosten seitens der Elektrofahrzeuge übernommen werden und andererseits der Bilanzgruppenverantwortlicher Ausgleichsenergiekosten einsparen kann. Diese Einsparungen könnten schließlich zur Finanzierung der Ladesteuerung genutzt werden.

Die erweiterte Form von Bilanzgruppenverantwortlichen in der zweiten Implementierungsphase weist eine engere Zusammenarbeit mit lokalen Verteilnetzbetreibern im Vergleich zu derzeitigen existierten Interaktionen im Elektrizitätsmarkt auf. Verteilteilnetzbetreiber sind in dieser Phase aufgrund der vorhandenen technisch ausgereiften Smart-Grids Anwendungen immer über den aktuellen Zustand der Netze informiert. Um die aktuellen Netzzustände mit vorgegebenen intelligenten Ladenstrategien seitens der erweiterten Bilanzgruppenverantwortlichen berücksichtigen zu können, kann der Verteilnetzbetreiber die aktuellen Netzzustände den Bilanzgruppenverantwortlichen, diskriminierungsfrei und transparent zur Verfügung stellen.

Executive summary

Motivation

The propulsion systems of passenger vehicles are generally based on internal combustion engines. This technological structure in combination with the estimated development of existing vehicles will intensify environmental damage. The European Union (EU) has recognized the mentioned aspects in conjunction with the development of transportation and mitigates these problems with targeted regulatory schemes and guidelines. The aim is to both start and support actions against the increasing levels of emissions by pollutants and GHG and also address fossil fuel dependence within the Member States.

The support of alternative propulsion technology being integrated into the transport and electricity system must be based on efficient and economically reasonable implementation. A successful integration of EVs 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, 2011], the business models for e-mobility need to show a so-called multidimensionality that consists of target groups (age group [young and old], students, commuters, frequent drivers, etc.), products (tariff models, energy packages) and services (sharing/renting models, mobility as a comprehensive package in combination with public transportation).

On the other hand, the business models – target functions – for EVs could be oriented to the demands and optimization possibilities in an electricity system, whereby the mobility needs must be fulfilled each time. In conjunction with the integration of EVs in an electricity system, appropriate business models are subdivided into two models, one of which concerns the mobile lifetime of vehicle batteries while the other concerns reuse of them after their automotive lifetime. The models for the mobile lifetime of batteries consist of use cases for targeted charging (Grid to Vehicle – G2V) and discharging strategies (Vehicle to Grid –V2G).

Core research questions

The overall objective of this thesis is to analyse how an efficient integration of electric vehicles (EVs) in the Austrian electricity system could be designed. In pursuit of this global objective, this thesis addresses the following questions:

- What kind of system-relevant V2G- and G2V-concepts can be designed?
- What are the impacts of framework conditions in an electricity market with regard to the economic performances of analysed charging/discharging strategies (business models) and their use cases?
- How do cost-benefit effects influence involved stakeholders (consumers, producers, retailers, mobility providers, vehicle owners, system operators, etc.)?
- What kind of charging/discharging concept or use case could efficiently support a system-relevant integration of EVs in an electricity system?

Method of approach

The considered business models for analysing the implementation of EVs in an electricity system are subdivided into two prime groups:

- The first category, which refers to the mobile lifetime of batteries and consists of

different charging (G2V) and discharging (V2G) strategies that are subdivided into the following:
    - Uncontrolled charging strategy
    - Controlled charging/discharging concepts
    - Intelligent charging/discharging strategies
- The second classification, which takes into account the reusing of batteries after their automotive retirement (second-life concept).

Identification of an efficient way to implement EVs in an electricity system is the aim of creating and analysing possible charging/discharging strategies. The goal of assessment of the second-life concept is given in the economical calculation of the minimum remaining battery (Li-ion battery) lifetime needed for reusing purposes. The considered charging and discharging strategies are:

- Market-based charging/discharging strategy: Participation in frequency reserve markets
- Generation-based charging/discharging strategy: Integration of electric vehicles in a fictional balancing group with various generation structures
- Generation- and load-based charging/discharging strategy: Charging at home if PV generation is available or from 00:00 to 06:00 hours; discharging of EVs at home in times of high electricity demand from 07:00 p.m. to 09:00 p.m.

Results and Conclusions

The participation of EVs in frequency reserve markets is conducted from an electricity system's point-of-view. Without consideration of the competitive situation of EVs with other providers of positive frequency reserve restoration (FRR), revenues are obtained between 45 € and 119 € per vehicle and year (participation in positive automatic FRR market). The costs incurred for the communication infrastructure and DC/AC converter are not considered in the estimation of the above revenues. The consideration of major competitors ("pumped hydro energy storages"; main supplier of positive FRR) shows that degradation costs of Li-ion batteries are much higher than the marginal costs of pumped hydro energy storages. On the other hand, the establishment of an international cross-border balancing market based on a common merit order will result in higher competition between the FRR suppliers and a reduction of offered balancing energy prices on an international cross-border balancing market. Therefore, the realisation of participation of EVs in positive FRR markets cannot be recommended in the current national market structure – not beneficial on the contrary to pumped hydro energy storages – and also in the future international cross-border balancing market.

Generally, the participation of EVs in negative manual/automatic FRR markets (times with existing surplus electricity within a control zone) with the assumed power and balancing energy prices obtains a spread of revenues between -87.6 € and 70.80 € per vehicle and year. From a competition point-of-view, EVs are able to provide negative FRR. However, even other small suppliers – like heat pumps – can also do the same with technological advantages. The stationary installation and thermal inertia of buildings are beneficial for the estimation of available reserve capacity of heat pumps in comparison to EVs. The mentioned properties of heat pumps enable high flexibility in the provision of different balancing products and therefore can easily contest EV shares in the negative FRR markets.

Therefore, it can be stated that the covering of costs incurred (organisation and communication expenditure) due to the participation of EVs in negative FRR markets with consideration of dispatch probability (1.34 % for negative manual FRR and 17.74 % for automatic FRR), alternative/future competitors and future establishment of an international cross-border balancing market seems to be impossible or very difficult.

Then, two different approaches to maintaining a balance between electricity generation and consumption regarding the integration of EVs in a fictional balancing group are analysed and subdivided into the following:

- Combined charging and discharging concepts for the implementation of EVs within the balancing group
- Charging concept for the implemented EVs within the balancing group only.

The combined charging and discharging concept for maintaining a balance between electricity generation and consumption of the created fictional balancing group results in higher cost incurred than in the charging-only concept (a difference of about 100 %). The reason is the high degradation costs of Li-ion batteries. Despite the assumed low battery investment cost of 500 €/kWh, the regarded battery degradation costs cannot be covered by revenues due to the selling of discharged electricity on day-ahead or intra-day markets.

In case of utilization of charging concept only, the charging costs (determination of charged electricity with electricity prices on day-ahead or intra-day markets) will be covered by vehicle users. On the other hand, the use of EVs (controllable devices) results in cost saving for non-consumed balancing energy. The saved balancing costs are between 32 € and 150 € per week.

Therefore, 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. The saved balancing costs can be spent and used for the control infrastructure needed for charging EVs.

The economical assessment of a combined generation- and the load-based charging/discharging strategy is comprised of the following:

- Determination of the possible diminishing of the transformation station dimension from a distribution system operator’s point-of-view.
- Estimation of possible revenues due to discharging vehicles within the time spread of 07:00 p.m. and 09:00 p.m.

Despite a penetration rate for EVs of about 40 % in LV-grids (the same number of PV units as EVs are also integrated), the combined generation- and load-based strategies do not affect the dimensioning of the transformation station. On the one hand, generation-based charging (from PV electricity generation) cannot store peak PV electricity generation (location: home) because of the non-availability of EVs during the times of peak PV electricity generation. On the other hand, the high penetration ratio of EVs (higher number of existing loads in LV-grids) does not increase the maximal load at the transformation station, because of possible charging from 00:00 a.m. to 06:00 a.m. and consideration of a low coincidence factor by charging. The discharging from 07:00 p.m. to 09:00 p.m. reduces the sum load of the transformation station but does not affect the maximum occurring value of the sum load profiles of analysed LV-grids.

The load-based discharging of EVs between 07:00 p.m. and 09:00 p.m. obtains positive revenues for any cases (driving patterns, household profile, availability at home and strength of solar radiation) from battery investment costs of 500 €/kWh downwards. The yearly revenues potential is given at around 50 € per year and vehicle (battery investment cost of 500 €/kWh). Due to a successful realisation 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 needed DC/AC converter. The realisation of the V2G concept in regard to the covering of the household electricity load profile is not able to cover all the costs accrued from the high level of battery degradation due to battery discharging.

Despite choosing an application for battery reusing, which shows high revenue potential, a long second lifetime of more than four years is needed to inspire an investment in this further application. The reaching of the mentioned minimum lifetime for the use of a battery after its mobile retirement depends on the stability of Li-ion battery technology and the remaining usable battery capacity.

The various analysed discharging strategies are not realisable because of capacity losses due to discharging and the resulting high degradation costs. The calculated revenues are too low to cover the associated system costs (DC/AC inverter, investment for communication and control system). The reduction of battery investment cost at a low range of about 250 €/kWh does not change this statement. A successful economical realisation of the V2G concept could be reached in conjunction with a considerable reduction of capacity losses in battery technology.

Therefore, an efficient integration of EVs in Austrian 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. Therefore, the target function of charging strategies is oriented to the requirements of balancing group representatives and linked consumption/generation portfolios.

Suggestion for an efficient integration of EVs in the Austrian electricity system

The economical assessment of mentioned charging strategies in this work are generally based on analysing the potential revenues for involved stakeholders, whereby the revenues are derived for each one of the considered EVs with associated diving pattern. On the other hand, the impact of a high penetration rate of EVs on eight different LV-grids (located in rural and urban areas) is analysed in [Prueggler, 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 charging approach (see definition in chapter 2.2). This means that a comprehensive reinforcement of LV-grids will not be needed until the mentioned penetration rate of EVs is reached. An introduction of controlled charging concepts, more precisely, load- and generation-based charging strategies 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 obtains integration of a higher number of EVs in LV-grids without comprehensive reinforcement activities within LV-grids. Therefore, depending on the chosen charging concept – uncontrolled or controlled strategy – 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 is subdivided into two implementation stages (see Figure 1). The first stage is linked to a moderate penetration of EVs in LV-grids, whereby a reinforcement of grids due to the integration of EVs is not needed. The second implementation stage begins after the first and is defined by the comprehensive reinforcement of LV-grids due to the continuation of uncontrolled or controlled charging concepts. The second implementation stage can also be characterised by the introduction of more complicated intelligent charging concepts, which determine real-time charging strategies based on market information and current status in LV-grids.

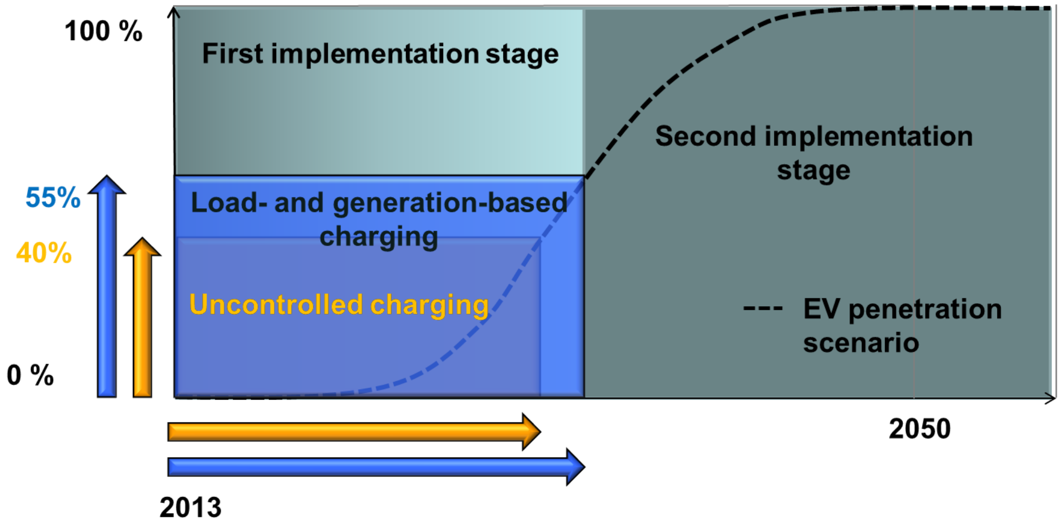

Figure 1: Implementation stages for e-mobility in the Austrian electricity system from the market point of view and based on an analysis of the impact of e-mobility on selected LV-grids (Source [Prueggler, 2013], own adaptation and depiction)

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:

- <u>First implementation stage, Integration of EVs in existing balancing group:</u> 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, linked balancing energy costs and furthermore the amount of activated frequency restoration reserves and associated costs within the control zone. EVs are suitable equipment (existing flexibility, long periods of inactivity and no investment costs [purchase of EVs] for balancing group representatives) to be integrated in existing balancing groups based on a charging concept that also considers the deviation between electricity generation and consumption within balancing groups. Therefore, a new task for a balancing group representative can be the determination of 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 needed energy management system and associated communication infrastructure for EV charging.

According to the existing architecture in the Austrian electricity market, a balancing group representative is able to announce intraday changes of internal schedules (within the APG control zone) 15 minutes ahead of each quarter-hour to the balancing group coordinator [E-Control, 2010]. A reduction of the mentioned time spread would increase the flexibility of the balancing group representative and support a more suitable (near to real-time) controlling of EV charging.

The implementation of EVs in an existing balancing group is based on current electricity market architecture. This means that a change or extension of the interaction between market participators or the integration of a new stakeholder for charging EVs is not necessary during the first implementation stage of EVs. Only the suggested reduction of the existing 15 minutes time spread regarding schedule changes needs an adaption of relations between affected stakeholders.

- 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. Development of smart grids in this stage occurs if the development of such technologies is more cost- and system-efficient than the actual electricity system design. For this stage (a high penetration rate of EVs in transportation), many previous studies mention the introduction of a new stakeholder in the electricity market model, which is mostly called the “aggregator” or “e-Mobility provider”. It can be stated, that an aggregator – whatever the control strategy might be – 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 the mobility needs of the controllable electric vehicles.

  A comparison between the roles of a balancing group representative and the tasks of an e-mobility aggregator shows an obvious similarity between them. In the case of a high range of EVs in the transportation sector an enhanced form of balancing group representative can be established in the electricity market. Due to the assumed existence of mature smart grid algorithms/applications in this stage, distribution system operators are informed about the actual status in their own low and also medium voltage 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. Due to a high range of existing vehicles, an efficient use of available grid (LV-grids) reserves, which can prevent or postpone LV-grid reinforcement, is more important and needs to be considered in controlled charging strategies.

From the complexity of the legal, economic and regulatory frameworks, the provision of grid data to an energy management system of an enhanced balancing group representative is easier to realise than the intervention of distribution system operator in the infrastructure of the balancing group representative. However, compliance with grid restrictions, according to the first approach, will also be a task for the enhanced balancing group representative. Therefore, the distributed system operator is obliged to publish relevant grid data based on a non-discriminatory access for involved stakeholders, e.g. balancing group representatives.

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1 Introduction

1.1 Motivation

The mass development of transportation was formed in the OECD (Organisation for Economic Co-operation and Development) countries during the 20th century. The rise in the number of both passenger and transport vehicles is linked to emissions of pollutants and greenhouse gases (GHG) as well as fossil fuel dependence [Kloess, 2011a]. [Dargay, 2007] estimates the worldwide prevalence of passenger cars in 2030 to be in the range of 2 billion vehicles (800 million vehicles in 2002). The amount of registered vehicles in non-OECD countries, like China, India and so on, is estimated to be at about 56 % in 2030.

The propulsion systems of passenger vehicles are generally based on internal combustion engines. This technological structure in combination with the estimated development of existing vehicles will intensify environmental damage. The European Union (EU) has recognized the mentioned aspects in conjunction with the development of transportation and mitigates these problems with targeted regulatory schemes and guidelines. The aim is to both start and support actions against the increasing levels of emissions by pollutants and GHG and also address fossil fuel dependence within the Member States. As an example, regulation 510/2011 [EU, 2011] limits the CO_2 emissions of new light commercial vehicles and sets a target for 2020 of 147 gCO_2/km on average for emissions of these registered vehicles in the EU. Further, regulation 443/2009 [EU, 2009] sets a target of 95 gCO_2/km as the average emission rate for new passenger cars from 2020. In the context of the “Europe 2020” strategy, a scheme for clean and energy-efficient vehicles – green cars – has been introduced, which sets a framework that supports the development and penetration of these vehicles. This initiative considers different propulsion technologies, like internal combustion engines, vehicles with alternative fuels (biogas, gas) and electric and fuel cell vehicles. Therefore, the implementation and integration of electric vehicles (EV) in the transportation sector can be argued as an option for mitigating environmental problems and reducing fossil fuel dependence. This perspective also constitutes an important development project for the Austrian transportation system because the system depends almost completely on fossil products. Road transport consumes 91 % of the total energy used in the Austrian transportation system [Herry, 2007]. A high range of penetration of electromobility (e-mobility) in road transport results accordingly in a significant reduction of CO_2. In the case of Austria, a 100 % substitution of passenger cars with EVs, which would be charged with renewable energy, would result in an emission reduction of about 75 %, which is equivalent to 93 million tones of CO_2-aquivalent, respectively.

The support of alternative propulsion technology being integrated into the transport and electricity system must be based on efficient and economically reasonable implementation. A successful integration of EVs 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, 2011], the business models for e-mobility need to show a so-called multidimensionality that consists of target groups (age group [young and old], students, commuters, frequent drivers, etc.), products (tariff models, energy packages) and services (sharing/renting models, mobility as a comprehensive package in combination with public transportation).

On the other hand, the business models – target functions – for EVs could be oriented to the demands and optimization possibilities in an electricity system, whereby the mobility needs must be fulfilled each time. In conjunction with the integration of EVs in an electricity system, appropriate business models are subdivided into two models, one of which concerns the mobile lifetime of vehicle batteries while the other concerns reuse of them after their automotive lifetime. The models for the mobile lifetime of batteries consist of use cases for targeted charging (Grid to Vehicle – G2V) and discharging strategies (Vehicle to Grid –V2G). As stated by [Timm, 2011], they can be associated with the term “products”. The vehicles can be recognised in the G2V-concepts as shiftable loads and in V2G-concepts as mobile storages.

1.2 Core research questions

The overall objective of this thesis is to analyse how an efficient integration of electric vehicles (EVs) in the Austrian electricity system could be designed. In pursuit of this global objective, this thesis addresses the following questions:

- What kind of system-relevant V2G- and G2V-concepts can be designed?
- What are the impacts of framework conditions in an electricity market with regard to the economic performances of analysed charging/discharging strategies (business models) and their use cases?
- How do cost-benefit effects influence involved stakeholders (consumers, producers, retailers, mobility providers, vehicle owners, system operators, etc.)?
- What kind of charging/discharging concept or use case could efficiently support a system-relevant integration of EVs in an electricity system?

By analysing the above-mentioned questions and consideration of the functioning of an electricity market model with involved stakeholders an efficient integration of EVs is discussed for different penetration stages.

1.3 Methodology

The objective of this thesis is implemented by defining related business models for EVs with associated use cases and descriptions of the main influencing factors. This is followed by the consideration of involved stakeholders and an assessment of their economic performances within each use case. The results of the mentioned economic performances concerning the stakeholders’ position in the electricity market results in suggestions for an efficient integration of EVs in different implementation phases.

1.4 Structure of the thesis

An overview of the current framework of liberalized electricity markets is given in chapter 2. This is subdivided into two further subchapters. The first one gives an overview of the existing ancillary services in an electricity system; more precisely, the frequency containment and restoration reserves. The second subchapter explains the allocation of imbalances in an electricity system and derived energy balancing costs.

Chapter 2 introduces the business models related to EVs from an electricity system point of view. The business models will be separated into subgroups: during and after the automotive lifetime of batteries in electric vehicles. Each business model consists of use cases, which consider the global and local aspect of the Austrian electricity system. The definition of each use case is also based on a literature overview and a short explanation of the results of various use cases – if available – in other electricity systems.

Chapter 3 provides a detailed description of the methodological approach used for an economic assessment of the presented use cases. The used methodologies for creating the V2G/G2V concepts – charging and discharging strategies – during the automotive lifetime of batteries are based on the definition and realization of optimization models with related constraints and statistic models. The simulation of reusing battery vehicles after their automotive lifetime results from an hourly sequentially linear optimization model that defines the charging and discharging times of the stationary battery.

Chapter 4 reasones on the needed database for the described methodological approaches in the previous chapter. The database consists of estimated prices on electricity and balancing energy markets in Austria in 2020, activated balancing energy in the APG (Austrian Power Grid) control zone, generation and load profiles, battery properties and driving patterns of vehicle users.

Chapter 5 describes the results of each use case and the respective contribution margins of involved stakeholders.

In Chapter 6, conclusions are derived.

Chapter 7 discusses and outlines – based on the economic assessment of use cases and the position of the involved stakeholders – an efficient integration of EVs in the Austrian electricity system. Therefore, the discussion focuses on time periods with varying implementation levels of EVs in the Austrian electricity system.

2 Background

The details given in this chapter refer to the framework of a liberalized electricity market. Starting in 1999, [Directive 96/92/EC] of the European Parliament and the Council had made significant, yet gradual contributions towards the liberalization of electricity markets in the Member States. Since 2001 the Austrian electricity market has been fully opened for competition and therefore consumers are free to choose any suppliers. The Austrian electricity market is operated by a cooperation of various market players and consists of the following:

- Control area managers (CAMs)
- Balancing group coordinator – Clearing and settlement agent (APCS) -
- Transmission system operators (TSOs)
- Balancing group representatives (BGR)
- OeMAG (settlement agent for green electricity) (German: Abwicklungsstelle für Ökostrom AG)
- Distribution system operators (DSOs)
- Suppliers
- Generators
- Electricity wholesalers, retailers and traders[1]

The possibility of consumers for 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[2].

The existing markets in an electricity system are organized as spot or bilateral markets. A spot market is operated by a central electricity exchange that receives the bids and offers of the market participants. The market settles based on accepted bids and offers a uniform price – the single marginal price. The single marginal price is defined as the price of the most expensive accepted bid. The physical delivery of electricity is typically performed on the day after gate closure [Obersteiner, 2010].

Power trading in bilateral markets is based on bilateral contracts. A high volume of exchanged electricity is traded in long-term contracts, which are based on bilateral agreements. The reason for the interest in long-term contracts[3] (years or months ahead of physical delivery) lies in the hedging of short-time price risks in day-ahead markets.

Besides day-ahead markets, intra-day markets have been introduced by some power exchanges thus mitigating the volatile electricity generation of renewable energy sources, particularly wind power. The intra-day markets are organized based on short-term bilateral contracts. As an example, on the intra-day market of the European Energy Exchange Spot

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[1] The definition of the role of the above market players and their relationship is described by the Austrian regulator authority in [E-Control, 2011].

[2] The balancing groups can be subdivided into three main categories: commercial balancing groups, balancing groups for grid losses and eco-balance group [E-Control, 2011b].

[3] The bilateral long-term contracts are subdivided into futures and forwards.

Market (EPEX SPOT; Germany), electricity can be traded for delivery on the same day in single hours or in a block of hours. Each hour or block of hours can be traded until 45 minutes before delivery starts.

Figure 2 compares the day-ahead prices of Energy Exchange Austria (EXAA) and intra-day prices of the EPEX SPOT market in Germany from 2010. The electricity prices of both markets depict almost the same median values for the whole year whereby the intra-day prices show higher volatility.

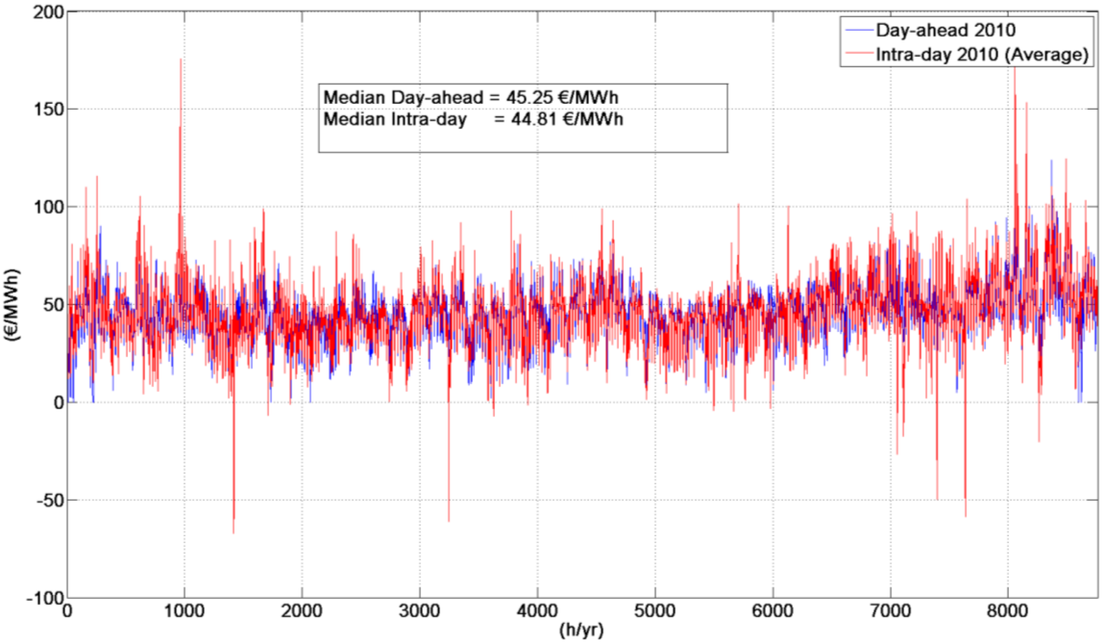

Figure 2: Comparison of the prices between the day-ahead (EXXA) and intra-day (EPEX SPOT) markets in 2010 (own depiction)

Generation and consumption in an electricity system must be equal at each instant. Due to the deviation between the forecasted and real-time needed 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, 2010]. The grid users and generation units (minimum installed capacity is 5 MW in Austria) bear the related costs of the activation of balancing energy in the Austrian electricity system.

The next subchapter examines the functioning of the mentioned balancing mechanism and related organized electricity markets in Austria. It explains also the allocation of imbalances and derived energy balancing costs.

2.1 Electricity balancing mechanism – frequency containment and restoration reserves

The amount of balancing energy needed at any point in time is derived from frequency measurements by the TSO in the high voltage grid in the corresponding control zone[4]. The amount of frequency deviation in comparison to its normal value (50 Hz) and the duration of this imbalance result in the activation of capacity reserves. The aim of this activation is to limit frequency deviation and further to restore it to normal value before an incident. 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. The intention of these lies in 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 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, 2010]. If the frequency deviation holds on in the control zone, 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 of electricity generation/demand. However, Figure 3 depicts the activation of frequency reserves due to an incident, which occurred in this specific case due to lower electricity generation than consumption.

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[4] This is defined as a geographical area where a single TSO operates the transmission network and is responsible for provision and activation of frequency containment and restoration reserves.

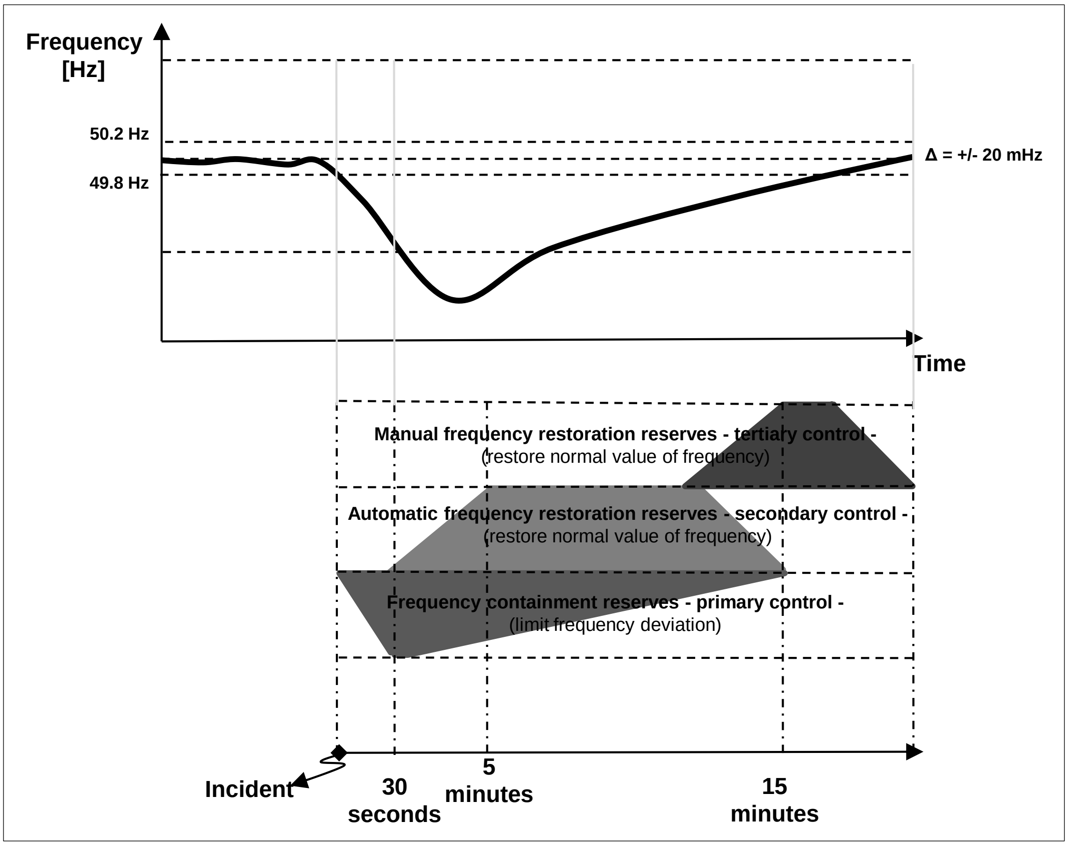

Figure 3: Retrieval of frequency reserves (own depiction)

2.1.1 Bilateral frequency reserve markets

The ensuring of needed frequency reserves for the provision of balancing energy is organised by the TSO through bilateral contracts with capacity reserve bidders. The tendering period[5] in the Austrian control zone (APG) for FCR covers the period from Monday (00:00 hours) to Sunday (24:00 hours) – a weekly product. The permanently available FCR is in a range of +/- 66 MW for 2013. A minimum bid is +/- 2 MW. Separate offers for positive[6] or negative[7] FCR capacities are not possible [APG, 2013].

The market participants (bidders) offer their reserve capacity to the market with associated prices. At the end of the bidding period – one week before the tendering period – the bids are ranked in a merit-order curve (from the cheapest to the most expensive), until the total volume of reserves (+/- 66 MW) is reached. Due to the implementation of a ”pay as bid” approach, the bidders, whose offers are accepted, receive the capacity price[8]. As mentioned in the previous chapter, the aim of frequency containment reserves (FCR) lies in the limitation of the frequency deviation after an incident. The automatic activated FCR capacity increases proportionally to the intensity of the deviation. Figure A.1 (see appendix) compares the monthly average capacity price for FCR in Austria and Germany (monthly tendering period) from January 2010 until April 2011.

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[5] The FCR is provided by contracted plants in this timeframe.

[6] Positive reserves: Increasing electricity generation and/or decreasing consumption even if generation is lower than consumption in a control zone

[7] Negative reserves: Decreasing electricity generation and/or increasing consumption even if generation is higher than consumption in a control zone

[8] There is no balancing energy price (€/MWh) for delivered energy in the frequency containment reserves (FCR) market segment.

The tendering period for automatic FRR (secondary control) in the bilateral market consists of two different products, a one week and a four-week product. Each is additionally subdivided into three product time slots:

- Peak week: Monday to Friday from 8:00 a.m. to 8:00 p.m.
- Off-peak week: Monday to Friday from 0:00 a.m. to 8:00 a.m. and from 8:00 p.m. to 00:00 a.m.
- Weekend: Saturday and Sunday from 0:00 to 24:00

In Austria, the permanently available automatic FRR is in a range of +/- 200 MW [APG, 2013] and separate tenders are implemented for positive and negative automatic FRR. The market participants (e.g. generators) offer their capacity to the market with associated reserve capacity and balancing energy prices. The submitted bids for a tendering period are sorted in a merit-order curve according to the offered reserve capacity prices until the total volume of reserves (+200 MW or -200 MW) is reached. All accepted bids – minimum bid is 5 MW – receive their offered capacity prices. In the next step, the submitted balancing energy prices of accepted bids are ranked in a merit order curve. According to the last merit order curve, the activation of reserved capacity begins at the cheapest offer. It has to be mentioned that market participators can set bids for the provision of frequency reserves, which fulfil the so-called pre-qualification requirement. For example, including other constraints, the minimum capacity changing ratio of providers for automatic FRR must be at 2 % of nominal capacity per minute (see, [FRR, 2011b]). The organisation of the capacity reserves for manual FRR (tertiary control) in the Austrian control zone is based on the same principle as described for automatic FRR. The differences are in available capacity reserves of +280 MW / -125 MW, tendering period and existing product time slots. The tendering periods are accomplished separately for both the coming weekend (Saturday and Sunday) and for the following week from Monday to Friday. Each tendering period includes six different product time slots, (0:00-4:00, 4:00-8:00, 8:00-12:00, 12:00-16:00, 16:00-20:00, 20:00-24:00).

Figure 4 presents the described award procedure and calling of automatic/manual FRR. The graph indicates that reserved capacity (maximal needed capacity for FRR) for restoration of the system frequency must not be utilized every time by the TSO.

The duration curves of the number of daily called positive frequency restoration reserves (FRR) within different years in the Austrian control zone are presented in Figure 5 and Figure 6. The 15-minute time resolution resulted in a potential of 96 possible calls within a day. The historical data from 2006 until 2010 show a reduction in the number of days that encounter a calling of manual FRR. These characteristics also result in a reduction in the amount of called manual FRR balancing energy from 2006 until 2010. The amount of, e.g., called positive manual FRR decreased from 62.47 GWh in 2006 to 9.25 GWh in 2010 resulting in a reduction of about 85 %. The activation of automatic FRR shows a different characteristic. Each day consists of several time periods with called secondary capacity. All analysed years show the same characteristics. The amount of, e.g., activated positive automatic FRR rose from 271.54 GWh in 2006 to 300.57 GWh in 2010.

From the balancing energy point-of-view, the mentioned historical data indicate the existence of higher liquidity in automatic FRR markets than in the manual FRR. This means that a frequency deviation due to an incident can usually be restored only with the activation of automatic FRR. Some future technical and market developments, like the improvement of prediction tools for estimating renewable electricity generation (RES-E) and the establishment of intra-day markets in various market areas, may intensify this trend.

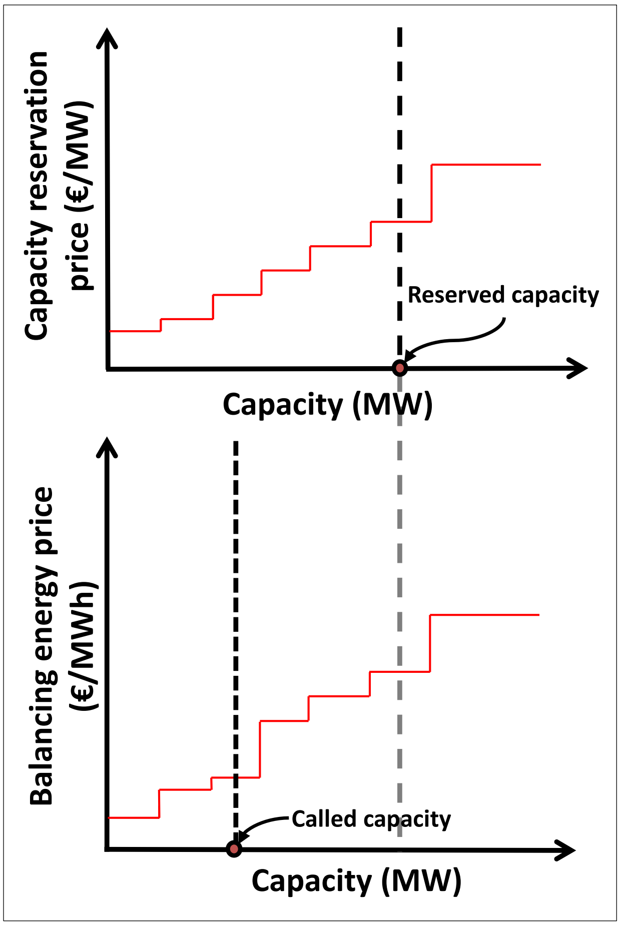

Figure 4: Award procedure and calling of automatic FRR (own depiction)

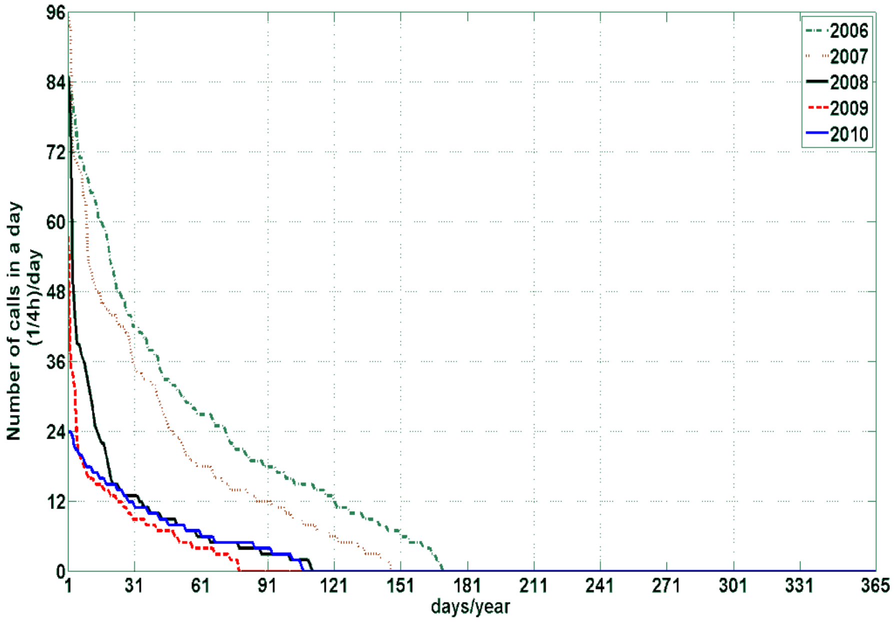

Figure 5: Number of calls of manual positive FRR in the Austrian control zone (APG) within days in different years (database [FRR, 2011a], own depiction)

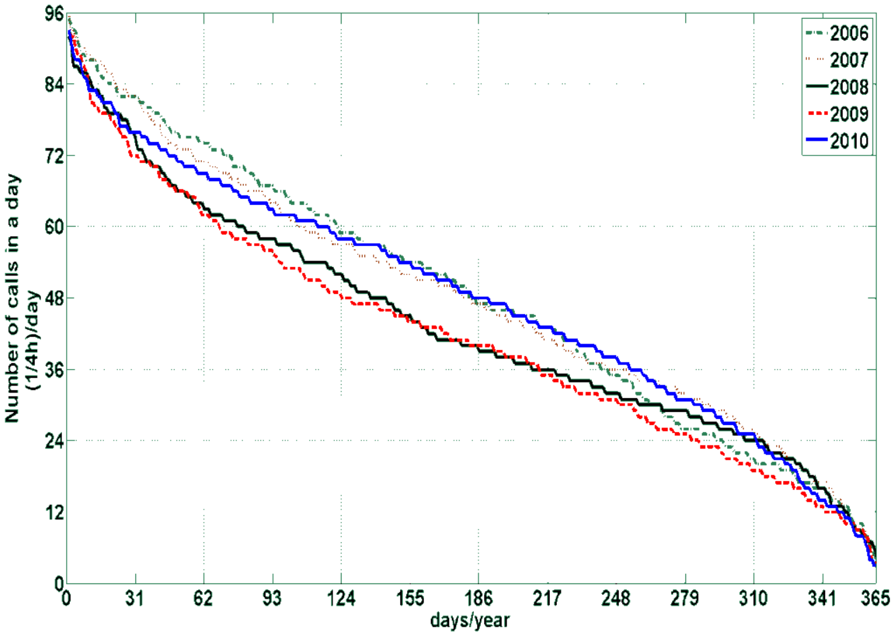

Figure 6: Number of calls of automatic positive FRR in the Austrian control zone (APG) within days in different years (database [FRR, 2011a], own depiction)

As mentioned above, the called FRR reserve capacity in each time period is maximal at the level of reserved capacity. Figure 7 depicts the yearly dispatch probability of called automatic/manual FRR which results in a ratio of called FRR to reserved capacity. Mean yearly values are derived from monthly average values. The monthly average values are calculated as a proportion of the called capacity in every time unit to the reserved capacity for each kind of FRR reserves (see equation [1]). The outcomes confirm – due to the existing higher liquidity of automatic to manual FRR – a higher dispatch probability for automatic FRR (17 % in 2010) than for manual FRR (1.34 or 0.37 % in 2010) – see Figure 7.

$$DP = \frac{\sum_{m=1}^{12} \frac{\sum_{Call=1}^{k} \frac{A_{m,Call}}{R}}{k}}{12} \qquad (1)$$

$DP: Dispatch\ probability\ (\%)$

$R: Reserved\ capacity, (MW)$

$m: Number\ of\ months$

$k: Number\ of\ capacity\ activations\ in\ a\ month$

$A: Activated\ capacity, (MW)$

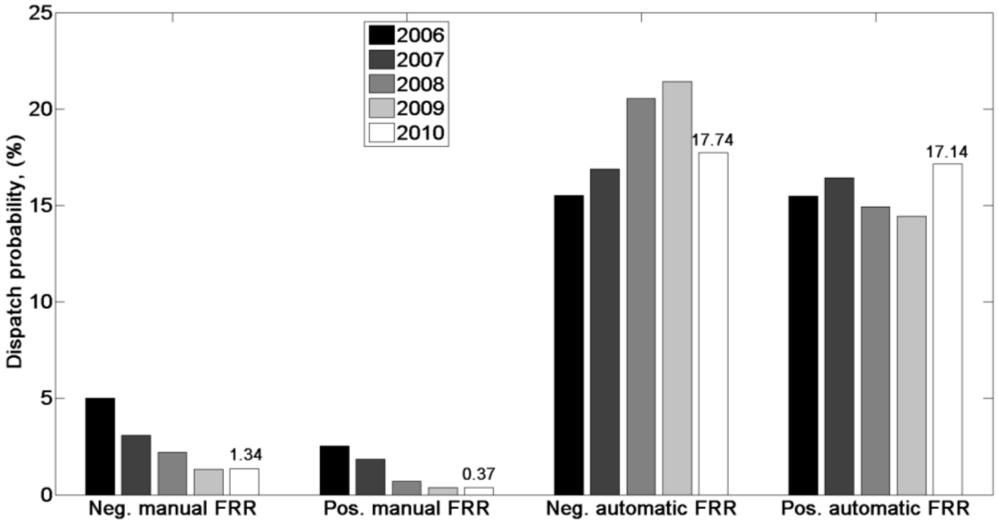

Figure 7: Mean value of dispatch probability for activated automatic and manual FRR in the Austrian control zone (APG) from 2006 to 2010 (database [FRR, 2011a], own calculation and depiction)

As previously explained, the participants in markets for automatic and manual FRR require prices to be set for reserve capacity and balancing energy. The balancing energy price for positive FRR is oriented towards the marginal cost of generators (fuel cost) and takes remuneration for corresponding flexibility into account.

For negative FRR, the generators obtain the energy price (compensation) for the reduction of electricity generation. Therefore, the currently available capacity of the generator needs to be cut back. The reduction of utilized fuel within the period of capacity reduction of the power plant results in lower energy prices for negative FRR than for positive FRR. However, in the case of generation reduction the costs due to associated efficiency losses[9] need to be considered in the balancing energy price. Figure 8 depicts the development of average balancing energy prices for negative and positive automatic FRR in the APG control zone in various years. The balancing energy price for delivery (positive) and reduction of reserve capacity is on average about 45 % and about 8 % above the average energy prices on day-ahead market from 2006 until 2010, respectively (compare [FRR, 2011a] and [EXAA, 2012]). Furthermore, [Fussi 2011] states an average capacity price for negative and positive automatic FRR of about 13 €/MW.

In 2010, the balancing energy price for manual FRR amounts to 98 €/MWh and 4 €/MWh for positive and negative FRR (average day-ahead price on EXXA in 2010: 44.81 €/MWh), respectively. The associated reserve capacity prices for manual FRR are about 1 €/MW/h and 5 €/MW/h [Fussi, 2011]. Generally, the reserve capacity price covers the opportunity costs of a generator, because due to the provision of capacity for frequency control, the generator is not able to utilise the generation capacity on, e.g., day-ahead or intraday markets.

In general, the market rules like tendering period and minimum size of offered bid affect the level of offered reserve capacity prices on the markets. As an example, two changes in

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[9] Efficiency losses happen due to high reductions of power gradients and depend on the power plant technology used [Flinkerbusch, 2011].

market rules for automatic FRR were established in Germany on 27th June 2011. On the one hand, the tendering period was reduced from one month to one week. On the other hand, the minimum bid was reduced to 5 MW (previously 10 MW). These changes resulted in a higher number of bidders offering frequency reserves, higher competition between the participants and a better estimation of the opportunity costs. Therefore, the average capacity prices in Germany in 2011 were lower than experienced in previous years (see appendix, Figure A.2).

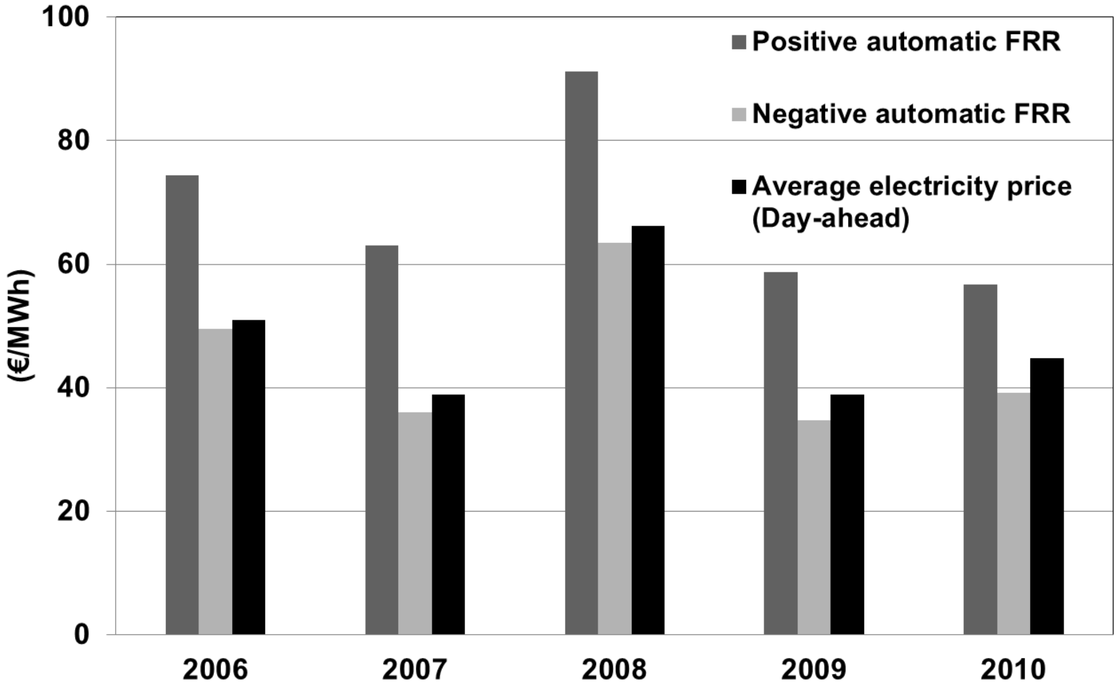

Figure 8: Balancing energy price of positive and negative automatic FRR in comparison to average electricity prices on the day-ahead market in the APG control zone (database [FRR, 2011a] and [EXAA, 2012], own calculation and depiction)

2.1.2 Assessment of balancing energy costs in Austria

As mentioned in the previous chapter, the activation of FCR and FRR is necessary due to the deviation of electricity generation and consumption. The reservation of needed capacity and its activation results in costs for ensuring a balance between electricity generation and consumption.

According to the Electricity Industry and Organization Act in Austria [ElWOG, 2010], each balancing group (BG) has to be balanced at several 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 (BGR), 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.

In Austria, the cost for balancing energy per unit is calculated by a balancing group coordinator (APCS[10]) by using the relevant databases (deviation between demand and generation for a time period, resulting cost for provision of FCR and FRR), which are

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[10] APCS: Austrian Power Clearing & Settlement

provided by the TSO. Compliant with [APCS, 2009], the following costs and incomes are considered in the calculation of the above-mentioned cost for balancing energy per unit (also known as “clearing price” [CP]):

- Costs and income of called manual FRR balancing energy
- Costs and income of provision of manual FRR reserve capacity
- Costs and income of provision and activation of automatic FRR: 78 % of associated costs (compare description of charge for system services [E-Control, 2012]) of automatic FRR will be covered by generation units with a connected generation capacity higher than 5 MW. The balancing groups bear the remaining 22 % of costs [Friedl, 2012].
- Costs and income of an inadvertent exchange between the control zones: the activated primary energy between the control zones is defined as an inadvertent exchange. In the case of receiving FCR energy, the TSO is obligated to purchase the consumed balancing energy on the energy market. The TSO compensates the volumes of inadvertent exchange in the following week in the form of a base load electricity delivery (compensation programme, weekly term).
- Costs for the provision of FCR capacity reserves are covered by generation units with a connected generation capacity higher than 5 MW in relation to their annual electricity generation.

The mentioned clearing price is defined as a function of the deviation of the control zone (deviation between electricity consumption and generation – delta of control zone) and is derived from the addition of the first clearing price and a constant value for a whole month (second clearing price). The general formation of the first clearing price is shown in Figure 9 and results from a base price and an auxiliary function (see equation [2])

$$BE_{CP,t} = BE_{BP,t} + sgn(V_t) \cdot A_t \tag{2}$$

$BE_{CP,t}$: $Balancing\ energy\ first\ clearing\ price\ (€/MWh)$
$BE_{BP,t}$: $Balancing\ energy\ base\ price\ (€/MWh)$
V_t: $Delta\ of\ control\ zone$
A_t: $Auxiliary\ function\ (€/MWh)$

The base price depends on a calculated so-called “market price for balancing energy” and the actual spot market price on EXXA. The base price increases if the delta of the control zone is positive (negative balance, consumption > generation) and decreases inversely. In that way, in times of electrical energy deficits within a control zone, the balancing groups with an electrical energy surplus will be rewarded. The auxiliary function itself is a quadratic function, being characterised as a supplement to or deduction from the base price depending on the sign of the delta.

The implementation of the described price model reduces the financial risks of the balancing group representative in times of low deviation in control zones (occurrence of lower clearing prices). This price model[11] accomplishes balancing group representative incentives regarding

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[11] The part of the cost for providing balancing energy which could not be covered by the calculated clearing price will be

the prevention of high deviations within the balancing group.

The balancing group representative reduces its own entrepreneurial risk due to the provision of a balance between electricity generation and consumption. The utilization of flexible equipment on the consumption and generation side can act against the imbalances in a balancing group. According to the explanation, storages could play a particular role whereby their optimal charging and discharging strategy would be oriented after the imbalances in the balancing group.

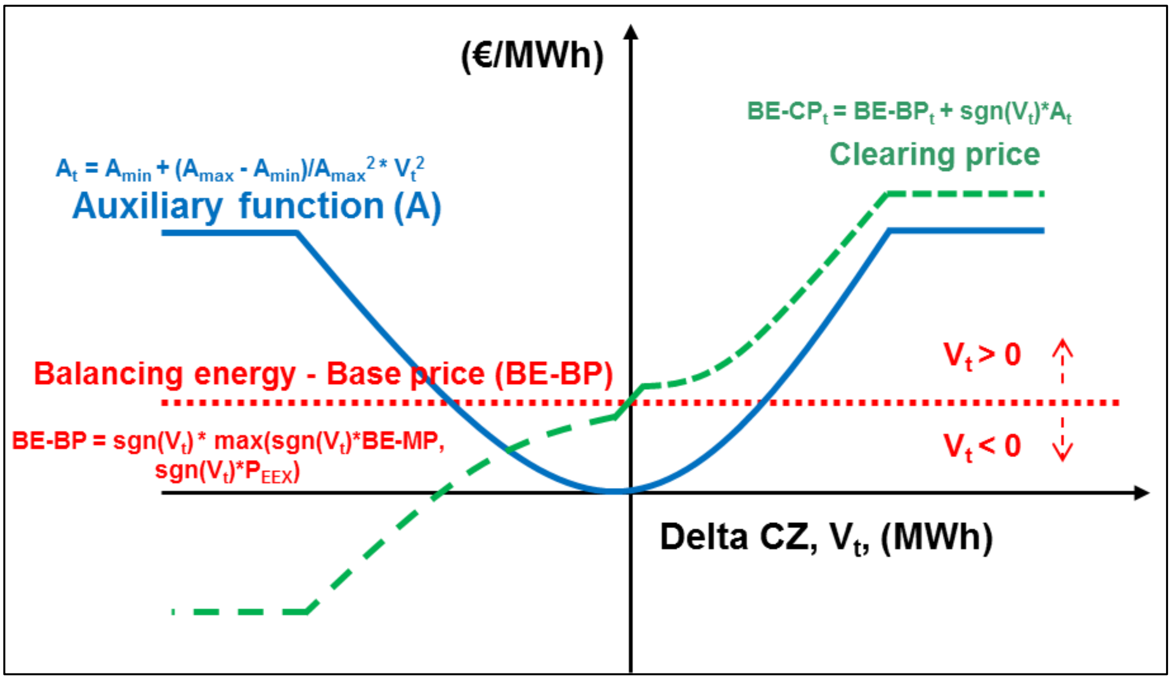

Figure 9: Formation of the first clearing price from the base price and an auxiliary function depending on the deviation between electricity generation and consumption in the control zone – delta of control zone – in Austria (own depiction)

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subdivided between the BGs. This approach is in line with a kind of reduction of financial risks [Auer, 2006].

2.2 Business models for e-mobility

The business models for implementation of e-mobility in the Austrian electricity system are subdivided into two main categories:

1. A business model which refers to the mobile lifetime of batteries and consists of different charging (G2V) and discharging (V2G) strategies that are subdivided into the following:
    a. Uncontrolled charging strategy: This concept implies that the charging of a battery starts immediately after reaching a defined location equipped with a charging station and with connection of the vehicle to the charging unit [Litzlbauer, 2012]. Charging will end if the battery is full or in the event that the vehicle is unplugged.
    b. Controlled charging/discharging concepts: These strategies are based on schedules that define the charging and discharging times of vehicles, whereby a schedule fulfils one or two predefined targets and functions with known constraints. The definition of a target function and associated constraints comes from statistical analysis of databases (e.g. electricity consumption and generation data). The resulting schedules implement the charging/discharging behaviour of vehicles and are valid/fixed for a specific time period.
    c. Intelligent charging/discharging strategies: These concepts, due to real-time electricity system information (market and grid), make feasible the definition of a schedule from different particular target functions, which fit for each system status. The implementation of this general schedule can be done manually through matching/coordination between various schedules or automatically by Smart Grid algorithms [Bacher, 2011].
2. A business model that takes into account reusing of batteries after their automotive retirement. This means that retired batteries can be used in this case as stationary batteries for different use cases (see chapter 2.2.5).

At present, comprehensive discussions are on-going in terms of efficient integration of EVs in an electricity system. Therefore, diverse charging/discharging strategies are analysed. The considered concepts are allocated to the described controlled charging/discharging strategies. They are subdivided into the following:

- Market-based charging/discharging strategies
- Load-based charging/discharging strategies
- Generation-based charging/discharging concepts.

The analysed use cases for reusing batteries generally result from a market-based charging/discharging approach (see chapter 3.5).

2.2.1 Market-based charging strategy: Cost minimising charging (STR 1)

As mentioned in the previous chapter, EVs can be charged and discharged in consideration of different G2V and V2G concepts. However, the realisation of these concepts is linked to uncertainties like local availability of vehicles and fulfilment of the constraints of target functions. As an example, only charging EVs from wind and photovoltaic (PV) sources – as a target for a G2V concept – is not always possible due to resource irregularities. Such factors, which affect the charging of EVs, must be circumvented via alternative strategies in order to fulfil the mobility needs of vehicle users and maintain user satisfaction. Such uncertainties of engaged G2V- concepts curtail the operational use of vehicles. A definition of a G2V basis concept counters this problem and occurs, if required, in combination with other G2V or V2G concepts, respectively. The G2V basis strategy is defined as a "market-based charging strategy" that alone can also fulfil the mobility needs of vehicle users. The target function (optimization function) of this G2V- concept lies in minimizing the charging costs. Meaning, in times of low electricity prices, the charging of vehicles occurs on a day-ahead market.

The market-based charging strategy occurs frequently in different studies. [Tirez, 2010] analyse an arbitrage model for the participation of EVs in spot market (Belpex, Belgian power exchange) from two varying points of view. One perspective is based on spot price changes (profit maximization). The other is based on spot price levels aiming for societal welfare maximization through the reduction of average electricity prices. [Hartmann, 2010] determine the impact of different charging strategies of electricity demand curves for Germany. Further, V2G- concepts (feeding electricity into the grid) are also considered. The concept of profit maximization[12] due to the participation of EVs in a day-ahead market (EEX, European Energy Exchange) is considered as a possible combined G2V and V2G concept.

However, chapter 3 describes the methodology used in this work and specifically offers a definition of charging times resulting from this market-based charging strategy.

2.2.2 Market-based charging/discharging strategy: Participation in frequency reserve markets (STR 2)

The economic potential of the participation of EVs in frequency reserve markets has been analysed in various studies for different countries. The analyses are based on diverse assumptions. [Tomić, 2007] analyse the participation of EVs in four control zones within the U.S., whereby a profit is made between 4.3 € and 64 € per month and vehicle. The calculations are completed for different years based on computed average prices within the mentioned control zones. Furthermore, the estimation of the economic potential is based on considerations of the driving pattern[13] of commuter vehicles and associated non-driving times – vehicles are connected to the low voltage grid. The historical data of activated frequency reserves are not considered.

[Brooks, 2002] study the US-case for plug-in hybrid electric vehicles without the consideration of battery degradation costs, resulting in a profit ranging from 196 € to 326 € per month and vehicle (participation of vehicles in markets for FCR and automatic FRR). The concept of "participation of EVs in frequency reserve markets" is also investigated for various European countries. [Larsen, 2008] estimate the profit for EVs by provision of manual and automatic FRR (combined with a high penetration level of renewable electricity generation)

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[12] Charging the vehicles in times of low electricity prices and discharging them in times of high electricity prices in a day-ahead market.

[13] Driving patterns of commuter vehicles: The driving profile generally consists of two ways with almost the same duration. The vehicle users drive the cars from their home to the commuter station in the morning and commute back in the afternoon [Tomić, 2007].

with a range between 6 € and 160 € per month and vehicle. The results are based on the theoretical availability of EVs, whereby neither driving patterns for the vehicles nor the characteristics of the called/activated frequency reserves are considered in the calculation. According to [Camus, 2009], the provision of frequency reserves (manual and automatic FRR) for associated markets in Portugal results in a profit of about 18 € per month and vehicle (plug-in hybrid). [Camus, 2009] apply the same approach as in [Tomić, 2007]. Based on the frequency deviation in 2008, [Andersson, 2010] calculate the economic potential for plug-in hybrid vehicles due to the provision of manual and automatic FRR in Germany and Sweden. In contrast to Sweden, a profit could be realized from 30 € to 80 € per month and vehicle in existing frequency reserve markets in Germany. The authors indicate the difference between the results of the two countries based on various market frameworks (no power price for reserved power in the balancing reserve market in Sweden) and different power plant structures. [Sioshansi, 2011], among others, examine the impact of V2G-concepts (provision of balancing reserves) on the procurement costs of plug-in hybrid vehicles in comparison with conventional cars. Due to the achieved profit from the participation of EVs in balancing markets, equivalent procurement costs can be reached between the two technologies (EVs and conventional cars). The historical data of activated frequency reserves are not considered.

Based on the described structure of bilateral frequency reserve markets in the APG control zone (see chapter 2.1.1) and various studies in conjunction with the participation of EVs in such markets, the provision of manual and automatic FRR in Austria is analysed in this work. Based on the literature mentioned above, the selected approach for this analysis is based on the use of historical data of activated frequency reserves in the Austrian control zone (APG) in consideration of competition from other providers/technologies. The selected methodology is described in chapter 3.2 in more detail.

2.2.3 Generation-based charging/discharging strategy: Electric vehicles and balancing group model (STR 3)

As described in chapter 2.1.2, the established approach for the calculation of the balancing energy clearing price sets an incentive for any balancing group representative to have a consistently balanced balancing group (see Figure 9). The balancing group representative can reduce its financial risk by utilizing flexible equipment, like storages. Therefore, EVs can be used by the balancing group representative for maintaining a balance between electricity generation and consumption due to long periods of inactivity and investments made in EVs by the vehicle owners (no investment costs for the balancing group representative). The balancing group representative determines the charging and discharging times of EVs according to its requirements, whereby the desire of the vehicle users for specific battery states at defined points in time must be considered (fulfilment of mobility needs). The vehicle users/owners take over the charging costs incurred and the balancing group representative the degradation costs that occur due to the discharging of batteries. Furthermore, the balancing group representative mitigates the schedule deviation with participation in day-ahead and/or intra-day electricity markets and reduces the needs for balancing energy and the following associated costs. Hence, the balancing group representative discharges the vehicles in times of electricity shortage (generation < consumption) and charges them in times of existing surplus electricity (generation > consumption).

The economic feasibility of implementing of EVs in a fictional balancing group with various generation structures (demand remains constant) is analysed in this work. Based on economic results, the reasonableness of implementation of the associated G2V concept – charging in times of high generation level – and V2G concept – discharging during times of low generation level – is analysed and discussed (see chapter 5.2). The costs of the charging/discharging concept are evaluated with prices on day-ahead and intra-day electricity markets. The calculation is derived from weekly analysis according to the provision of a balance between generation and consumption in the balancing group. The forecast error of schedules (schedule deviation) of the integrated consumers and generators in the balancing group are not considered in the calculations. It is assumed that the balancing group representative reduces a part of the schedule deviation even with participation in day-ahead and intra-day markets. The mitigation of schedule deviation enables the balancing group representative to reduce the balancing energy costs of the balancing group. The selected methodology for analysing these concepts, which are also called “generation-based charging/discharging strategies”, is given in chapter 3.3.

2.2.4 Generation- and load-based charging/discharging strategy (STR 4)

[Vliet, 2010] examine the GHG emissions of EVs by using different power generation technologies. The charging of EVs based on coal power units causes GHG emissions in the range of 150 gkm^{-1} (Well-to-Wheel[14] without consideration of embedded energy for manufacturing of vehicles and generation units). [Kloess, 2011a] analyse the GHG emissions of EVs, whereby the emissions for manufacturing the EVs and the generation units used for their charging are considered. The average emissions based on the Austrian electricity generation structure – around 65 % of installed electricity generation capacity is based on renewable generation technologies (mainly hydro) [E-Control, 2011] – are about 90 gkm^{-1}, whereby use of a combined cycle gas turbine (CCGT) for charging vehicles results in emissions of about 140 gkm^{-1} [Kloess, 2011a]. The outcomes of the emission analyses confirm that the improvement of the emissions balance of EVs occurs due to the use of renewable electricity generation for charging EVs. As a result, a significant improvement in the environmental impact occurs due to substitution of conventional vehicles with EVs. [Zhang, 2012] show that EVs and heat pumps can support the integration of a higher range of Photovoltaic (PV) electricity generation technologies through the use of the surplus of PV-generated electricity. Therefore, a higher reduction of CO_2 emissions can be reached simultaneously.

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 (typically 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 (typically for winter days) with a high number of EVs need to be charged during the day.

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[14] The entire comparison of efficiency between different propulsion systems consists of analysing the emissions due to production of fuels (Well-to-Tank, WTT), an energy conversation step that occurs on-board and manufacturing of vehicles and power generation units. The two last aspects are known as Tank-to-Wheel (TTW).

The interaction between renewable electricity generation (here: PV) and EVs can be coordinated locally with generation- and load-based charging/discharging concepts. The generation-based charging from PV can be accomplished depending on the location of the PV plant – either at home or at a workstation – whereby charging of vehicles also occurs at night, if required (insufficient PV generation for charging the vehicles).

The described G2V-concept can be complemented by a load-based discharging strategy (V2G concept). The aim of the load-based discharging strategy can be defined as the discharging of EVs in times of household consumption peaks, typically occuring in the evening. Depending on the explanation above, the analysed generation/load-based charging/discharging strategy presented in this work is defined in the following way:

- Charging vehicles at home from an installed PV unit or – if needed – at night and
- Discharging the EVs at home from 07:00 p.m. to 09:00 p.m.

The main analysed aspects are as follows:

- The economic potential of discharging vehicles (V2G, load-based discharging strategy) at home by night.
- The impact of this combined G2V- and V2G- concept on the load level and dimensioning of the transformation station for different types of LV-grids:

  Figure 10 depicts the sum load profile of a transformation station due to the implementation of PV. The impact of the described combined G2V and V2G-concepts is also shown in the figure. The main question is: Can the implementation of the combined concept for integrated electric vehicles (EVs) in a low voltage grid result in a lower dimensioning of the installed transformation station? Furthermore, can the distributed system operator (DSO) save costs in conjunction with a new dimensioned transformation station?

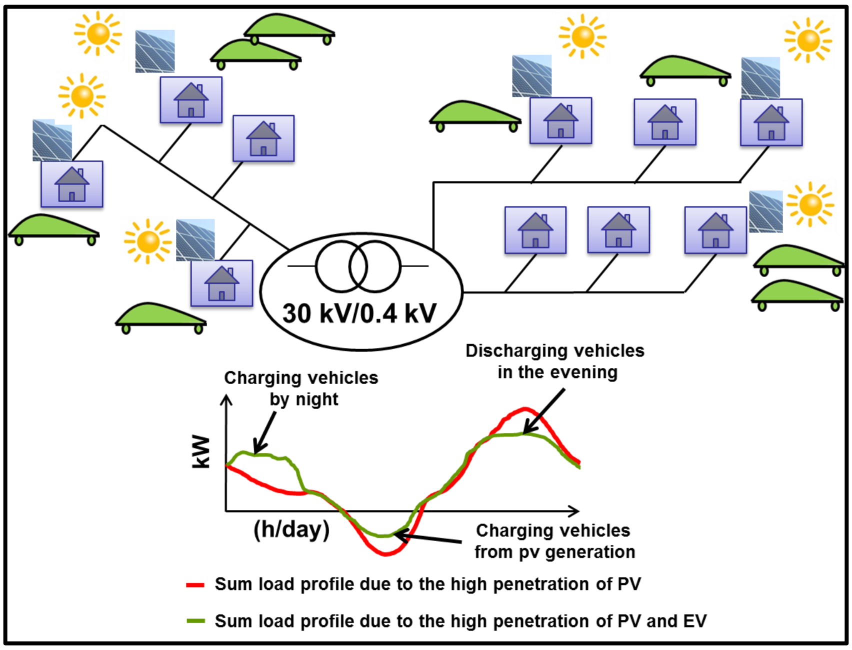

Figure 10: Impact of the implementation of a high range of PV and EVs on the sum load profile of the transformation station for a LV-grid (own depiction)

2.2.5 Reusing of batteries – second life

The high investment costs of lithium-ion (Li-ion) batteries – installed in EVs – significantly affect the implementation of EVs in the transportation system. According to [EMST, 2011], the prices for used Li-ion batteries in EVs would decline due to mass production (economies of scale), innovation in manufacturing and additional expenditure for research and education. [EMST, 2011] expect a cost reduction for batteries from round 800 €/kWh in 2011 to about 370 €/kWh in 2020. The assumption for this conclusion is based on a learning rate of about 15 % and an achievable minimum price for batteries of about 180 €/kWh, whereby the minimum price would be obtained in 2028.

[Rezania, 2011a] analyse the operation of various storage technologies (batteries and hydro pump storages), purposing a regional power balance for selected low and medium voltage grids. The results illustrate that the possible achievable revenues cannot cover the operation and maintenance costs of the determined storages. Further papers, like [Glatz, 2011] and [Rezania, 2012], have considered the participation of battery systems in day-ahead markets, including the supply of a connected consumer and also the combined participation of a battery system on day-ahead and balancing energy markets in the APG control zone in Austria. The cost-benefit analysis of mentioned applications shows that the highest contribution margin (without consideration of the costs for communication systems and so on) will be reached by simultaneous participation of storages on day-ahead and balancing energy markets. The aim/idea of the business model “second life” is based on the reuse of batteries after their automotive retirement, which could thus contribute to lower e-mobility costs. The reason can be found in an added disposal value of the used battery, resulting in the reduction of the initial battery prices of EVs. The mentioned disposal value depends on the application’s purpose (target function of the application). In this conjunction, three important instability factors need to be considered:

- the remaining lifetime of reused batteries,
- costs for reassembling batteries from vehicles,
- cost development of competing battery technologies.

[Neubauer, 2011] analyse different applications for Li-ion batteries after the automotive lifetime[15] based on described cost problems of these batteries. The economic calculations of the considered applications in [Neubauer, 2011] rely on a comparison between the reused batteries and new batteries of the same technology. The chosen approach with an assumed cost reduction for Li-ion batteries results in profits due to battery reuse and, therefore, a reduction in the procurement cost of EVs.

The calculation for the business model “second life” in this work examines the application “coordinated participation of battery on electricity and balancing energy markets”, whereby the consideration of historical characteristics of the activated capacity reserves receives a main role, contrary to [Drury, 2011][16]. The estimation of the disposal value of reused batteries for this application occurs, contrary to [Neubauer, 2011], in comparison to the most inexpensive battery technology[17] (basis for an investment decision). Therefore, the needed

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[15] The disposal value (compare [Peterson, 2009]) is based on various scenarios.

[16] [Drury, 2011] analysed the economic potential of compressed air energy storage (bulk storage) according to its participation on energy and balancing reserve markets.

[17] The lead-acid battery is chosen as the reference technology. According to [Hadjipaschalis, 2008], the future investment cost of this kind of battery would be in a range between 50 and 100 €/kW. The lifetime is given as 12 years.

minimum lifetime for batteries during the second-life stage can be derived from the implementation of this approach. Additionally, the methodology evaluates the feasibility of the analysed application.

3 Methodology

The objective of this thesis 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 chapter and comprises of following applications:

- Market-based charging strategy: Cost minimising charging (STR 1)
- Market-based charging/discharging strategy: Participation in frequency reserve markets (STR 2)
- Generation-based charging/discharging strategy: Electric vehicles and balancing model (STR 3)
- Generation- and load-based charging/discharging strategy (STR 4)
- Reusing of batteries – second life.

3.1 Market-based charging strategy: Cost minimising charging (STR 1)

As described in chapter 2.2.1, the market-based charging strategy of EVs occurs in times of low electricity prices, whereby the mobility needs of vehicle users must also be considered. This G2V concept is defined as a G2V-basis strategy for other analysed G2V and V2G applications (see chapter 2.2.1). More precisely, the participation of EVs in frequency reserve markets is sometimes not possible because of various market conditions. In such cases the activation of the G2V-basis strategy results in charging vehicles and the fulfilment of mobility needs[18].

The assignment of the times with the lowest electricity prices refers to profit maximization ($\mathrm{Profit}_{\mathrm{max}}$) of a stationary battery system (Li-ion battery). The charging (x_i) and discharging (y_i) power (maximum charging power is given by maximum connection capacity) for each time step are derived from the implementation of a linear optimization problem (Matlab-script) – i describes the associated time unit (hour) within a day (compare [Rezania, 2011b]). The assumed/predicted wholesale electricity prices are given for the calculation (see chapter 4.1). The maximum charging power (P) as well as the minimum ($C_{min,net}$) and maximum net capacity $C_{max,net}$ of the battery are defined as main constraints for the optimization problem (see equation [3]). $C_{max,net}$ and $C_{min,net}$ indicate, on the other hand, the maximum storage volume and the maximum depth of discharge of the considered battery technology (Li-ion). The variables $C_{max,net}/C_{min,net}$ are defined as 90%/10% for battery electric vehicles (BEVs) and 80%/20% for plug-in hybrid electric vehicles (PHEV) of the total capacity (C). The mentioned maximum and minimum boundaries protect the batteries against overloading and deep discharging.

$$Profit_{max} = Max\left(\sum_{i=1}^{24} y_i \cdot p_i - \sum_{i=1}^{24} x_i \cdot p_i\right) \tag{3}$$

$0 \leq x_i \leq P,$
$0 \leq y_i \leq P$

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[18] Mobility needs of a vehicle user: desire of the vehicle user for specific battery states at defined points in time.

$$C_{min,net} \leq x_i + y_i \leq C_{max,net}$$
$$C_{min,net} = 0.1 \cdot C, for\ BEV,\ C_{max,net} = 0.9 \cdot C, for\ BEV$$
$$C_{min,net} = 0.2 \cdot C, for\ PHEV\ ,\ C_{max,net} = 0.8 \cdot C, for\ PHEV$$
$$C: Total\ battery\ capacity\ (kWh)$$

Figure 11 depicts the state of charge (SOC) of a stationary battery (48 kWh total battery capacity) due to market-based charging and discharging. The charging times with low electricity prices are derived from the results of profit maximization. In this case, charging and discharging are based on a one-phase connection (maximum charging/discharging power 3.5 kW[19]), whereby the connection efficiency is 95 %[20]. Technical realisation can be conducted based on a simple approach, using a time control switch – sets the beginning of charging [Schey, 2012] – or in an advanced approach via communication with an energy management system.

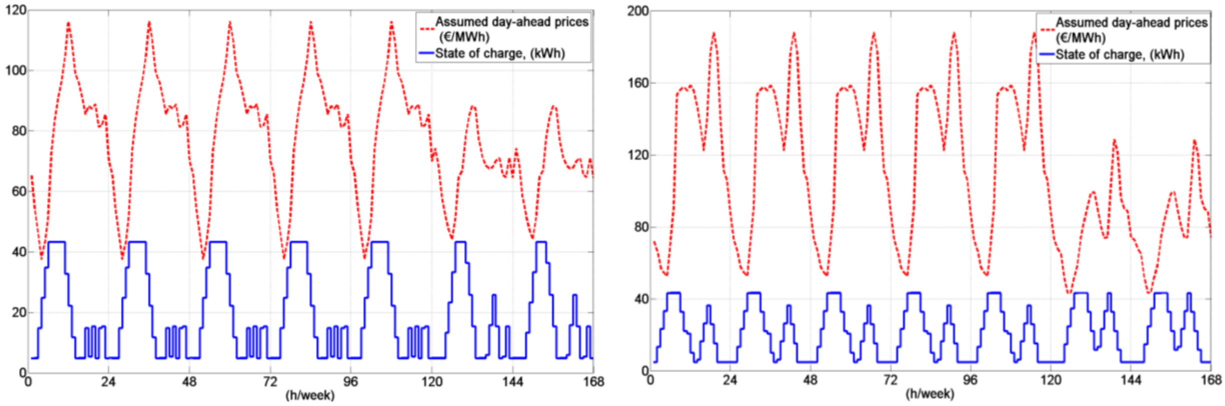

Figure 11: Assumed day-ahead wholesale electricity prices for 2020 (left: one summer week, right: one winter week) and the charging state (Li-ion battery 48 kWh net capacity, maximum charging power 3.5 kW_{el}) (own calculation and depiction)

Figure 12 shows in dotted lines the sum load profile of existing EVs (40 % penetration rate) in an LV-grid. The lines illustrate that EVs react to the price signals with a high coincidence (coincidence factor is one) because each individual vehicle user wants to fulfil the target function – minimal charging costs. This individual behaviour results in power peaks in LV-grids as a result of implementation of the market-based charging strategy for integrated EVs.

A large amount of grid reserves would be consumed because of the high coincident factor for charging the vehicles (high power peaks). [Prueggler, 2013] conclude that a maximum penetration rate of about 25 % of EVs, using the market-based charging strategy, would violate the predefined grid restrictions[21] in most LV-grids in Austria. As mentioned above, the market-based charging strategy serves as a charging basis concept for other analysed G2V and V2G concepts. Therefore, the combination of several concepts reduces appreciably the value of the described coincidence factor.

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[19] The maximum charging/discharging power of a three phase connection station is 10.5 kW.

[20] [Gibson, 2009] assumes a connection efficiency of about 95 %, independent of the type of connection (one or three phases).

[21] Grid restriction: Maximum degree of voltage and capacity utilization.

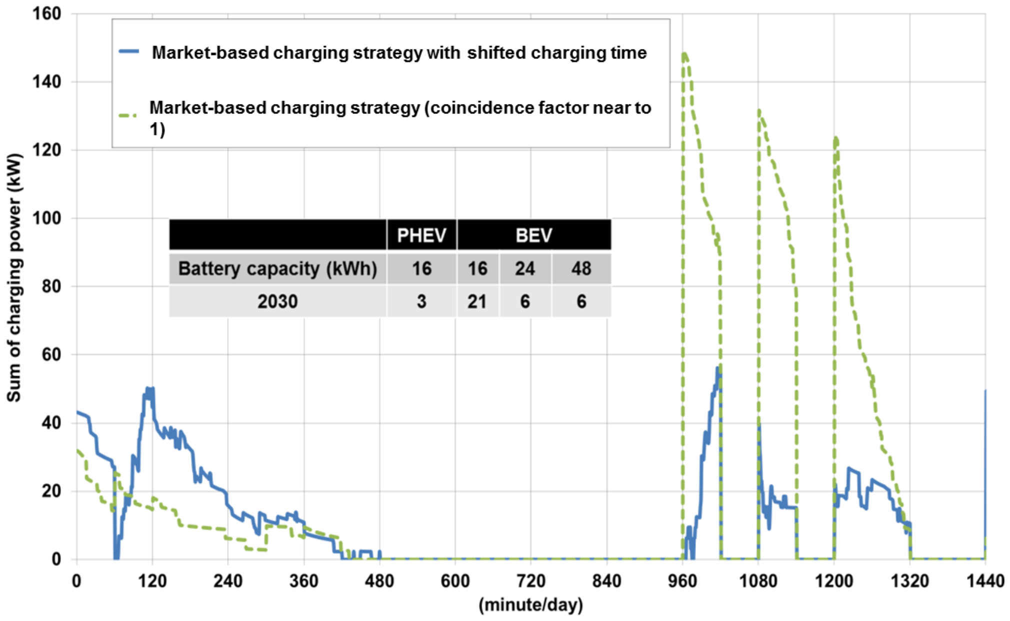

Figure 12: Sum load profile of implemented EVs in an LV-grid, resulting from market-based charging strategy (own calculation and depiction)

3.2 Market-based charging/discharging strategy: Participation in frequency reserve markets (STR 2)

The activation and the duration of the activated automatic/manual frequency reserves are defined as a function of the current level of frequency in ENTSO-E's[22] "Regional Group Continental Europe (RGCE)". Each one of the daily activated frequency reserve capacities (automatic/manual, negative/positive) differs itself in conjunction with the amount of activated reserve capacity and the number of incidents/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 occurred frequency reserves from 2006 to 2010 build up the database. The modelling prepares six different scenarios for each kind of frequency reserve, e.g. positive manual frequency reserves, with six different scenarios. The scenarios differ in the amount of activated reserve capacities and the number of activations during a day. The combination of basic G2V strategy (see chapter 3.1), the driving pattern of various car users (see chapter 4.5) and daily performed scenarios provides a detailed economic analysis of the participation of EVs in the frequency reserve markets.

3.2.1 Modelling of scenarios for activated frequency reserves

The simulation of needed frequency reserves is based on analysis of historically activated frequency reserves in the APG control zone and a following model of daily needed/activated frequency reserves. The descriptive statistics [Holland, 2010] and a systematic investigation of historically called frequency reserves are the basis for modelling control reserves in the APG control zone. Regarding the analysis, knowledge of yearly trends, obvious and

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[22] ENSOE: European Network of Transmission System Operators for Electricity (see www.entsoe.eu).

measurable seasonal differences and time-dependent (daily) characteristics of activated frequency reserves can be derived and considered in the modelling. The modelling of the called frequency reserves which is based on the previous information is oriented according to the following scheme:

- Assignments of probability density function to each time segment (15 minutes) of the day: The database consists of five years – from 2006 to 2010 – with a 15-minute time resolution (around 35.040 or 35.136 values per year). Therefore, for each time unit there exist 1.826 values [FRR, 2011a]. This quantity of existing values builds up a robust data basis for the assessment of the probability density function for each time step (compare Figure 13).

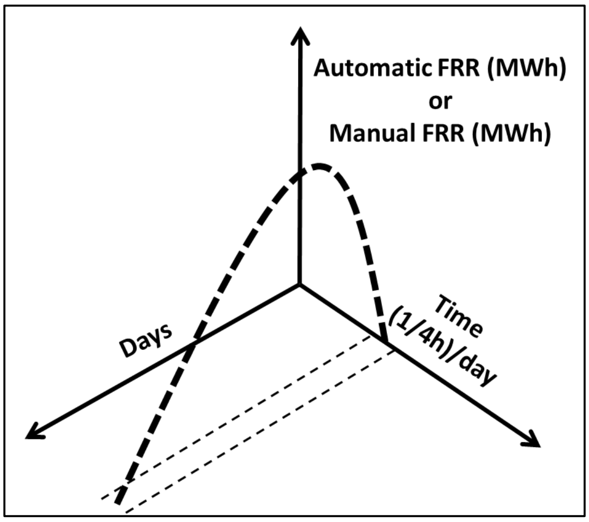

Figure 13: Assignment of the probability density function to a time segment (own depiction)

The graphical evaluation of the manual FRR – as well as FCR – in the APG control zone shows a continual activation of low amounts of reserved capacity (see chapter 4.2). Therefore, the appropriate probability density function for describing the characteristics of called manual FRR follows the "generalized extreme value distribution" (compare equation [4]). Figure 14 guides us through an example of the mentioned distribution function according to the characteristics of the called frequency reserves for a selected time segment during the day. The appearance of activated automatic FRR is generally characterised by a normal distribution function.

$$f(x) = \frac{1}{\sigma} \cdot e^{\left(-\left(1+0{,}5\cdot\frac{(x-\bar{x})}{\sigma}\right)\right)^{\frac{1}{k}}} \cdot \left(1 + k \cdot \frac{(x-\bar{x})}{\sigma}\right)^{-1-\frac{1}{k}} \qquad (4)$$

$$1 + k \cdot \frac{(x-\bar{x})}{\sigma} > 0$$

$\sigma: Standard\ deviation\ (scale\ parameter)$

$\bar{x}: Average\ value\ (location\ paramter)$

$k \neq 0: Shape\ parameter$

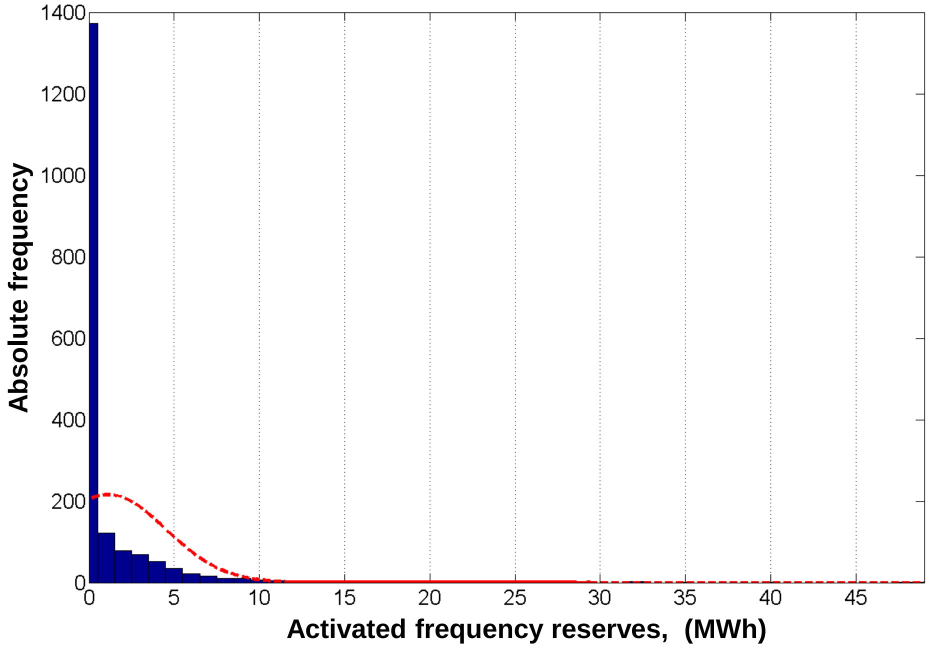

Figure 14: Histogram (number of activations) for a time unit during the day from 2006 to 2010 and the associated probability density function (own calculation and depiction)

- Analysing occurred time and the number of activations per day: The examination depicts a random characteristic for occurred time and the number of activations per day – no typical daily pattern is recognized. Therefore, a normal distribution is assumed for the description of the number of activations per day. Hence, different intensity scenarios – defining the number of activations of frequency reserves per day – are derived from the mean and the standard deviation value of the assigned normal distribution functions. The distribution of activated frequency reserves per day follows a random pattern as well as no specific time-dependent characteristics within a day. In this conjunction, the activations occur almost in blocks, meaning four consecutive time steps (descriptive statistics analysis, see chapter 4.3).
- Determination of applicative pseudo-random numbers from the probability density functions: The methodology is based on the “Acceptance-Rejection” approach. The basic idea of the methodology is based on the determination of random values, which pass a predefined distribution function f (see [Kolonko, 2008]). The simulation by using the “Acceptance-Rejection” approach is derived based on a help density function (g), which is close to or can present all of the acceptable values of function f. The basis of the Acceptance-Rejection method is as follows (see Figure 15):
    - Generate x, a random number from the interval (0,1) according to g(x)
    - Generate u, a random number uniformly distributed between 0 and 1
    - If u satisfies $\frac{f(x)}{c \cdot g(x)} > u$, return u as a valid value, otherwise remove to the first step and generate the next sample ($c \epsilon R$).

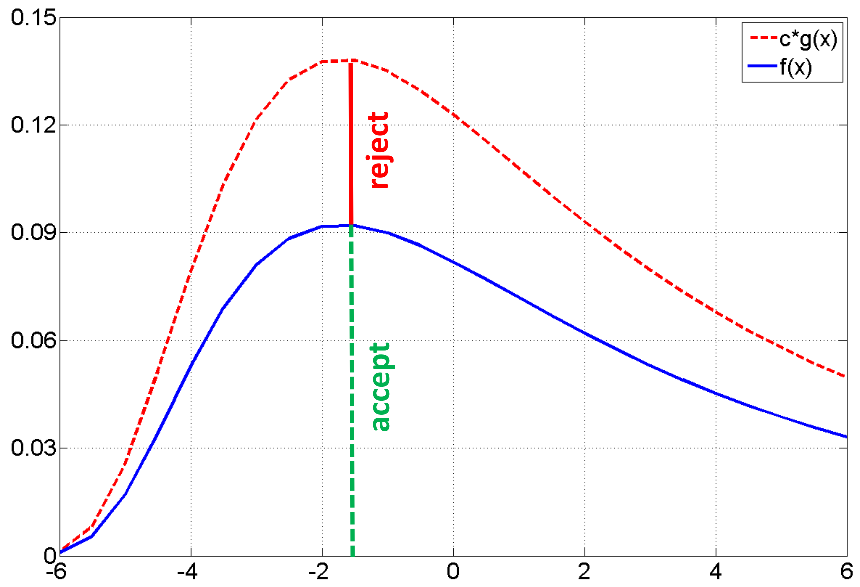

Figure 15: A graphical representation of the “Acceptance-Rejection“ method (own depiction)

The implementation of the mentioned steps results in different frequency reserve scenarios. The scenarios vary in the activated frequency reserves (balancing energy scenarios) and the number of daily activations (call scenarios, daily intensity). Each of the mentioned balancing energy scenarios is subdivided into three sub-scenarios, which depict different numbers of activated frequency reserve capacity within a day (daily intensity):

- MAX scenario: The balancing energy scenarios will be combined with a given maximal number of activations within the day. The maximum number of activations is derived from the mean value of the number of daily activations derived from historical data plus the associated standard deviation.
- MEAN scenario: The balancing energy scenarios are linked to the mean value of the number of daily activations.
- MIN scenario: The minimum number of activated frequency reserves is derived from the difference between the mean value of the number of daily activations and the linked standard deviation.

According to the evaluated balancing energy and called scenarios, six various scenarios for each kind of frequency reserve (see Figure 16) are derived, whilst the balancing energy scenarios[23] depict differences in the amount of activated balancing energy and not the time of the corresponding activations.

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[23] HighEnergy (HE) - scenario: The maximum value of the derived pseudo-random numbers (1,826 values) for each time step (15-minute time resolution) defines the activated energy.
MeanEnergie (ME) - scenario: The mean value of the derived pseudo-random numbers (1,826 values) for each time step (15-minute time resolution) defines the activated energy.

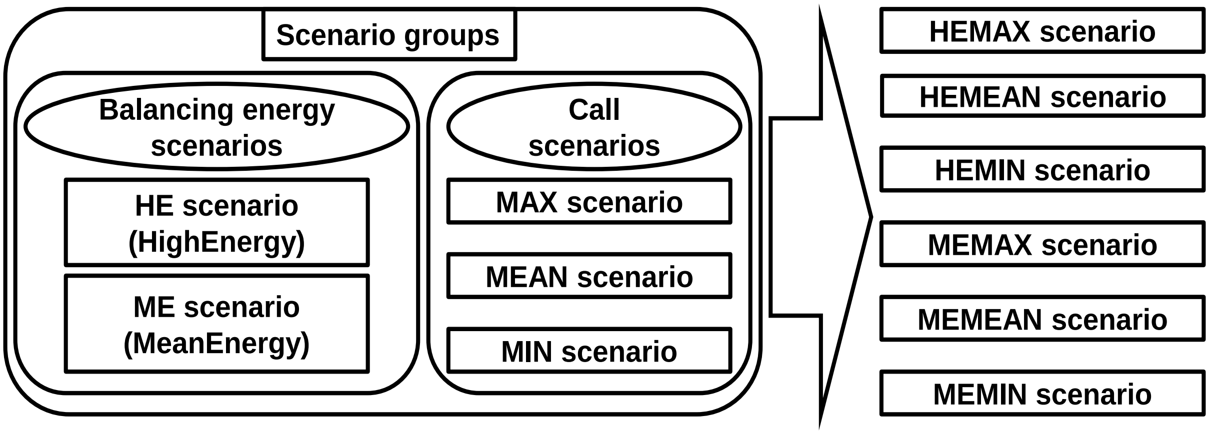

Figure 16: Combination of balancing energy and call scenarios for each kind of restoration reserve (own depiction)

3.2.2 Implementation of the concept "participation of EVs in the frequency reserve markets"

One EV can either participate in the markets for negative FRR or positive FRR. The use-case participation in the positive FRR takes into account the battery state defined by the user for predefined times. The SOC (state of charge) of the battery would be before the first daily usage between the state defined by the vehicle users and the maximum net capacity of the battery (see chapter 2.2.1). The vehicles are charged in times of low wholesale electricity prices (cost minimising charging strategy) not facing an activation of positive FRR.

The participation of EVs on the negative FRR market is developed in a similar way as the approach described for participation in positive FRR markets, whereby the differences are given in two positions:

- On the one hand, the vehicles face two charging strategies,[24] whereby the priority for charging is given due to the activation of negative FRR. The G2V basic strategy (cost minimising charging concept, see chapter 2.2.1) is activated, if the mobility needs of the vehicle user require more energy.
- On the other hand, the second difference comes from dealing with the predefined battery state before the first daily trip/usage of the vehicle user. The charging state determines the maximum battery state before the first daily trip and is set to the electricity needs of the drivers for the whole day. This approach ensures that the battery is not charged at an unnecessarily high level. Therefore, this battery state would support a successful participation of EVs on the negative FRR markets.

After the simulation of the participation of EVs in the FRR markets, the economic potential of this concept is assessed using the resulting charging/discharging power for each time segment and the calculated or assumed balancing energy and reserve capacity for the year 2020 (see chapter 4.2). The robustness of the economic results is given due to the use of different scenarios for called frequency reserves and consideration of various driving patterns for EVs. Furthermore, results are presented based on a sensitivity analysis of battery investment cost, capacity and balancing energy prices on the frequency reserve markets.

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[24] Cost minimising charging and charging as a result of activation of negative frequency reserves.

The whole approach indicates the maximum possible profit for each participating vehicle on the frequency reserve markets (theoretical value) during a specific time frame. The real possible profit of the use case is derived from an evaluation of the status of the current and possible future participants/competitors on the FRR markets. In addition, a discussion on the linked tendering processes occurs. Figure 17 depicts the whole methodological assessment of the concept "participation of EVs on the FRR markets".

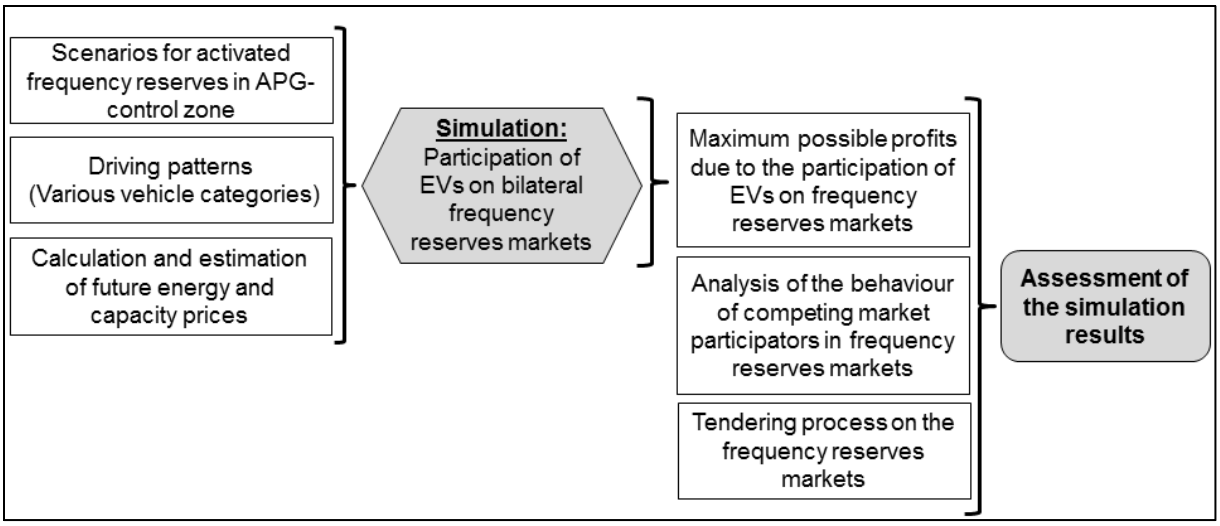

Figure 17: Methodological assessment of participation of EVs in bilateral frequency reserve markets (own depiction)

It is important to note that the maximum charging or discharging power is 10.5 kW (three-phase charging station [16 ampere and 230 volt pre phase, respectively]). Charging of the battery is based on the described CC/CV (constant current/constant voltage) characteristic curve in chapter 4.4.1.

3.3 Generation-based charging/discharging strategy: Electric vehicles and balancing model (STR 3)

The analysis of the implementation of EVs in a balancing group is based on the creation of a fictional balancing group. The fictional balancing group depicts a single demand profile being mainly comprised of households. The household profiles are derived from weekly measurements (one winter and one summer week) conducted within the project [ADRES, 2011]. The measured data sets show a minute resolution (see Figure 20, chapter 3.4). The demand of the balancing group is oriented according to the existing consumers (divided into household and commercial consumers) in an existing LV-grid. 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, consisting at least of PV, wind and biogas plants. 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

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 explanation in chapter 2.1.2, the balancing group representative is interested in attaining a balance between electricity generation and consumption ($\Delta_{BG,i} = 0$). The balancing group representative can utilize EVs for reaching this purpose. The basic principle of the "generation-based charging/discharging" strategy or "implementation of EVs in an existing balancing group" consists of charging EVs in times of electricity surplus ($\Delta_{\mathrm{BG,i}} < 0$, electricity consumption < generation) and discharging them during the inverse situation ($\Delta_{\mathrm{BG,i}} > 0$, electricity consumption > generation). EVs are implemented in the balancing group either by the combined charging and discharging concepts (see chapter 3.3.1 below) or by the charging strategy only (see chapter 3.3.2).

3.3.1 Combined charging and discharging concepts for the implemented EVs within the balancing group

In this case, the implementation of EVs in the balancing group is generally based on the enhancement of the optimization problem described in equation (3). The weekly delta curve 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.

Availability is given if the vehicles are not in use for mobility services. One assumption is made: EVs are always connected to the grid during non-driving time periods.

The availability is characterised by a dual variable (v_i) of either one or zero. One means that the vehicle is available and is in a non-driving status. The driving periods of the vehicles are linked to value one. An enhancement of equation (3) is given in equation (5). The number of time units is 10,080 as a consequence of the minute resolution of the databases (weekly basis). The vehicle can be charged at any location, which is equipped with a charging station.

$$\Delta_{min} = Min\left(\sum_{i=1}^{10080} v_i \cdot y_i \cdot \Delta_{BG,i} - \sum_{i=1}^{10080} v_i \cdot x_i \cdot \Delta_{BG,i}\right) \tag{5}$$

$\Delta: Deviation\ of\ balancing\ group\ (MWh)$

$v_i: Dual\ variable\ describing\ the\ availability\ of\ EVs$

$x: Charging\ power\ (kW)$

$y: Discharging\ power\ (kW)$

The implemented vehicles are charged/discharged as an aggregated vehicle fleet according to the delta of the balancing group, which results from a comparison of electricity consumption and generation within the balancing group.

3.3.2 Charging concept for the implemented EVs within the balancing group only

The application is relevant only for charging EVs in times of existing surplus electricity in the balancing group ($\Delta_{BG} < 0$, consumption < generation), e.g., times with high wind generation or extreme global irradiation. The EV can be charged (like the previous use case) at any location equipped with a charging station. The vehicles will be integrated separately in the balancing group. The fulfilment of the mobility needs of the driver – charging occurs only at times with deltas less than zero – results in the integration of the EV in the balancing group. Each integrated vehicle changes the trend of Δ_{BG} 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 oriented after the new trend of Δ_{BG}. The next vehicle would be implemented in the balancing group if the mobility needs – charging only in times when electricity generation is higher than consumption – can be covered (see equation (6]).

$$\Delta_{BG,k} = \Delta_{BG} + EV_k \tag{6}$$

$\Delta_{BG}: Delta\ of\ the\ balancing\ group$

$\Delta_{BG,k}: Delta\ of\ the\ balancing\ group\ after\ integration\ of\ EVs$

$k: Number\ of\ implemented\ EVs$

Figure 18 depicts the deviation between electricity consumption and generation prior to ($\Delta_{BG,0}$) and after (dotted line) the implementation of EVs ($\Delta_{BG,43}$) in the balancing group for a single day in a given week.

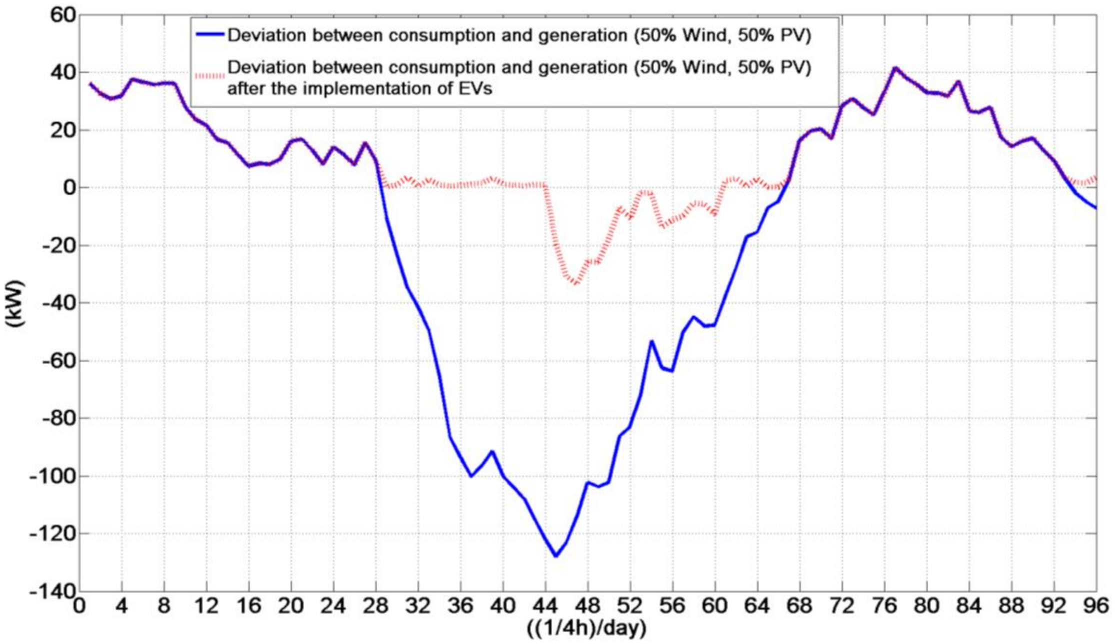

Figure 18: Deviation of the balancing group prior to and after the implementation of EVs (43 EVs) (own calculation and depiction)

The maximum charging or discharging power is 3.5 kW (one-phase connection [16 ampere and 230 volt pre phase, respectively]). Charging of the battery is not based on the described CC/CV characteristic curve in chapter 4.4.1.

In both use cases associated with the balancing group model, the economic assessment of the concepts is organised as follows:

- The determination of the maximum number of integrated EVs in the BG is reached if $\Delta_{\mathrm{BG,k}} < \Delta_{\mathrm{BG,k-1}}$. Therefore, the difference between the delta prior to and after integration of EVs in the balancing group can be calculated.
- The reduction of delta occurs due to the participation of the balancing group representative in the day-ahead and intra-day electricity markets. Therefore, the charging/discharging costs/revenues are evaluated with the historical price developments on both markets.
- The assessment ends with a comparison between charging and accruing discharging costs. The discharging costs also include the battery degradation cost (without considering the costs for control of charging and discharging).

3.4 Generation- and load-based charging/discharging strategy (STR 4)

As mentioned in chapter 2.2.4, a charging strategy with the target function of maximizing the usage of regional renewable electricity generation (RES-E) is defined based on PV-oriented charging of EVs (generation-based charging strategy). The charging strategy is based on the usage of PV electricity generation at home for charging EVs, mainly in times of high generation level. 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 LV-grids.

Figure 19 depicts, as an example, an LV-grid [Prueggler, 2013] in an urban area mainly consisting of household consumers. Based on the calculated/estimated electricity consumption factor (power factor) of each connection point – data are provided by the associated DSO – and assuming a mean value of yearly electricity consumption of about $1500\ \frac{\text{kWh}}{\text{Person.yr}}$ [Haas, 2010], the number of residents at each connecting point is calculated.

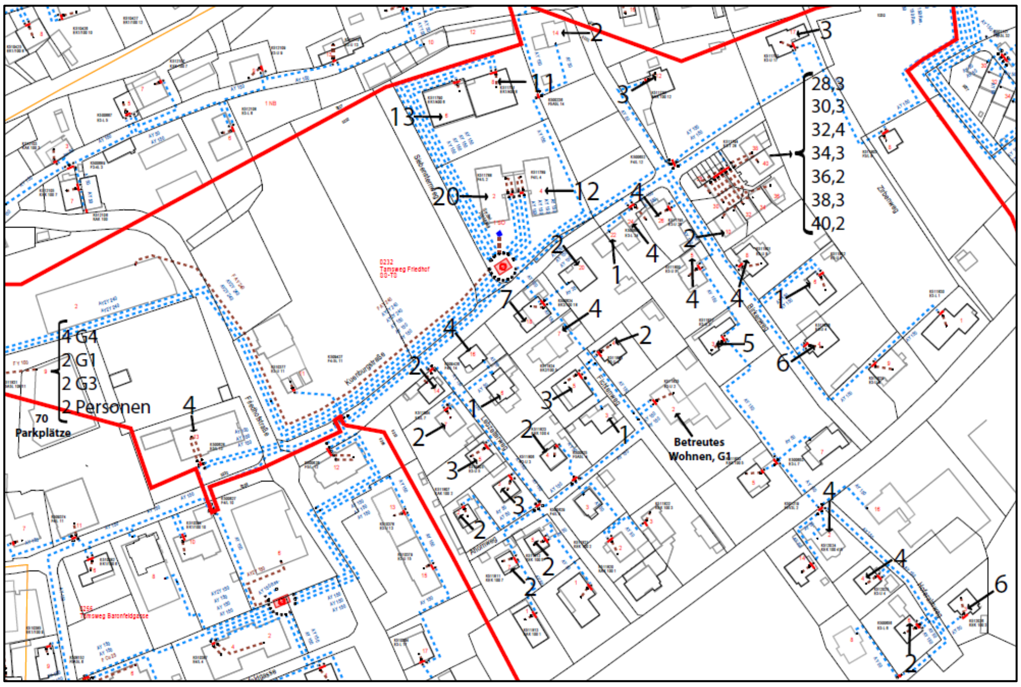

Figure 19: An LV-grid in a rural area (grid number 2) with the estimated number of residents for each connection point (Source: [Prueggler, 2013])

Each of the connection points are matched with the derived number of residents with measured consumption profiles [ADRES, 2011] based on a minute resolution. A summary of all existing matched measured profiles – using standardised profiles for commercial consumers – within an LV-grid results in the associated sum load profile. The sum load profile of the shown LV-grid (see Figure 19) for a selected summer and winter day is given in Figure 20. The lowest level of electricity consumption is during the night. The maximum load level (on the connection point of the transformer) mainly occurs between 07:00 p.m. and 09:00 p.m..

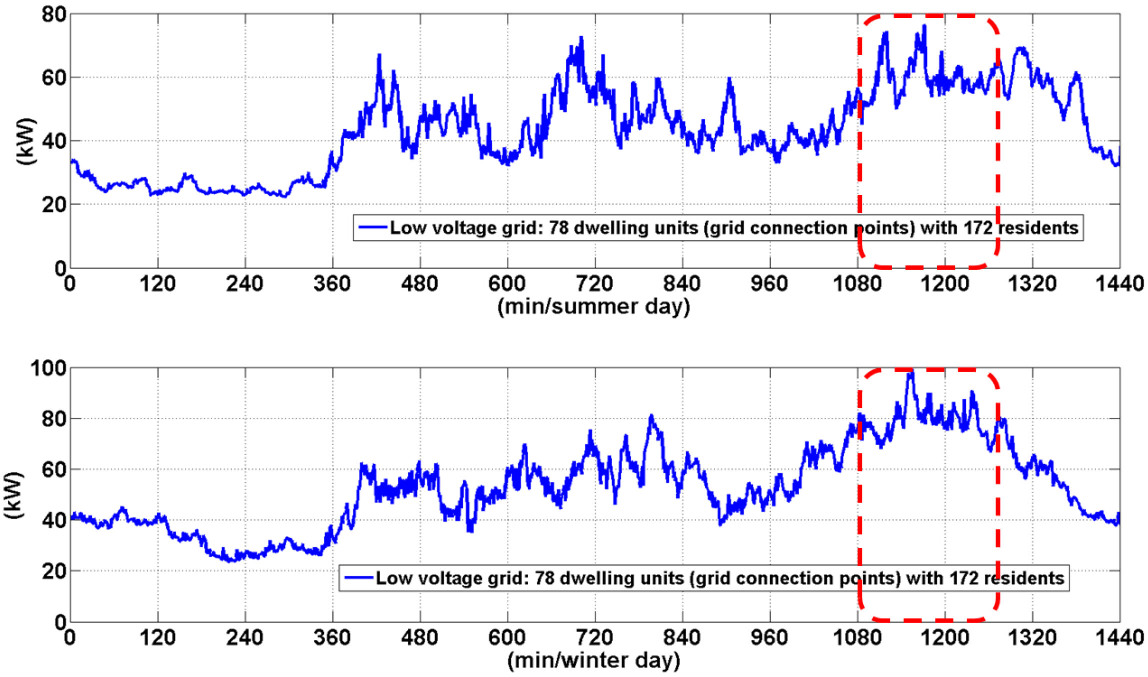

Figure 20: Sum load profiles of the previous depicted LV-grid for selected summer and winter days (Source: [Prueggler, 2013], own depiction)

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

- If the vehicle user's desire for specific battery states at defined times – in this case, before the first daily drive – 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.
- The two described charging concepts[25] 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 discharging of the Li-ion batteries can be realised by constant or dynamic discharging power and results in specific battery degradation (capacity losses). The mentioned degradation due to dynamic discharging power is higher by a factor of 2.2, as is the case with constant discharging (see chapter 4.4.2). Therefore, because of this technological property and the mean value of the consumed power of households from 07:00 p.m. to 09:00 p.m. – based on [ADRES, 2011] profiles – the discharging power is set at 1 kW_{el} during this time period.

The simulation of this generation- and load-based charging/discharging strategy is organised as follows: The battery state prior to the first daily drive is set to double the daily needed energy for driving. The energy is covered by charging from 00:00 a.m. to 06:00 a.m. and from PV generation, if available, before the first daily drive. The assumption ensures the fulfilment of the mobility needs of vehicle users independent from PV generation and weather conditions. Furthermore, sufficient energy for the V2G strategy from 07:00 p.m. to 09:00 p.m. can be expected because of the high battery status before the first daily drive. If available, the remaining battery state (maximum battery capacity minus defined battery state prior to the first daily drive), the so-called "shifted energy" will be covered by PV generation. The aim

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[25] Consideration of CC/CV (constant current/constant voltage) charging characteristics of Li-ion batteries (see chapter 4.4.1).

of charging from PV is mainly to reduce the PV generation peak.

Figure 21 depicts, based on one EV with a maximum battery capacity of 24 kWh, the deduction of the described generation- and load-based charging/discharging concept. The upper chart shows the resulting battery state curves (minute resolution), whereby the lower figure depicts the whole concept in more detail. The availability of vehicles at home (red line) defines the possibility of charging or discharging of an EV in predefined time frames or during PV generation (location-dependent charging/discharging).

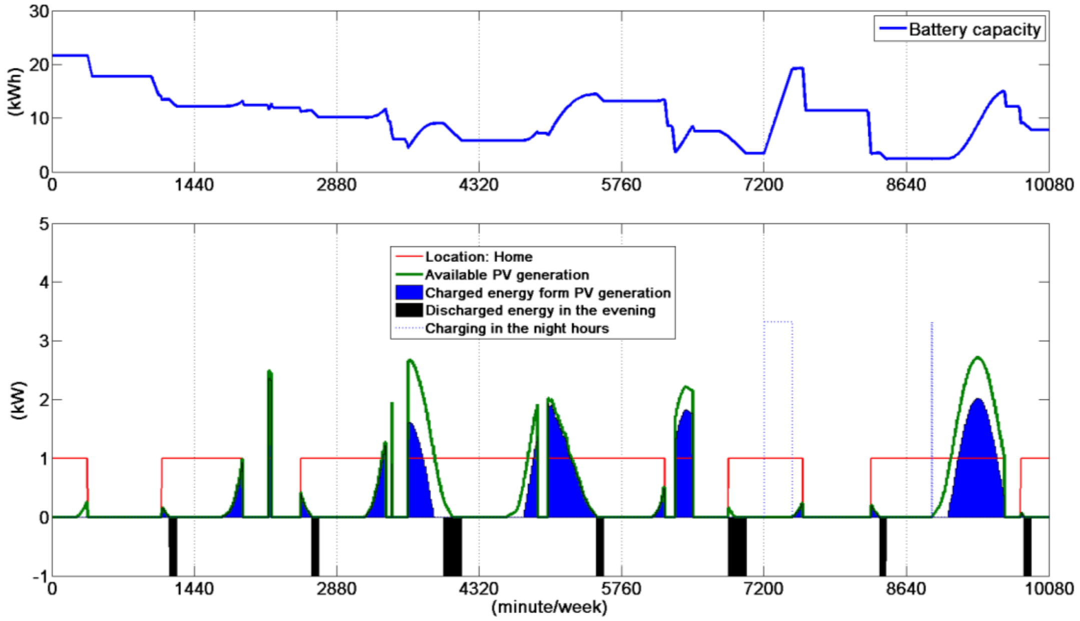

Figure 21: Battery state of an EV with 24 kWh maximum capacity based on the realised generation- and load-based charging/discharging strategy (own calculation)

According to the location-dependent charging of EVs from PV generation, two descriptive factors exist:

- Coverage ratio of battery capacity and
- Integration ratio of PV generation.

Both are settled and described according to [Leitinger, 2011] as follows[26]

$$Coverage\ ratio = \frac{\sum_{i=1}^{1440} Coincident\ load}{Battery\ capacity} \tag{7}$$

$$Integration\ ratio = \frac{\sum_{i=1}^{1440} Coincident\ load}{\sum_{i=1}^{1440} PV\ generation} \tag{8}$$

The economic analysis for the described concept is subdivided into two different aspects:

- The first one is to assess the V2G-concept (load-based discharging of EVs) at home, where the maximum possible revenues of discharging are evaluated without consideration of the charging cost, as charging from PV at home is assumed to be free. The assessment does not take into account the cost of the needed control

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[26] The data show a minute resolution. One day consists of 1,440 minutes.

communication system[27] because common system architecture is not yet defined.
- The second aspect of the economic analysis is based on determination of the possible diminishing of the transformation station dimension and therefore the associated cost saving due to realisation of the described generation- and load-based charging/discharging strategy. The shown LV-grid in Figure 19 and the other five LV-grids – from Figure A.3 to Figure A.7 – from rural and urban areas are considered for this examination.

3.5 Reusing of batteries – second-life

Figure 22 depicts the operation strategy – combined participation in day-ahead and frequency reserve (FRR) markets – of a reused battery (electricity energy storage [EES]). The shown operation obtains in detail the combined participation in the day-ahead and manual FRR market. For a consistent comparison of the results the same operation schedule is used in the case of participation of EES in the day-ahead and automatic FRR markets in the APG control zone.

Figure 20 shows the number of calls of manual FRR capacity per time period in 2010. The called positive manual FRR represents an incremental characteristic matching the increase in electricity demand between 08:00 and 12:00 hours and from 04:00 p.m. to 08:00 p.m. – deviation of the forecasted demand or generation level. The decrease in demand – lower than the current generation level – between 00:00 a.m. and 04:00 a.m. is indicated by increases of called negative manual FRR.

Hence, the mentioned time blocks, referred to as control blocks, with consideration of adapted battery charging/discharging profiles (see chapter 4.4.1) build up the time periods where the battery ensures, if needed, the delivery of a certain capacity (maximum value), such as FRR capacity (assumed 100 % dispatch probability on FRR markets contrary to Figure 7). If the EES (or EES-operator) does not receive a signal (automatically) or a phone call (manually) requesting the delivery of FRR capacity in the mentioned control blocks (one signal for each hour), the battery is able to take part in the electricity spot market for peak/off-peak arbitrage. The other time blocks – interim blocks (04:00 to 08:00, 12:00 to 16:00 and 20:00 to 24:00) – define areas where EES takes part in the day-ahead market – peak/off-peak arbitrage – and can set its capacity (EES status) to a certain level at the beginning of the control blocks. Accordingly, the interim blocks conduct the interim calibration of the EES status.

By assuming the same charging and discharging efficiencies for the second-life application being used for V2G and G2V applications of about 95 % (see chapter 3.1), the following formulas introduce a sequential linear optimization model. The goal of the optimization is the maximization of EES (or EES operator) revenues due to the participation in the day-ahead and different FRR markets. Equation (9) describes the calculation of the battery state, being computed from the previous state and charging/discharging power as a function of the previous state (consideration of CC/CV curve, see chapter 4.4.1). The state of charge (SOC), as shown in equation (10), can be varied between 10 % and 80 % of the entire battery

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[27] Information of battery status for each time and a stepless control of charging/discharging power is needed (see [Prueggler, 2013]).

capacity[28]. Equation (11) describes the range for variation of charging and discharging power, whereby the maximum charging power is equal to the maximum discharging power. According to common household installation, the maximum charging power can be 3.5 kW (one-phase connection, 16 ampere and 230 voltage) or 10.5 kW (three-phase connection, 16 ampere and 230 voltage).

$$S_{Li}(t+1) = S_{Li}(t) + P_{Charge}(t+1) \cdot S_{Li}(t) \cdot \eta_{Charge} - P_{Discharge}(t+1) \cdot S_{Li}(t) \cdot \eta_{Discharge} \tag{9}$$

$$0.1 \cdot C_{Li} \leq S_{Li}(t) \leq 0.8 \cdot C_{Li} \tag{10}$$

$$\begin{cases} 0 \leq P_{Charge,t}\big(S_{Li}(t)\big) \leq P_{Charge,Max} \\ 0 \leq P_{Discharge,t} \leq P_{Discharge,Max} \\ P_{Charge,Max} = P_{Discharge,Max} = 10.5\ kW_{el} \end{cases} \tag{11}$$

Even a battery or EES with a maximum charging/ discharging power must be able to fulfil the conditions of participation in the FRR markets. Such conditions, like a minimum bid of 10 MW or 5 MW reserve capacity, can be ensured by a pooling of small EES, including their management, through an EES operator. Therefore, it must provide the maximum charging/discharging power for the entire period of mentioned control blocks in Figure 22. For example, a battery with a capacity of 24 kWh will be operated between 2.4 (24*0.1) and 19.2 kWh (24*0.8) with an operation range of 16.8 kWh. Therefore, the maximum charging/discharging power is 3.5 kW because charging or discharging of the battery at 10.5 kW for four hours would exceed the operation range of 16.8 kWh.

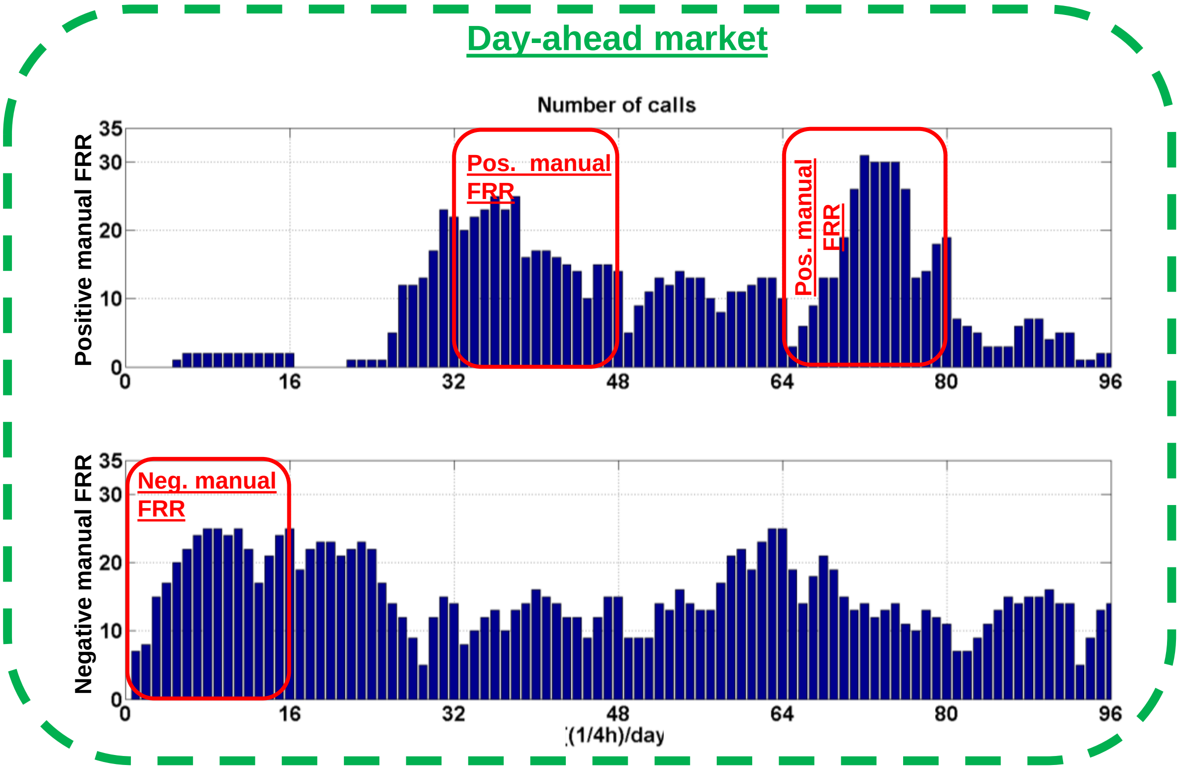

Figure 22: Operation strategy of a battery for combined participation in day-ahead and FRR markets (own depiction)

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[28] This range lies between 10 % and 90 % of the battery capacity in the described G2V and V2G concepts.

Equations (12) and (13) depict the condition of the battery state at 00:00 a.m., 08:00 a.m. and 04:00 p.m. for successful participation in the FRR markets.

$$S_{Li,negative\ FRR} \leq 0{,}8 \cdot C_{Li} - 4 \cdot P_{Discharge,Max} \tag{12}$$

$$0.1 \cdot C_{Li} + 4 \cdot P_{Discharge,Max} \leq S_{Li,positive\ FRR} \leq 0.8 \cdot C_{Li} \tag{13}$$

In the model, the maximum revenue is calculated based on the activated time of FRR (2010 values) [FRR, 2011a], assumed spot market price curves for 2020 (see chapter 4.1) and assumed capacity and balancing energy prices for the provision of FRR in 2020, which is given in chapter 4.1. In order to be able to assess revenues (second-life usage) from the point-of-view of an investor, a comparison with another technology – reference technology – is conducted. The lead-acid battery is chosen as the reference technology because of its low investment cost. In the first step, the maximum revenues of both technologies (Li-ion and lead-acid) are evaluated using the optimization model. The next step is to calculate the present value of the reference technology with the discounted revenues of the reused Li-ion battery (see equation [14]). Solving equation (14) describes the time (number of years) needed to reach the same economic situation with a reused Li-ion battery compared to a cost-effective alternative technology – a lead-acid battery. The resulting duration therefore is an indicator of the needed minimum lifetime of the reused battery. Hence, an investment decision for the reuse of vehicle batteries exists if the calculated minimum lifetime is given.

$$\begin{aligned} \sum_{j=Base\ year}^{k} E_{Base\ year,\,Li-Ion} \cdot \left(1+\frac{r}{100}\right)^{-(j-Base\ year)} &= -I_{0,lead\ acid\ battery} \\ &+ \sum_{j=Base\ year}^{k} E_{Base\ year,\,lead\ acid\ battery} \cdot \left(1+\frac{r}{100}\right)^{-(j-Base\ year)} \end{aligned} \tag{14}$$

k: $Minimum\ lifetime\ of\ reused\ Li-ion\ batteries$

$E_{Base\ year,x}$: $Revenues\ of\ the\ analysed\ technologies\ in\ base\ year$

$I_{0,lead\ acid\ battery}$: $Investment\ costs\ of\ lead\ acid\ battery$

r: $Interest\ rate$

4 Database

The database used in this work for selected methodological approaches (see chapter 3) is described and depicted in these following chapters and is subdivided as follows:

- Development of electricity prices until 2020.
- Scenarios for activated FRR and associated capacity/balancing energy prices for 2020.
- PV profile for the generation-based charging strategies (STR 4) from generated PV electricity.
- Battery properties.
- Driving patterns and alternative propulsion technologies.

4.1 Development of wholesale electricity prices until 2020

The determination of the market-based charging strategy “cost minimising charging” is based on the weekly wholesale electricity price curves because other databases, like measured household profiles for winter/summer and considered driving patterns (see chapter 4.5), are also weekly data sets. The use of representative wholesale electricity price curves is conducted based on the analysis of historical patterns of spot electricity prices from 2002 until 2009 [EXAA, 2012]. The analysis consists of investigation of the seasonal (winter, summer, transition time) and weekly (working day, Saturday and Sunday) characteristics of historical spot electricity price curves. The impact of the high penetration of PV generation technologies in recent years in Germany (26.3 GW installed PV-capacity from 2009 to 2012 [Solar_Association, 2013]), which shifted the supply curve to the right and led to temporarily very low market prices close to zero (mainly in summer) [Haas, 2012] is not considered. The seasons are subdivided after [Fünfgeld, 2000] into the following periods:

- Winter – from 01.11 to 20.03
- Summer – from 15.05 to 14.09
- Transition time – from 21.03 to 14.05 or from 15.09 to 31.10, respectively.

After the characteristic analysis, typical daily spot electricity price curves of the mentioned seasons are selected from the year 2009. Afterwards, the chosen price curves are adapted and scaled according to the forecasted mean spot electricity price of about 80.82 €/MWh [Haas, 2009]. This mean spot electricity price is the estimated average value for 2020. The resulting spot electricity price curves for 2020 are shown in Figure 23. Figure A.8 (see appendix) shows the selected reference spot electricity price curves from the year 2009. It has to be mentioned that the determination of the economic potential of the case participation of EVs in FRR markets and reusing of batteries refers to base year 2020.

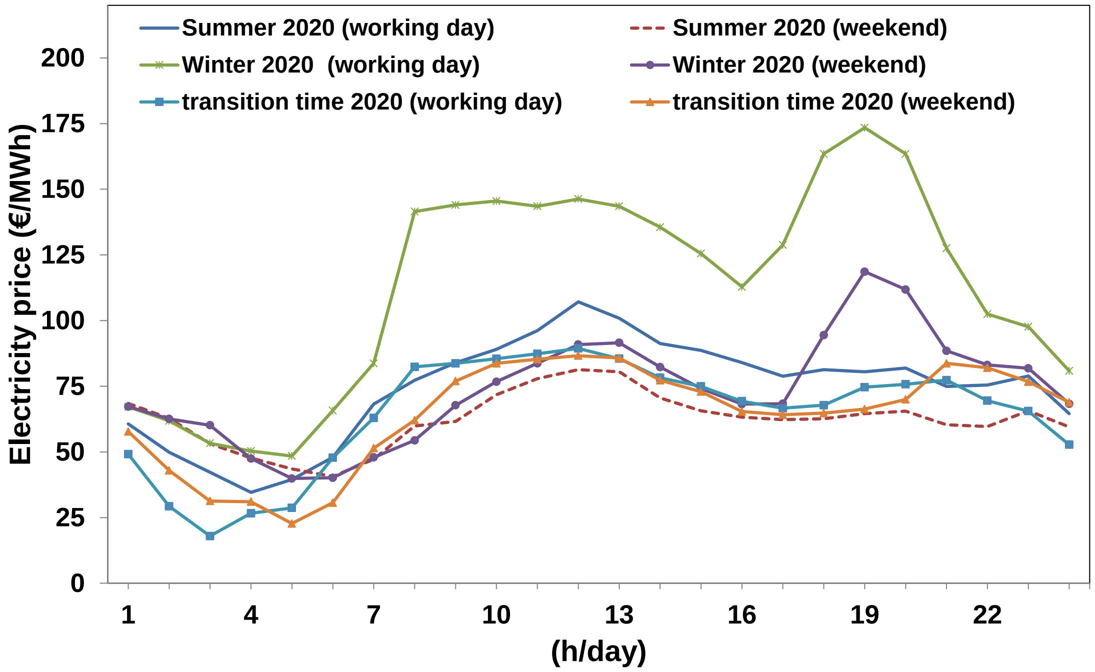

Figure 23: Assumed spot electricity prices for 2020 based on typical spot electricity price curves in 2009 (own depiction and calculation)

4.2 Scenarios for activated FRR and associated capacity/balancing energy prices for 2020

As described in chapter 3.2, an economical assessment of the participation of EVs in FRR markets in the Austrian control zone is based on the modelling of different FRR scenarios that are derived from historical activation of balancing energy within the Austrian control zone. On the other hand, estimation and calculation of future capacity and balancing energy prices build up the next major data needed for economical assignment of use case “participation of EVs in Austrian FRR markets”.

4.2.1 Modelling of activated automatic and manual FRR in the APG control zone

As described in chapter 3.2, the aim of the modelling of activated frequency restoration reserve (FRR) under different scenarios (see Figure 16) is to determine a spread for different extreme situations of daily activated manual and automatic FRR. Therefore, determination of an economic spread for the use case “participation of EVs in the existing FRR markets” results from the combination of FRR scenarios with diverse driving patterns of EVs. The initial data for the modelling of the activated manual or automatic FRR consists of statistic variables, which are derived from the database – historical activated manual and automatic FRR. So, the qualified variables for the modelling are as follows: expected value and standard deviation of activated balancing energy for each time unit of a day (15-minute resolution) as well as the expected value and standard deviation of the number of daily activations.

Figure 24 and Figure 25 depict the average value of activated manual and automatic FRR according to the daily times of the years 2006, 2008 and 2010. The average values of activated manual FRR show a clustering of the positive activation mainly during the day. The highest average values of activated negative manual FRR occur mostly by early in the morning and also in the evening. The depiction of activated automatic FRR according to activation times shows a correlation with the appearance of consumption peaks in the early morning and in the evening. Subdivision of the yearly called FRR energy into the consisting months does not result in recognizable seasonal differences in activated positive and negative balancing energy. The determination of the daily activation time of FRR reserves indicates that the activation of manual FRR reserves occurs in time blocks, meaning a minimum of four consecutive time steps. The same characteristic is also derived for activated automatic FRR (descriptive statistics).

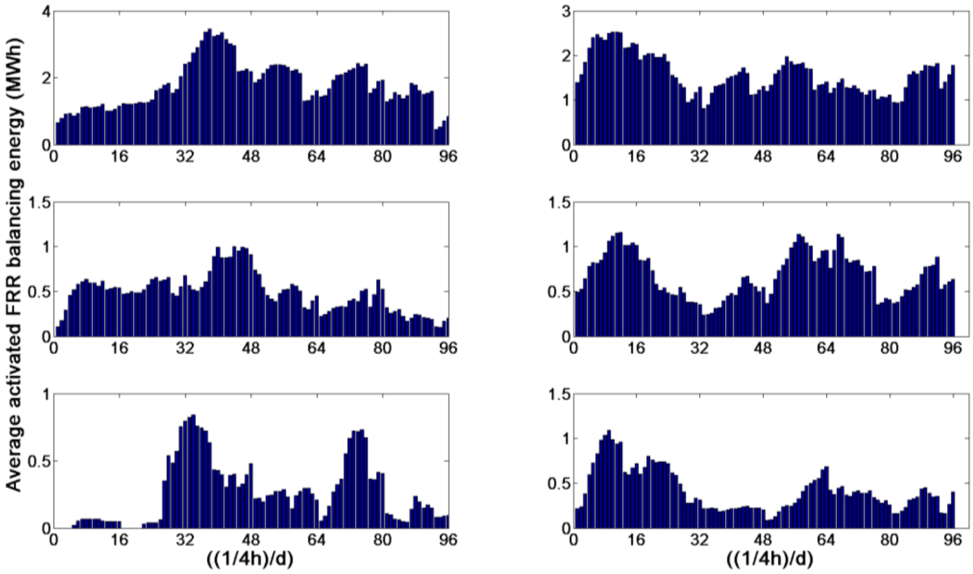

Figure 24: Average activated manual FRR energy in different daily times (left: positive automatic FRR, right: negative automatic FRR) from 2006 (1st row), 2008 (2nd row) and 2010 (3rd row) (own depiction)

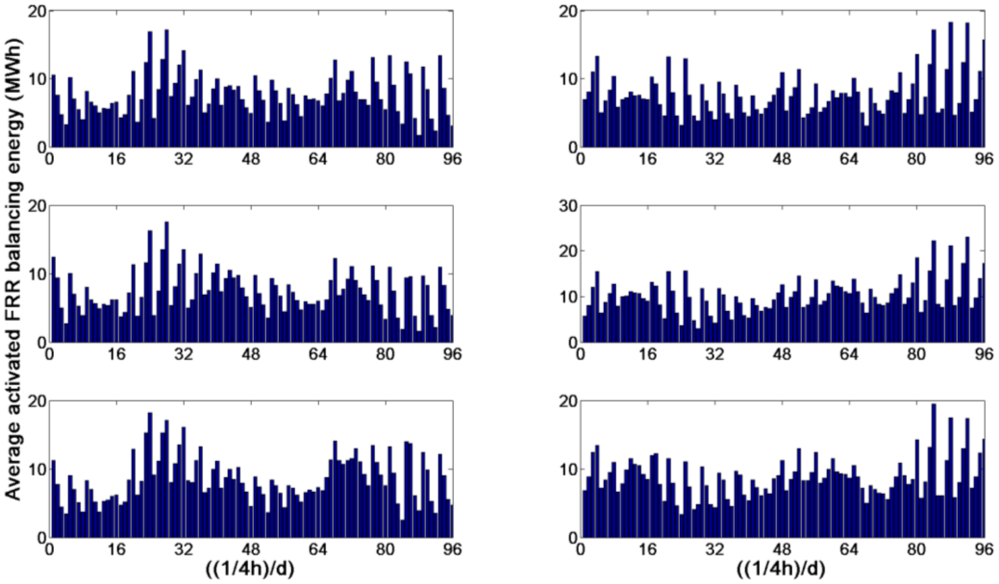

Figure 25: Average activated automatic FRR energy in different daily times (left: positive automatic FRR, right: negative automatic FRR) from 2006 (1st row), 2008 (2nd row) and 2010 (3rd row) (own depiction)

Figure 26 depicts the distribution of positive automatic FRR, whereby the description comprises the daily amount of activated balancing energy from 2006 to 2010 (15-minute resolution, 175,296 entire time periods within all analysed years). The graphical evaluation indicates mainly frequent appearance of called balancing energy at a low level. The statistical analysis shows that the amount of activated automatic FRR energy per daily time period can be matched to a normal distribution function. The assigned distribution function to each daily time period for activated FCR and manual FRR is “generalized extreme value distribution” (see appendix, Figure A.9 and Figure A.10).

It is important to mention that utilization of average values for the modelling of activated FRR results in the loss of stability of the model outcomes. Therefore, the model errors are accepted as follows:

- The daily activation time of FRR reserves are defined on a random basis and if necessary they occur in predefined time areas (see chapter 3.2).
- The future development of activated balancing energy cannot be derived from the existing database. Therefore, the log time trends could not be considered based on the database. It was not possible to use log time aspects for the parameterization of the model.

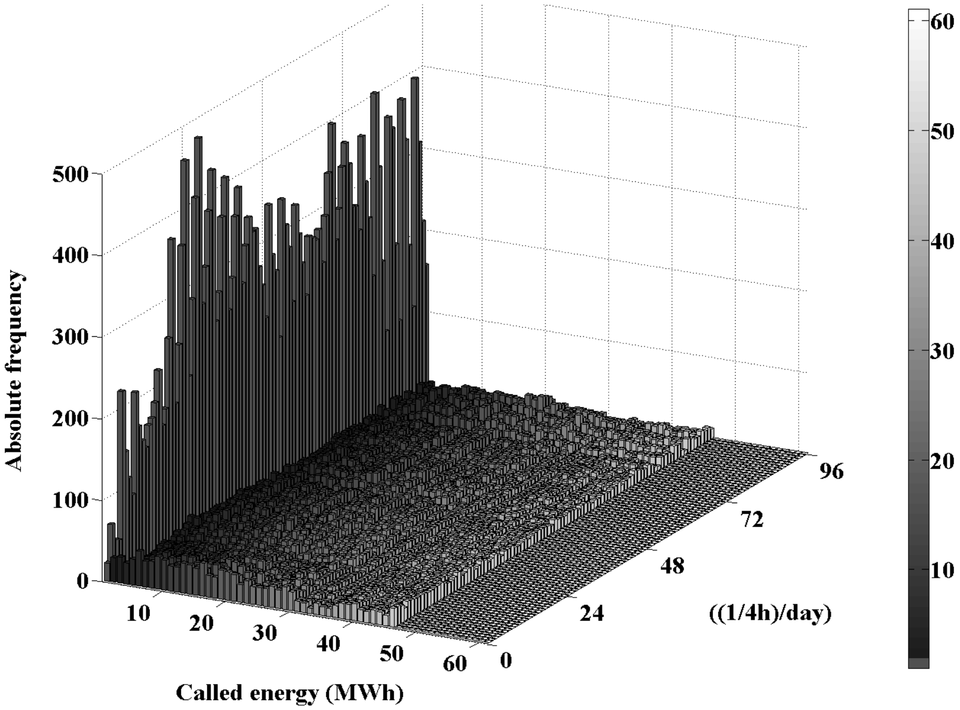

Figure 26: Number of activations of positive automatic FRR per time period (15-minute resolution) in the Austrian control zone from 2006 to 2010 (own depiction)

Table 2 concludes the results for all scenarios subdivided into the total activated daily FRR energy and the number of daily activations. The number of daily appearances of manual FRR is lower than the activated number of automatic FRR (see also Figure 5 and Figure 6). The needed automatic FRR energy for restoring the frequency deviation is also higher than the needed manual one.

Table 2: Scenarios for called/activated FRR reserve in the Austrian control zone

Balancing energy scenarios		Manual FRR						Automatic FRR					
		Positive			Negative			Positive			Negative		
		Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min
Total activated balancing energy (GWh/day)	Max	0.2	0.04	0	0.127	0.04	0	4.3	2.8	1.4	4.9	3.4	1.7
	Mean	0.023	0.005	0	0.015	0,005	0	0.53	0.35	0.17	0.64	0.43	0.23
Number of daily activation (15-minute resolution)		19	6	0	20	7	0	67	46	25	71	50	29

4.2.2 Balancing energy and capacity prices of manual/automatic FRR for 2020

Actual balancing energy and capacity prices for manual/automatic FRR, their dependency on the day-ahead electricity prices and marginal cost of the involved suppliers/bidders in Austria and Germany are given in chapter 2.1.1 and the appendix.

The existing tendering products on the manual FRR market in Austria are based on two different time periods (weekly and weekend products) and each one consists of six different time slots (0:00-4:00, 4:00-8:00, 8:00-12:00, 12:00-16:00, 16:00-20:00, 20:00-24:00). It is assumed that the offered balancing energy price of an e-mobility provider for participation of vehicles in the mentioned market from a strategic point of view (successful participation in the manual FRR market) is oriented after the minimum of the day-ahead electricity prices during each described time slot (see Figure 23). Therefore, the calculation of the average value of offered balancing energy prices for participation in the negative manual FRR market (in further evaluation also for negative automatic FRR) is based on the determination of an average weekly value (see equation [15]).

$$P = \sum_{i=1}^{7}\left(\sum_{j=1}^{6} min\left(T_{i,j}\right)\right)\Big/ 7 \cdot 6 \tag{15}$$

$T: Day - ahead\ electrcity\ prices\ within\ 15\ minutes$

The offered electricity price of the e-mobility provider is derived as an average value of the calculated mean weekly electricity prices for summer and winter weeks (see equation (16)[16]).

$$P_{G2V} = \frac{\left(P_{Summer} + P_{Winter}\right)}{2} \tag{16}$$

The assumed average electricity price on the day-ahead market is about 80.82 €/MWh for 2020 (see chapter 4.1). The balancing energy prices for positive 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 (see also the description of historical balancing energy prices in chapter 2.1.1 and Figure 8). It is assumed that the capacity prices in FRR markets will double until 2020 (base year = 2010). Table 3 shows the predicted and assumed balancing energy and capacity prices for offers of an e-mobility provider due to the participation of EVs in the FRR markets in 2020. The economic evaluations of the use-cases “participation of EVs in the FRR markets” and “second-life usage” are estimated based on the prices depicted in Table 3.

Furthermore, the robustness of the economic results are evaluated and discussed based on sensitivity analysis of the battery investment cost, capacity and balancing energy prices on the various FRR markets.

Table 3: Average capacity and balancing energy prices for FRR products in the Austrian control zone in 2020

	Positive (V2G)		Negative (G2V)	
	Capacity price (€/MW/h)	Balancing energy price (€/MWh)	Capacity price (€/MW/h)	Balancing energy price (€/MWh)
Automatic FRR	26	116.90	26	73.1
Manual FRR	2	176.75	10	73.1

4.3 PV profiles for the generation based charging concept (STR 4)

The load-based discharging concept of EVs from 07:00 p.m. to 09:00 p.m. (see chapter 3.4) is combined with charging of the vehicles from PV generation. After discharging of the vehicles and because of fulfilment of the mobility needs of vehicle users for the following day, the EVs could be charged by night from 00:00 a.m. to 06:00 a.m. until predefined battery states are achieved, which are set by the users.

The determination of covering household demand with the V2G-concept (discharging) is based on the weekly measured values for one winter and summer week [ADRES, 2011]. The economic analysis of the V2G strategy is based on the assumption that the shifted energy[29] (see chapter 3.4) would be used for the discharging and therefore no charging costs would be considered. Hence, the simulation of the generation-based charging strategy is established based on various PV radiation scenarios that also represent extreme weather situations. In considering the mentioned PV radiation aspect, it is important to note that the yearly global radiation values [Soda-is, 2011] of all Austrian rural and urban districts build up the basis for determining of an average yearly PV profile with an installed capacity of 1 kW_p (roof installation, direction: south, angle: 30 °). The simulation considers for each analysed vehicle – driving pattern – one installed PV module. The installed capacity of each PV

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[29] Shifted energy: This is the difference between the battery status after discharging the vehicle and before the first usage of the vehicle on the following day. The battery status before the first daily usage is set by the vehicle user. The shifted energy is covered by electricity generation from PV.

module is oriented according to the average yearly electricity consumption of the considered vehicles (see chapter 4.5). This means that the electricity consumed by a vehicle (see chapter 4.5) – the mean value – is equal to electricity generated by the installed and linked PV module. Hence, the installed PV capacity for each vehicle is about 2.7 kW$_p$. The associated PV profile is derived by multiplying the calculated average profile by the installed capacity of 2.7 kW. The analysis of the generation- and load-based charging/discharging strategy is based on the weekly evaluation. Therefore, representative weekly PV profiles are derived from the yearly profile. They reflect different climate conditions. Figure 27 depicts the histogram of daily generated PV electricity (average profile) with the associated cumulative distribution function for winter which shows three areas with recognisable gradients. These sections denote days with weak (area 1), medium (area 2) and strong (area 3) PV electricity generation. A similar approach to that of the winter case is used for the summer season (see Figure 28).

The cumulative distribution function for daily PV generation during the transition times cannot be divided into sections with recognisable and obvious gradient differences (see appendix, Figure A.12). Hence, the probability density function and the derived average value μ and standard deviation σ are used for defining the radiation areas similar to the winter case. The medium section (area 2) is defined as days that the associated generated electricity lies in the spread: $\mu \pm \sigma$.

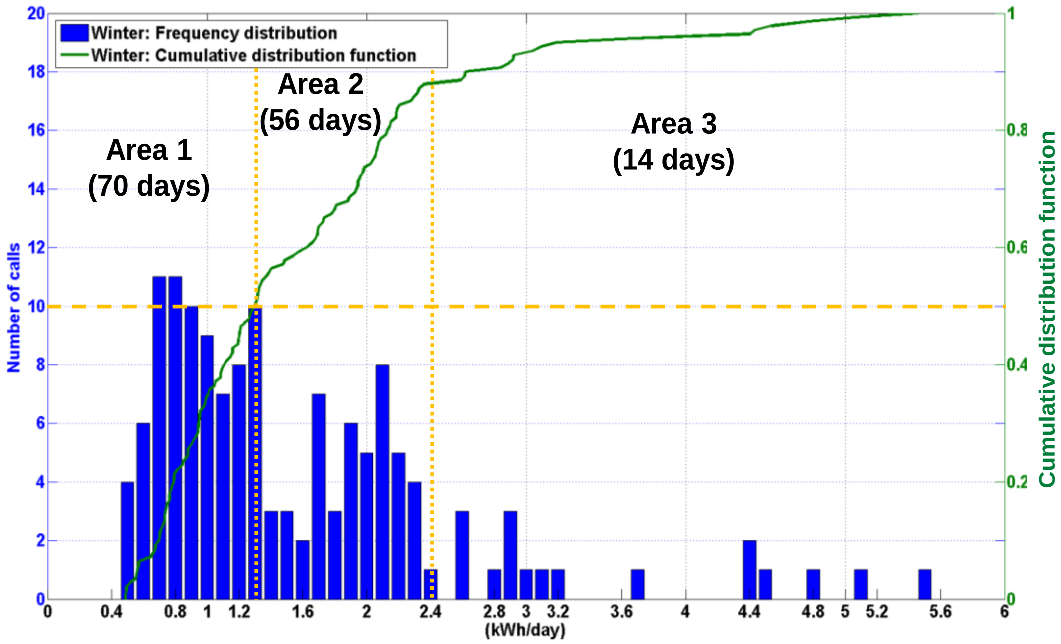

Figure 27: Histogram and cumulative distribution function of daily generated PV electricity with an installed capacity of 2.7 kW$_p$ during the winter season (own calculation and depiction)

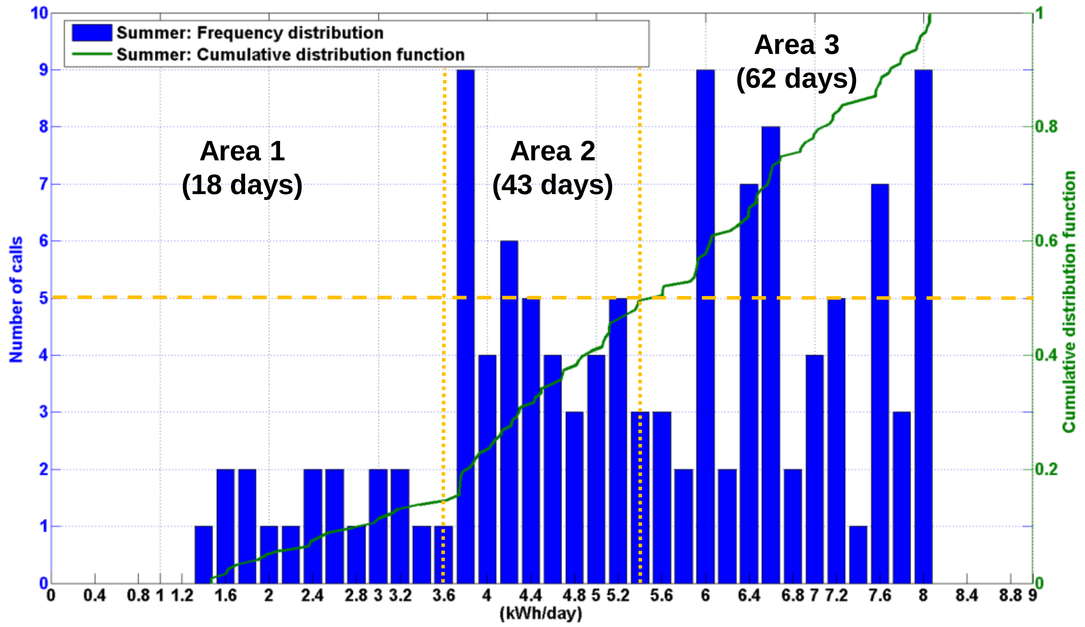

Figure 28: Histogram and cumulative distribution function of daily generated PV electricity with an installed capacity of 2.7 kW during the summer (own calculation and depiction)

4.4 Battery properties

The battery properties are subdivided into two aspects which have been considered in the simulation of described use cases during and after the mobile lifetime of batteries (see chapter 2.2). These properties include the charging (CC/CV curve) pattern of Li-ion batteries and the degradation due to discharging of the vehicles with constant or dynamic discharging power.

4.4.1 Charging characteristic of Li-ion batteries

According to [Schuster, 2008], the charging characteristic of Li-ion batteries consists of two phases. The charging of the battery happens with constant current (CC) or constant voltage (CV) during the first or second stage of charging, respectively. In the CC phase, charging power is able to take over a constant maximum charging power (depends mainly on the charging infrastructure) because the variation of cell voltage is very low. The transition between the two phases is defined by the CC/CV transition point (T) in % of charging state (state of charge, SOC). The section with constant voltage (CV), which depicts an exponential charging characteristic (see equation (17[17]), follows after the CC- phase.

$$P = P_{const} + e^{\frac{T-SOC}{COC}} \tag{17}$$

P_{const}: $Constant\ charging\ power\ during\ the\ first\ phase\ (CC{:}\ Constant\ Current)$

T: $Transition\ point$

SOC: $State\ of\ charge$

COC: $Cut-off\ current$

The charging power within the CC-phase is for one or three-phase connecting points (charging infrastructure) around 3.5 kW or 10.5 kW, respectively. The transition point is defined as 80 % of the maximum battery state. The cut-off current depends on the P_{const}, T and cut-off power, whereby the cut-off power is directly dependent on the net battery capacity. The values for the cut-off current are about 6.82 A, 7.92 A or 10.91 A for battery capacities of 16 kWh, 24 kWh or 48 kWh, respectively. Figure 29 depicts the described CC/CV charging characteristic for one-phase charging equipment with a maximum charging power of 3.5 kW.

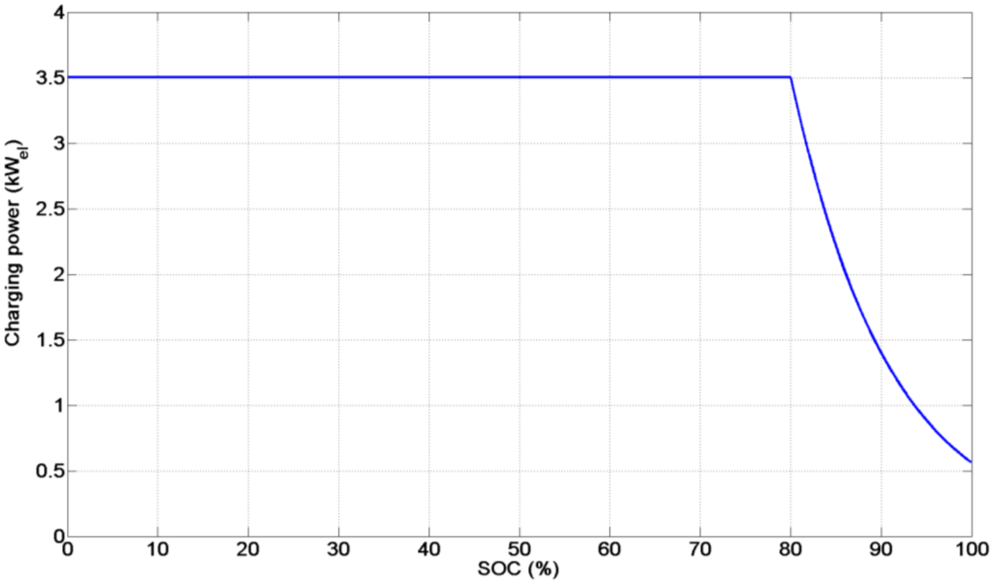

Figure 29: CC/CV charging characteristics of Li-ion battery (Source: [Schuster, 2008])

4.4.2 Degradation of Li-ion batteries

The influence of the lifetime on Li-ion batteries due to the realisation of various V2G-concepts (feeding electricity into an LV-grid) is considered in the economical calculation and assessment of the V2G use cases. [Peterson, 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 discharging power for driving is simulated with a dynamic (inconstant) characteristic, whereas the additional discharging – V2G – is based on constant discharging power. The results show that deep discharging has a lower impact on the capacity losses of the regarded LiFePO4-batteries than on older battery versions. Furthermore, the outcomes depict that per cent capacity lost per normalized Wh or Ah is as follows: -6.0×10^{-3}% for driving support (dynamic discharging) and -2.70×10^{-3}% for V2G application (constant discharging). According to [Peterson, 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.

4.5 Driving patterns and alternative propulsion technologies

The evaluation of charging or discharging profiles for analysed EVs is based the on assignment of driving patterns, which are derived from the statistic data sets of the mobility survey conducted in Salzburg city (see [Herry, 2005]). The survey is based on written household interviews on three working days in 2004. [Litzlbauer, 2012] gather information on motorized individual transport from the existing data set and extract 2,606 anonymous distance and time curse profiles of interviewees. Figure 30 depicts an example of one distance and time curse profile for one working day, which consists of cumulative distance and the associated location of the vehicle before and after each usage. The adaption of the mentioned survey data set to the concerned propulsion technologies (EV and PHEV) with different battery capacities (16, 24 and 48 kWh) – see Table 4 – results in the evaluation of appropriate electricity consumption profiles with minute resolution [Litzlbauer, 2012]. Due to existing weekly measured household profiles [ADRES, 2011], the driving profiles of EVs represent weekly driving patterns composed from the mentioned daily survey.

Figure 31 depicts the sum load profile of needed electrical power (kW) for the driving of 200 EVs (see Table 4) for a working day. The sum load profile indicates a concentration of trips (driving activities) in the morning and early evening, whereby a significant decline of driving activities can be recognised beyond the extreme time segments. Furthermore, 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) (see Figure 32).

The assignment of the charging or discharging profiles of an EV is based on two input parameters. On the one hand, the electricity consumption of an EV and driving time must be given through a driving consumption profile. On the other hand, the charging and discharging times must be clearly based on the utilized charging and discharging strategies (see chapter 2.2).

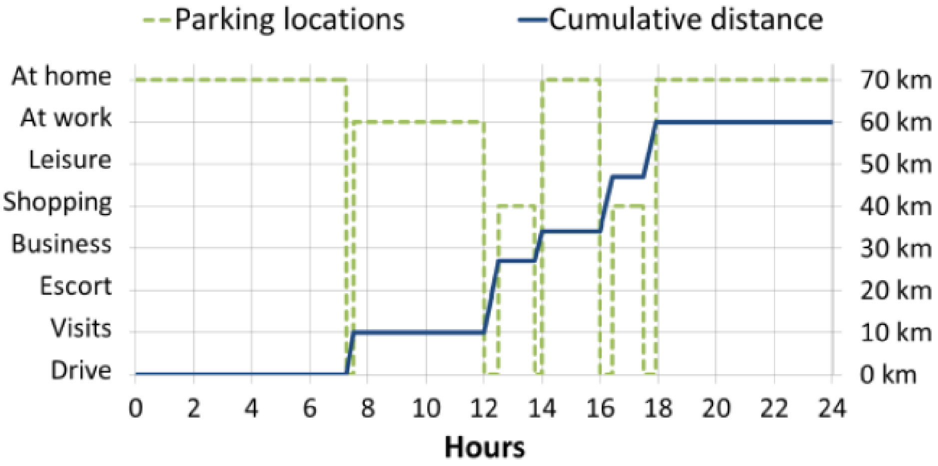

Figure 30: Time course of parking locations and cumulative distance – one exemplary vehicle (Source: [Litzlbauer, 2012])

Table 4: Alternative propulsion technologies

	Alternative propulsion technologies			
	EV			PHEV
Battery capacity (kWh)	16	24	48	16
Number of weekly driving patterns	94	36	28	42

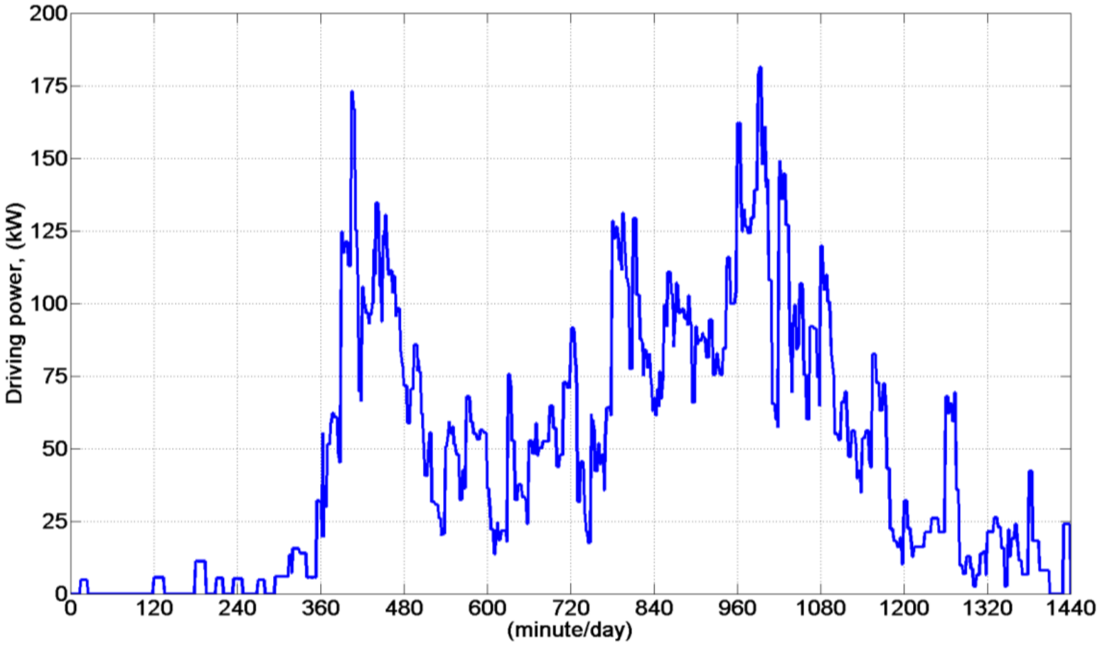

Figure 31: Sum of driving power of all existing vehicles (200 EVs) for a chosen day (Source. [Litzlbauer, 2012], own depiction)

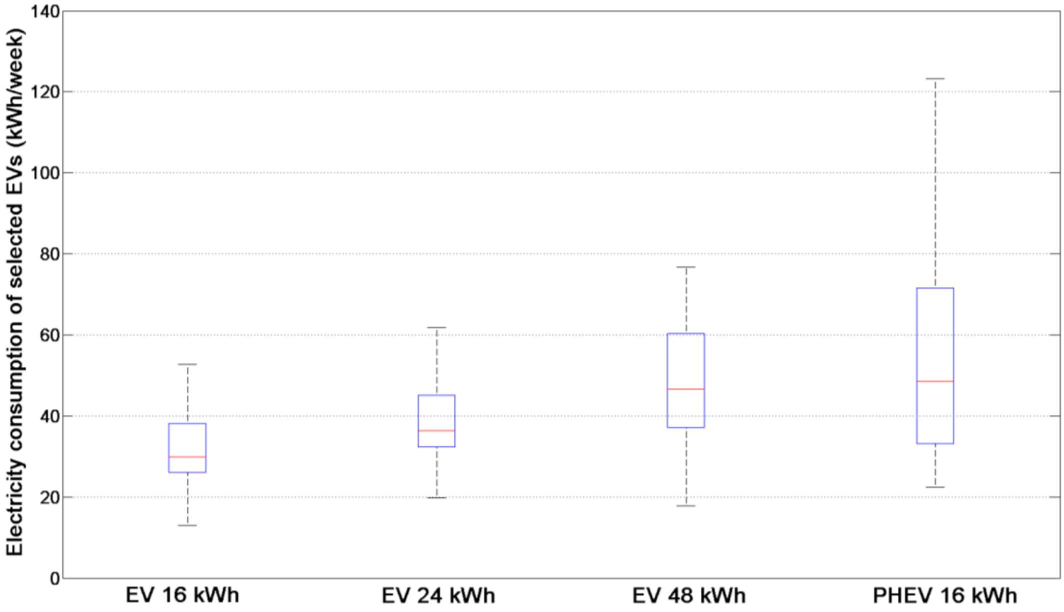

Figure 32: Consumed electricity for driving of different EV categories (Source: [Litzlbauer, 2012], own depiction)

5 Results

The results of the described charging and discharging strategies (see chapter 2.2) are given in the coming subchapters 5.1 – 5.4. The economic and technical outcomes are based on the introduced methodology (see chapter 3) and the utilized database (see chapter 4). The results are given for analysed concepts, which are subdivided into the following:

- Market-based charging/discharging strategy: participation in frequency reserve markets (STR 2)
- Generation-based charging/discharging strategy: electric vehicles and balancing model (STR 3)
- Generation- and load-based charging/discharging strategy (STR 4)
- Reusing of batteries – second life.

5.1 Market-based charging/discharging strategy: Participation in frequency reserve markets (STR 2)

The outcomes of the assessment of the market-based charging/discharging strategy, more precisely, participation in frequency restoration reserve (FRR) markets, are subdivided into two result groups:

1. Revenues of EVs due to their participation in positive FRR markets (V2G)
2. Revenues of EVs due to their participation in negative FRR markets (G2V) in comparison to the cost minimising charging strategy.

5.1.1 Participation of EVs in positive FRR markets (V2G)

The calculation in this work reveals that the participation of EVs in positive manual as well as automatic FRR markets results in positive revenues if battery investment costs are less than or equal to 500 €/kWh. Revenues due to participation of EVs in the positive manual FRR market (entire activated manual balancing energy of 9.25 GWh in 2010 [FRR, 2011a]) obtain a spread between 63.5 € and 198 € per vehicle and year (battery investment cost = 500 €/kWh, battery capacity 16 kWh, 24 kWh and 48 kWh). The consideration of a dispatch probability of reserved capacity in the positive manual FRR market of about 0.4 % (compare Figure 7) implies a strong decline of the mentioned possible revenues. The resulting revenues after consideration of the dispatch probability are between 4 € and 9 € per vehicle and year (see Figure 33). The methodological approach in context with the determination of revenues is based on different weekly FRR scenarios (activated balancing energy). The yearly revenue results are based on scaling of weekly outcomes for various seasons within a year. The revenues mentioned above are the computed median values resulting from the participation of EVs in FRR markets within the Austrian control zone.

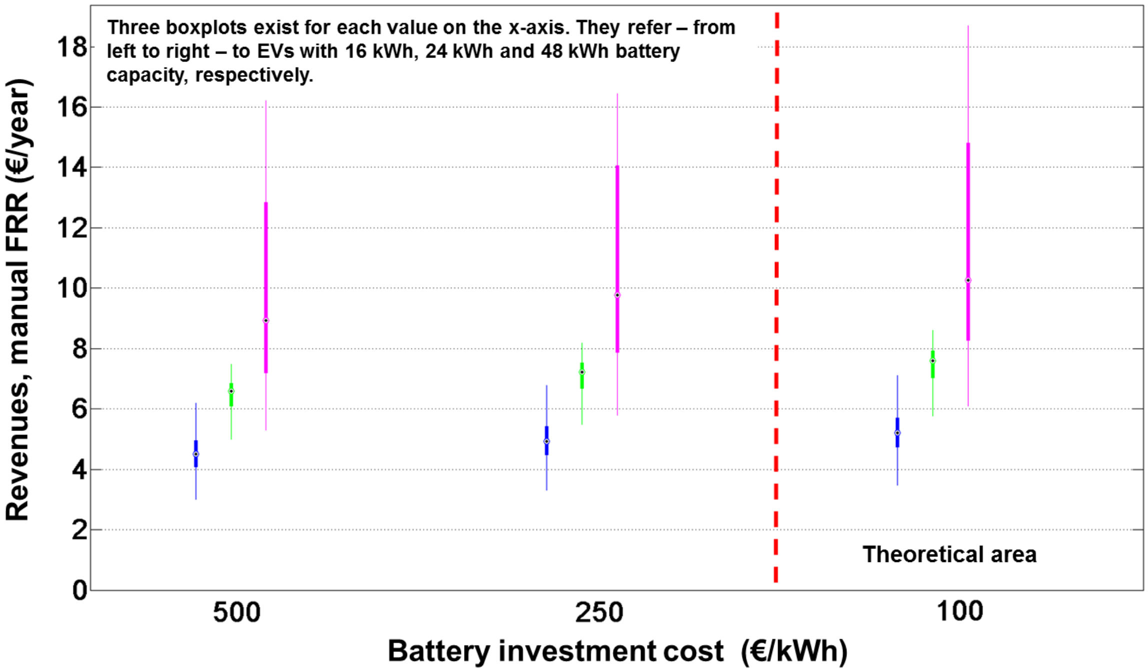

Figure 33: EV revenues due to their participation in manual FRR market

The entire activated automatic FRR within the Austrian control zone was about 300 GWh in 2010 [FRR, 2011a]. The consideration of the evaluated dispatch probability of reserved capacity in the range of 17 % obtains revenues between 45 € and 119 € per vehicles and year due to the participation of EVs in the automatic FRR market. The battery investment costs are 500 €/kWh (see Figure 34).

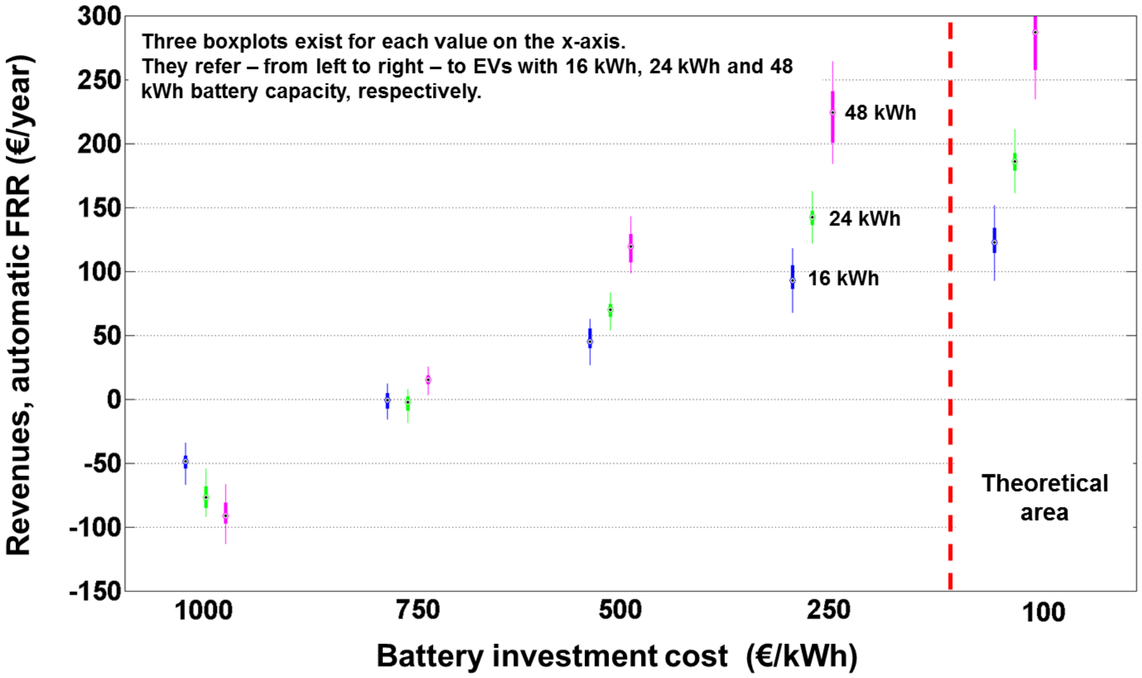

Figure 34: EV revenues due to their participation in automatic FRR market

Figure 33 and Figure 34 also show revenues in the case of a battery investment cost of 100 €/kWh. The depicted revenues are seen as theoretical possible revenues due to the fact that according to [EMST, 2011] such an investment cost could not be reached for Li-ion batteries in the future (see also chapter 2.2.5).

The described revenues represent maximum possible revenues resulting from the participation of EVs in positive FRR markets within the Austrian control zone, which must be sufficient to cover the technical equipment and transaction costs for a successful participation. The presented results do not consider competition with other market participators, like generators and other storage technologies. Consideration of the competition situation of EVs with other providers of positive FRR reserves prevents or reduces to a high degree the realization of the mentioned revenues. The following argumentations are given in this conjunction:

1) The offered capacity prices of market participators count as compensation for the opportunity costs (lost profit in day-ahead and intraday markets). The decline of the spot electricity price spread between peak and off-peak periods has resulted already in reduction of the opportunity costs of existing pumped hydro energy storages (major suppliers of FRR in the APG control zone) in Austria. This development on the day-ahead market makes the consideration and inclusion of EVs in the power pool more difficult according to the described FRR market architecture in Figure 4.
2) According to the explanation in chapter 2.1.1, the offered balancing energy price for positive FRR covers at least the costs of suppliers in the case of balancing energy delivery/activation. Therefore, the offered balancing energy price must cover at least the marginal generation cost of a supplier. Figure 35 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 (balancing energy delivering) in comparison to pumped hydro energy storages and other bulk energy storages. Pumped hydro energy storages provide a major portion of the activated automatic FRR reserves in Austria and can be seen as significant competitors to EVs.

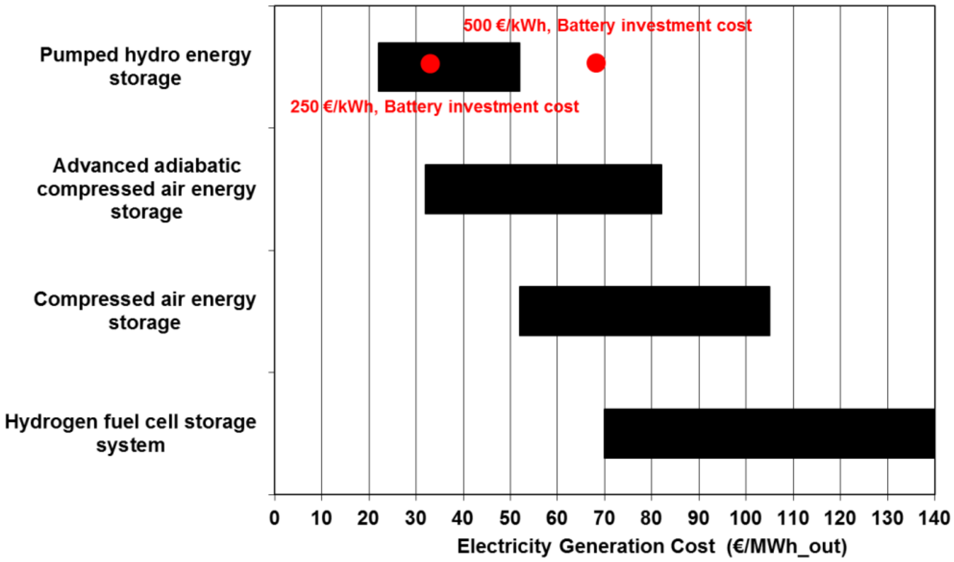

Figure 35: Comparison between the electricity generation costs of difference bulk storage systems (see [Zach, 2012]) and the degradation costs of Li-ion batteries as a function of battery investment costs

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 (see Figure 35). The mentioned degradation costs do not consider either the cost for the needed communication infrastructure, control systems and the DC/AC converter (V2G-Inverter), which enables the discharging of batteries.

3) Changes and adaption of the FRR market rules can encourage EVs (or e-mobility providers) to participate in FRR markets. An example would be the reduction of the minimum bid on the automatic FRR market in the APG control zone, e.g., from 5 MW to 2 MW[30]. This adaption 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.) and therefore a higher number of market participants are able to provide restoration reserves. The higher the number of suppliers, the greater the competition, which result in a reduction of offered capacity and balancing energy prices in the positive FRR markets. The described situation results in the decline of possible revenues for EVs and increase the challenge to cover the V2G costs (degradation, communication and control costs including the investment costs for the V2G inverter).

In summary, it can be stated that the possible/potential revenues of EVs due to their participation in the positive manual/automatic FRR markets in the APG control zone are low (bearing in mind the described competitive situation on the FRR markets) and not sufficient to cover associated costs (degradation, communication, V2G inverter, control system [energy management system]). On the other hand, the Agency for the Cooperation of Energy Regulators [ACER, 2012] forces the development of a cross-border balancing market based on a common merit order between the Member States to increase competition and also to achieve better integration of renewable energy sources for electricity generations (RES-E) (see Figure 36) in the coming years. The establishment of such a market design results in increased competition between the market participants and reduction of offered capacity and balancing energy prices. In contrast, the disadvantage of EVs for energy delivery – high degradation cost – remains and makes successful participation of EVs in the future common balancing energy market unfeasible.

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[30] [Reiter, 2011] determines the needed number of EVs for the provision of manual FRR reserves in a timeframe of four hours with a constant capacity of 30 MW. The results show that at least about 17,000 EV are needed for providing the mentioned capacity from 04:00 a.m. to 08:00 a.m.

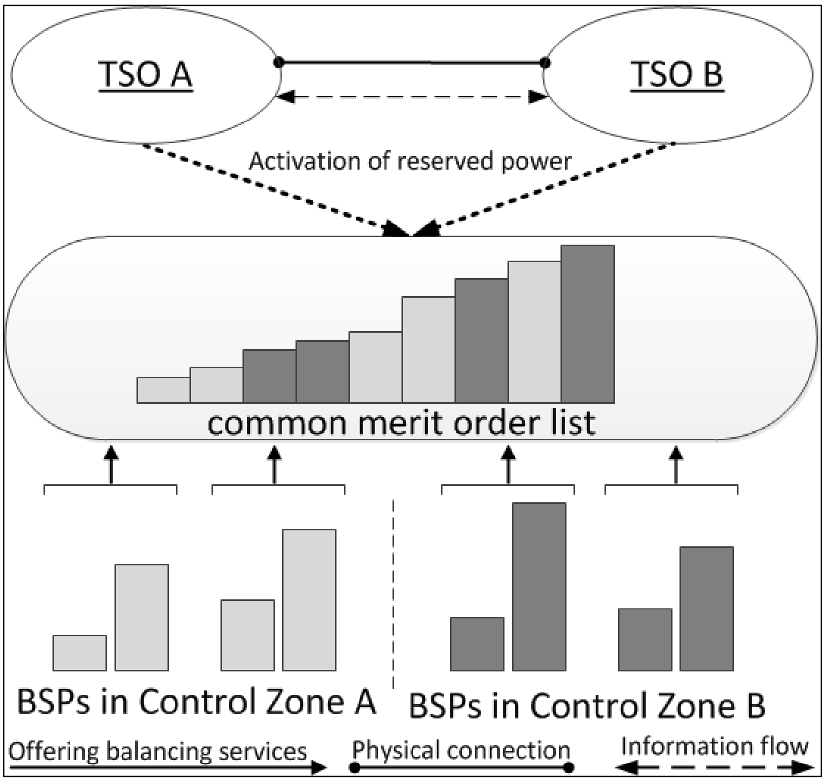

Figure 36: Cross-Border TSO-TSO balancing model with common merit order [ebadge, 2013]

5.1.2 Participation of EVs in negative FRR markets (G2V)

The determination of revenues for the use case participation of EVs in negative FRR markets occurs based on the comparison of resulting charging costs with a reference charging strategy – cost minimising charging, see chapters 2.2.1 and 3.1. Figure 37 depicts the basic principle of the assessment of charging cost due to the participation of an EV in negative manual/automatic FRR markets, which results from a comparison to the charging cost derived from the cost minimising charging strategy.

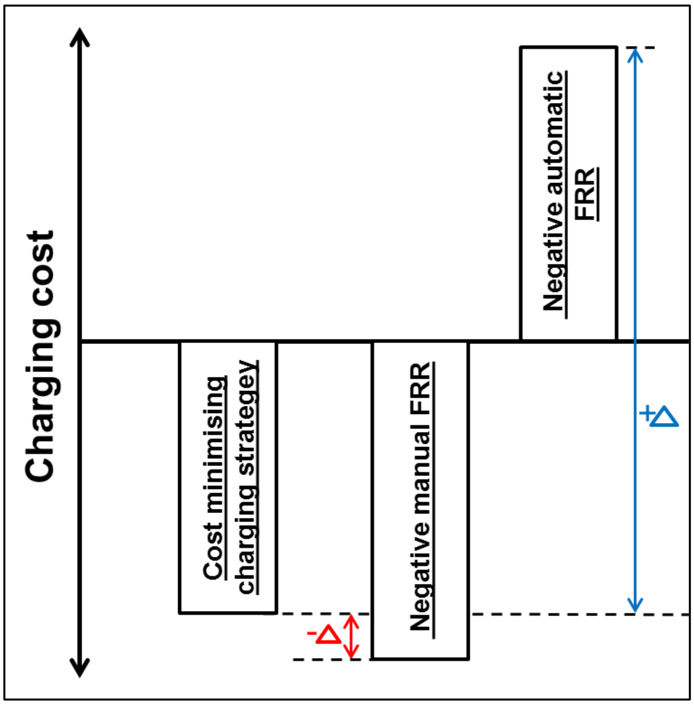

Figure 37: Determination of charging cost of participating EVs in negative manual/automatic FRR markets in comparison to the cost minimising charging strategy

Figure 38 shows the results of the G2V application (provision of negative FRR balancing energy from home, office and public charging station) and indicates the difference (average value) between charging costs due to the cost minimising charging strategy (not participating in FRR markets) and the G2V application (combined charging on day-ahead and manual/automatic FRR markets). The depicted results refer to the vehicle category with a battery capacity of 48 kWh. The described revenues/differences depend on given capacity and balancing energy prices in the manual/automatic FRR markets. The X-axis indicates the variation of capacity and balancing energy prices for the manual and automatic FRR markets. Due to the assumed average electricity price in the day-ahead market in 2020 (see chapter 4.1), a lower charging cost can be achieved in the range of 80 € per year and vehicle in conjunction with the participation of EVs in the automatic FRR market (see Figure 38, assumed capacity and balancing energy prices for 100 % point on the x-axis).

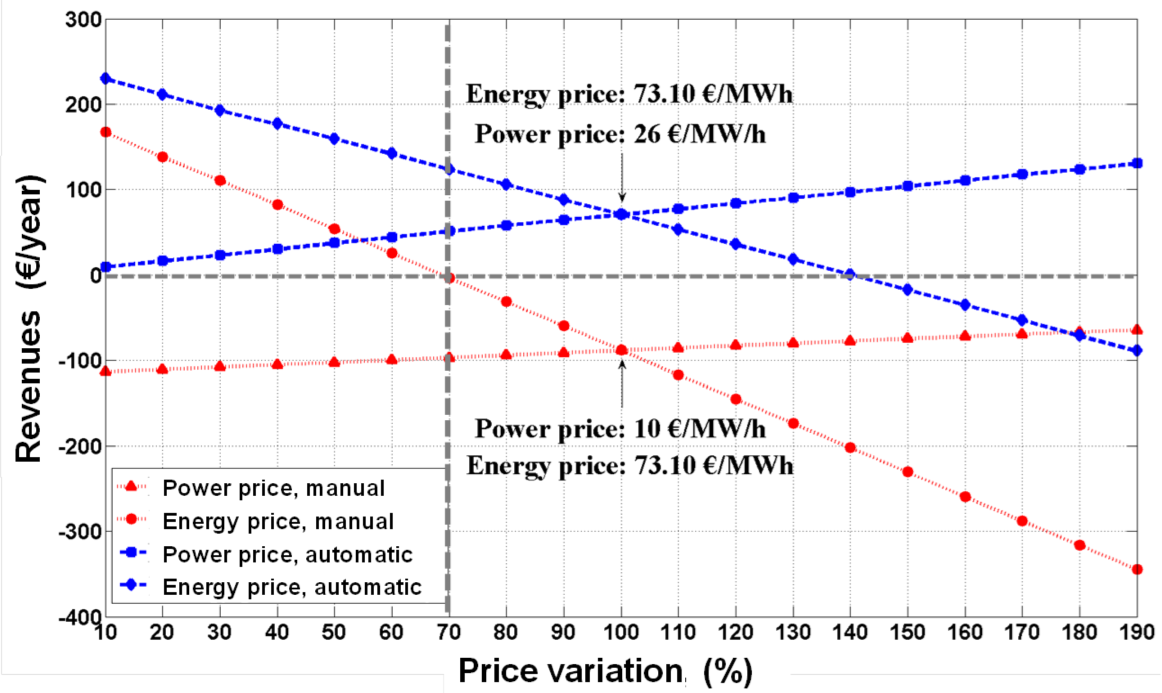

Figure 38: Revenues (average value) for an EV due to participation in negative FRR markets in the Austrian control zone dependent on capacity and balancing energy prices (EV with 48 kWh battery capacity)

Charging costs due to the participation of EVs in the manual FRR market are higher than the cost minimising charging strategy (see Figure 38, balancing energy price = 73.10 €/MWh, capacity price = 10 €/MW/h). The reason given is due to the concentration of called manual FRR balancing energy between 06:00 a.m. and 08:00 p.m. and lower activation numbers of manual FRR in comparison to automatic FRR. Therefore, the vehicle must be charged with higher charging costs than the cost minimising charging strategy (charging in the early morning or late evening). The capacity price cannot compensate for the mentioned gap (still negative revenues). A positive gap can be reached by a balancing energy price reduction of about 30 % from the main point with a balancing energy price of 73.10 €/MWh (73.10 * 0.30 = 51.17 €/MWh). Generally, the participation of EVs in negative manual/automatic FRR markets with the assumed capacity and balancing energy prices (see Table 3) obtains a spread of revenues between 87.6 € and 70.80 € per vehicle and year (-7.32 and 5.9 € per vehicle and month). As shown in Figure 7, the consideration of the calculated average dispatch probability (1.34 % for negative manual FRR and 17.74 % for automatic FRR) greatly reduces the mentioned/possible revenues from the participation of EVs in negative FRR markets.

From a strategic point-of-view, a supplier of negative FRR reserves offers bids with low balancing energy prices (assumption: accepted capacity prices and consideration of the balancing energy bid in associated merit order curve, see Figure 4) to ensure the activation of its offered capacity reserve. This behaviour by market participants results in increased competition and also declining possible achievable revenues for the involved suppliers. The implementation of an international balancing energy market according to guidelines in [ACER, 2012] results in fierce competition between the suppliers and a reduction of offered balancing energy prices. On the other hand, there exist other small suppliers, like heat pumps, which in comparison to EVs have technological advantages in the provision of negative FRR reserves. The stationary installation and thermal inertia of dwellings are beneficial for the estimation of the available capacity of heat pumps in comparison to EVs. The mentioned properties of heat pumps give them a high flexibility in the provision of different balancing products.

In summary, it can be stated that the coverage of costs incurred due to the participation of EVs in negative FRR markets (organisation and communication expenditure) with consideration of dispatch probability (see Figure 7) and the future development of international negative FRR markets (see Figure 36) seems to be not possible or very difficult.

5.2 Generation-based charging/discharging strategy: Electric vehicles and balancing model (STR 3)

As mentioned in chapter 3.3 two different approaches to the integration of EVs in a fictional balancing group (see the various associated generation structures in Table 1) are analysed and subdivided into the following:

1. Combined charging and discharging concepts for the implemented EVs within the balancing group.
2. Charging concept for the implemented EVs within the balancing group only.

Figure 39 depicts the changing of the weekly deviation of created fictional balancing groups according to the integrated EVs, which are charged if electricity generation is higher than electricity consumption and discharged in times of lower generation levels in comparison to current electricity consumption.

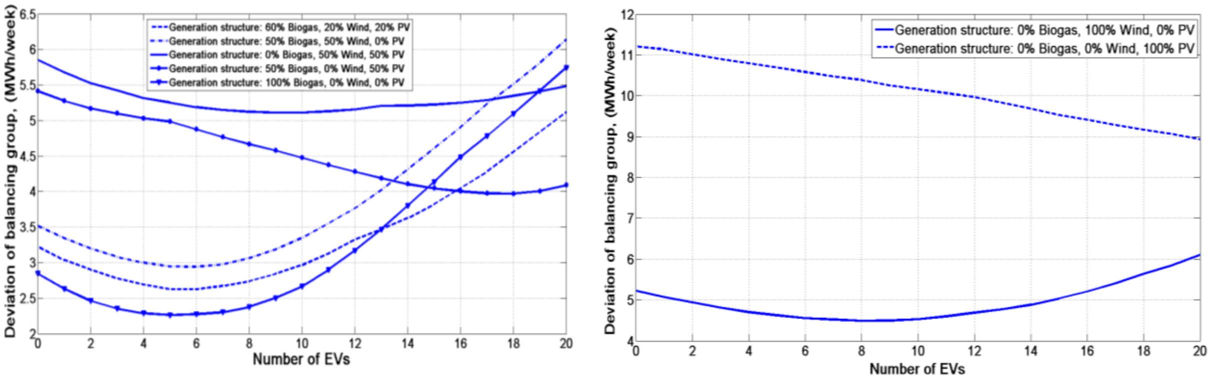

Figure 39: Deviation between electricity generation and consumption dependent on the number of integrated EVs in a fictional balancing group (combined charging and discharging)

The deviations are also given for the different selected generation structures as described in Table 1. Figure 40 shows the second approach for the implementation of EVs in a balancing group, whereby deviation of the balancing group only declines due to the charging of integrated EVs. Despite using two different methodologies for the integration of EVs in the balancing group (see chapter 3.3), the impact of EVs on the deviation of the balancing group is recognizable. The characteristics of daily generated PV electricity are compatible with reduced driving activities between the first and last daily usage (see Figure 31) of electric vehicles and allows the implementation of a higher number of EVs for reducing of the balancing group deviation. Figure A.13 (see the appendix) compares the percentile reduction of imbalances of the analysed generation structure based on the two different integration approaches.

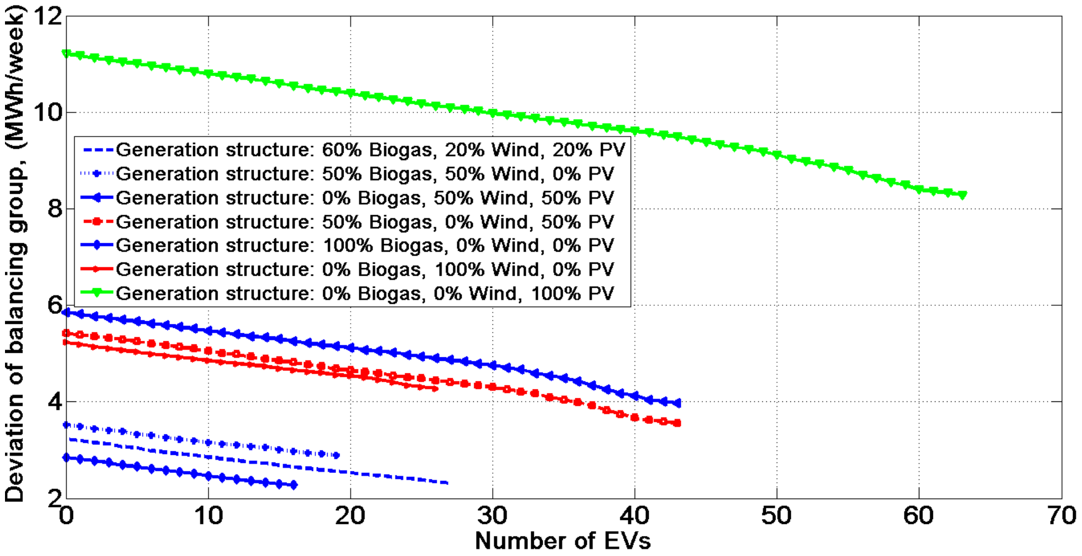

Figure 40: Deviation between electricity generation and consumption resulting from the number of integrated EVs in a fictional balancing group (only charging) (own calculation and depiction)

Figure 41 compares the costs incurred (median values) by both implementation strategies based on day-ahead electricity prices in 2010. 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 using a combined charging and discharging strategy – independent of the concerned generation structure – are significantly higher than the strategy, which only includes the charging of EVs. The described economical aspect in combination with the maximum number of integrated EVs in the balancing group (see Figure 39 and Figure 40) shows that realisation of charging would result in a more efficient route than the combined charging and discharging strategy.

According to [Pfleger, 2012], forecast errors for wind and PV generation in Germany were at about 13.6 % or 11.4 % in 2010 and 2011, respectively. 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). An advantage in this case is the coverage of charging costs by vehicle users.

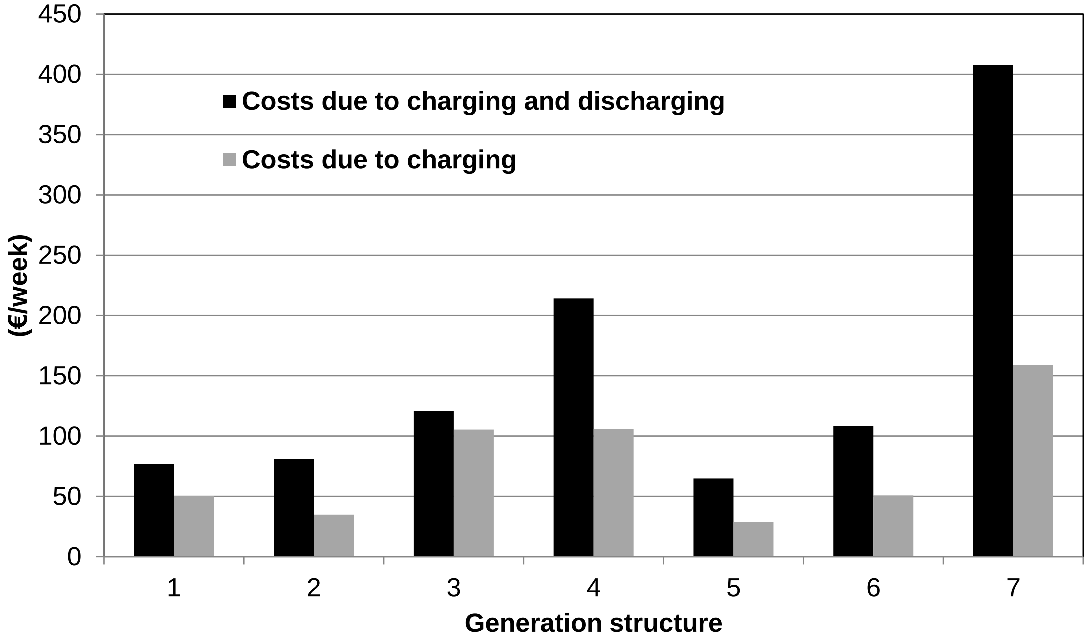

Figure 41: Comparison of the costs incurred by a combined charging/discharging strategy (without consideration of communication, organisation cost and procurement of DC/AC inverter) to the charging-only approach of integrated vehicles within a fictional balancing group (own calculation and depiction)

Figure 42 depicts for each generation structure (see Table 1) the charging costs incurred for a maximum number of integrated EVs in the balancing group (see Figure 40) with relevant prices on day-ahead and intra-day electricity markets from 2010, whereby the charged energy is also assessed with the resulting balancing energy clearing prices from 2010 in the APG control zone. In this case, it is assumed that the charged energy is part of a scheduled deviation of the balancing group. Hence, the third boxplot (see Figure 42) for each value (generation structure) on the x-axis depicts the theoretical maximum value, which refers to saved balancing costs. The electricity prices on the intra-day market present a higher volatility than those from the day-ahead market (see Figure 2). Therefore, the determination of charging costs by intra-day electricity prices depicts a generally higher cost level than the derived charging cost based on day-ahead electricity prices.

To sum up the described results, it can be concluded that the use case discharging of EVs in conjunction with a balancing of the balancing group cannot be realised from an economical point-of-view. Despite the assumed low battery investment cost of 500 €/kWh, the regarded battery degradation costs cannot be covered by revenues from selling of discharged electricity on day-ahead or intra-day markets (no consideration of cost for DC/AC inverter).

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, the use of EVs (controllable devices) in this conjunction results in cost saving due to non-consumed balancing energy. The saved balancing costs can be spent and used for the control infrastructure needed for charging EVs. To calculate a convincing value of cost-efficiency for this concept, it is recommended to use data sets of existing balancing groups (generation and consumption structure with associated profiles), their historical deviation and balancing energy clearing prices within the linked control zone.

Figure 42: Charging costs of the second implementation strategy (only charging) calculated with day-ahead and intra-day electricity prices in comparison to theoretical saved balancing costs (assessed by balancing clearing prices from 2010) (own calculation and depiction)

5.3 Generation- and load-based charging/discharging strategy (STR 4)

As described in chapter 3.4, generation-based charging occurs from generated PV electricity in combination with load-based charging from 00:00 a.m. to 06:00 a.m.. In terms of charging from PV generation, the coverage ratio of battery capacity and the integration ratio of PV-electricity generation are evaluated according to equations (7) and (8).

Figure 43 depicts the coverage ratio according to the use of each one of the considered driving patterns (see chapter 4.5) in interaction with a PV unit with an installed capacity of 2.7 kW_p (compare chapter 3.4). The daily coverage ratio is between 5 % and 43 %, which is also dependent on the driving patterns of vehicle users and the strength of solar radiation (see chapter 4.3 and Figure 27). In comparison to these results, [Leitinger, 2011] determines an average coverage ratio of about 60 % for an observation period of six months and possible charging from PV electricity generation at home as well as in the workplace.

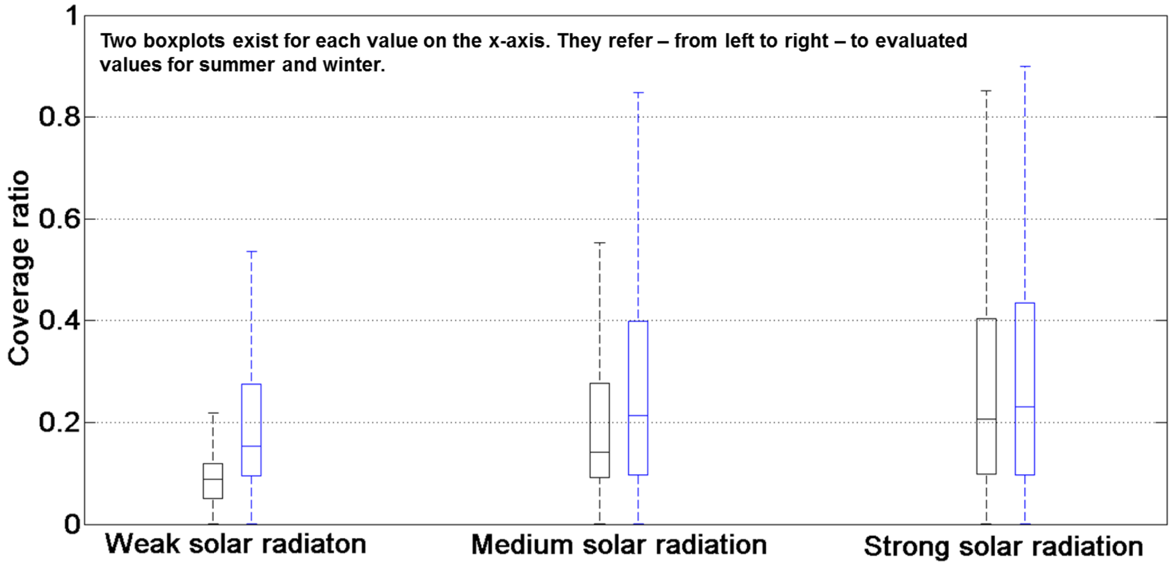

Figure 43: Coverage ratio of the battery capacity of EVs according to the weekly available entire battery capacity (own calculation and depiction)

The integration ratio, shown in Figure 44, depicts a contrary behaviour in comparison to the calculated daily coverage ratio. The coverage ratio changes in proportion to the strength of solar radiation, whereas the integration ratio increases if the strength of the solar radiation is declining (see Figure 44). A higher integration ratio can be reached by reducing the installed capacity of the considered PV unit, which results in a decrease of the achievable coverage ratio.

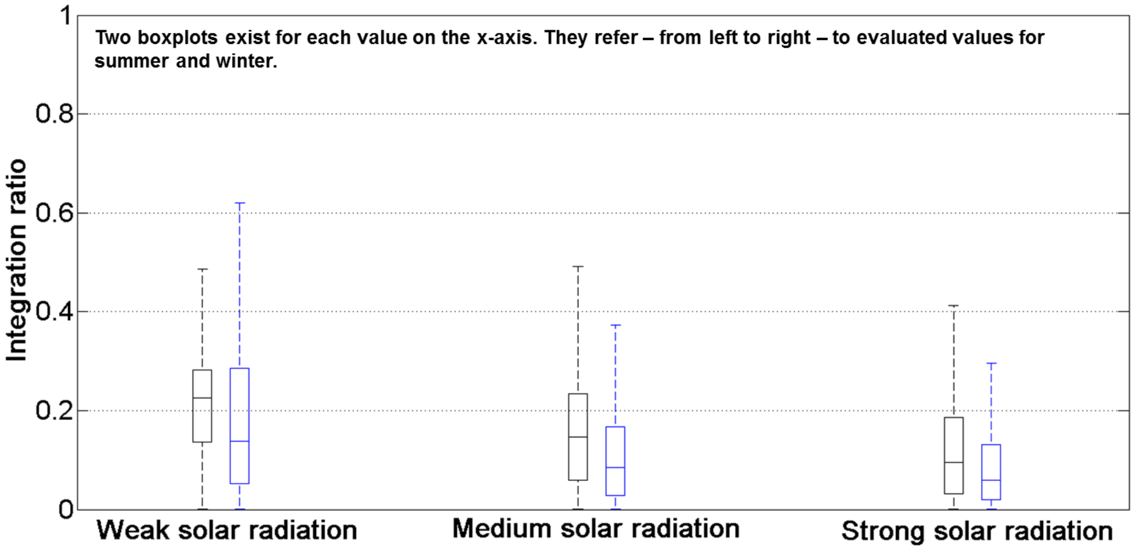

Figure 44: Integration ratio of PV electricity generation – portion of generated PV electricity used for charging of connected EVs (own calculation and depiction)

Again, as mentioned in chapter 3.4, the economical assessment of a combined generation and load based-charging/discharging strategy comprises the following:

1) Determination of the possible diminishing of the transformation station dimension and therefore the associated saved costs from a distribution system operator's point-of-view.
2) Estimation of possible revenues due to the discharging of vehicles within the time spread between 07:00 p.m. and 09:00 p.m. The assessment does not take into account the cost of the needed control communication system because a common system architecture is not yet defined. The costs for the needed DC/AC converter are also not considered.

To evaluate the first mentioned point, the selected LV-grids (see Figure 19, Figure A.3 to Figure A.7), which are located in the federal state of Salzburg, are extended with a high number of PV units (the installed capacity of each unit is 2.7 kW). This extension builds up the reference case. In the next stage, reference LV-grids (LV-grid + PV) face integration of EVs, which are at the same number as integrated PV units in the reference case. The penetration rate of EVs in this case is about 40 %. The degree of motorisation in the federal state of Salzburg is in the range of round 477 vehicles per 1,000 residents in Salzburg city and generally round 530 vehicles per 1,000 residents in rural areas [Statistics Austria, 2011]. Table 5 shows the number of estimated residents in each selected LV-grid (see the estimation approach in chapter 3.4) and the integrated number of EVs (40 % penetration rate) based on mentioned motorisation degrees.

Table 5: Number of integrated EVs due to evaluation of the impact of a generation- and load-based charging/discharging strategy on the selected rural and urban LV-grids (see chapter 3.4 and the appendix)

		Number of inhabitants	Number of EVS (40 % penetration rate)
Rural area	LV-grid 1	169	36

	LV-grid 2	172	38
	LV-grid 3	114	24
Urban area	LV-grid 4	312	65
	LV-grid 5	79	16
	LV-grid 6	181	35

Figure 45 (see the x-axis, one week consists of 10,080 minutes and one day has 1,440 minutes) depicts the impact of a generation- and load-based charging/discharging strategy on the sum load profile of the LV-grid, which is illustrated in Figure 19, in two extreme situations. One is in regard to a winter week with weak solar radiation (upper graph) and the other one refers to a summer week with strong solar radiation (lower graph).

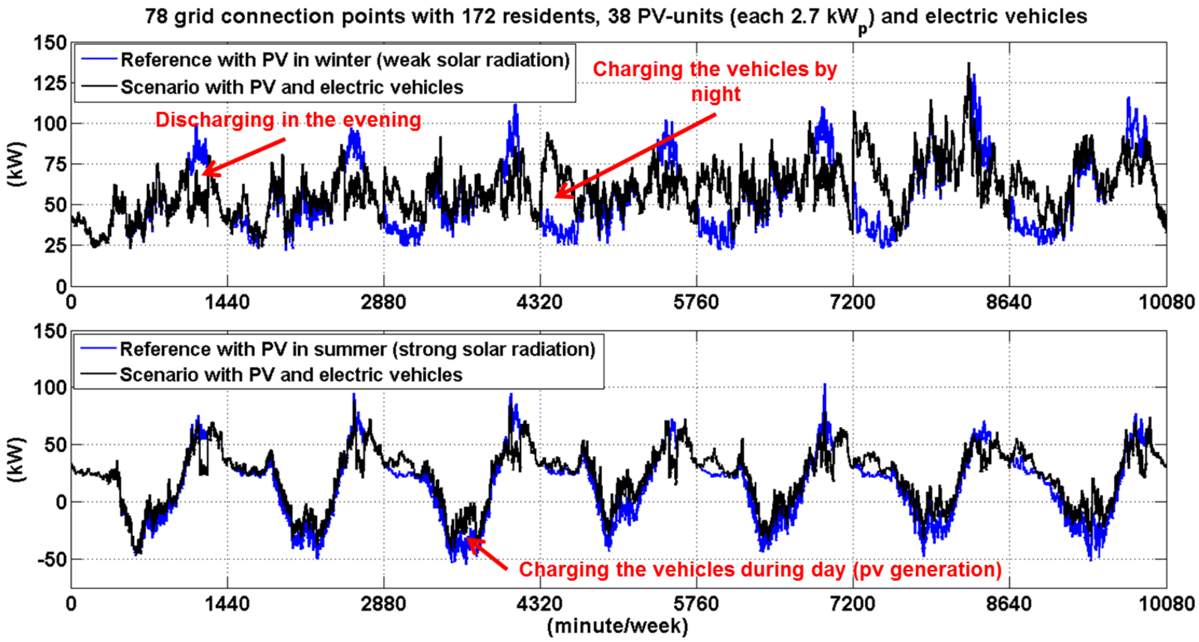

Figure 45: Impact of a generation- and load-based charging and discharging strategy on the sum load profile of LV-grid number 2 (own calculation and depiction)

The upper graph is characterised by low available PV electricity generation and therefore greatly reduced existing PV electricity generation for charging EVs at home. Therefore, EVs must be charged in the alternative time frame from 00:00 a.m. to 06:00 a.m. for reaching the set battery status before the approaching first daily usage (setting is done by the vehicle user). The charging of available vehicles at home in the timeframe from 00:00 to 06:00 does not begin for all considered vehicles at 00:00, which results in a very high activated entire power for the charging of vehicles. This kind of charging control results in a coincidence factor equal to one and in the consumption of whole available grid reserves. This charging approach violates the predefined grid restrictions (see also [Prueggler, 2013]). Therefore, a scaled charging control is considered during the time frame between 00:00 a.m. and 06:00 a.m., which reduces the mentioned coincidence factor. A lower coincidence factor reduces the resulting maximum power occurred due to charging vehicles that are located in an LV-grid.

The lower graph in Figure 45 depicts a high level of PV generation. Hence, higher available

PV electricity generation exists for the charging of vehicles which are located at home during times of PV electricity generation. Therefore, the electricity needed in complementary charging times from 00:00 a.m. to 06:00 a.m. for reaching the set capacity status of batteries before the first daily drive is lower than the case in winter with weak solar radiation. As mentioned in the case of winter, a scaled charging control is also considered in the summer case.

As described before, the two charging concepts for each day are combined with the discharging of vehicles in the time spread from 07:00 to 09:00 p.m. In both figures, the scenario with PV and EVs (40 % penetration rates) shows a lower level of consumed electricity from 07:00 p.m. to 09:00 p.m. than in LV-grids with installed PV units only.

The analysis of the impact of the integration of EVs with the described charging/discharging control in LV-grids (see Figure 19, Figure A.3 to Figure A.7) on the dimensioning of the transformation station is based on the extreme situation shown in Figure 45 (a winter week with weak solar radiation and a summer week with strong solar radiation). Figure 46 depicts the impact of generation-based charging control on minimum power occurred on the transformation station (scenarios LV-grids with PVs and EVs) in comparison to the same values from LV-grids with PV units only. From a transformation station point-of-view, the minimum power values in a summer week (negative direction of load flow), which are the result of PV electricity generation, can be reduced due to charging available vehicles in times with high PV generation (see Figure 21).

Figure 47 shows the next extreme situation (winter week with weak solar radiation) which refers to the impact of load-based charging – from 00:00 a.m. to 06:00 a.m. – and load-based discharging from 07:00 p.m. to 09.00 p.m. on the maximum occurred power in the sum load profile from a transformation station point-of-view. On the one hand, despite a high penetration level of round 40 % EVs (additional loads), an increase of maximum power in all LV-grids does not occur.

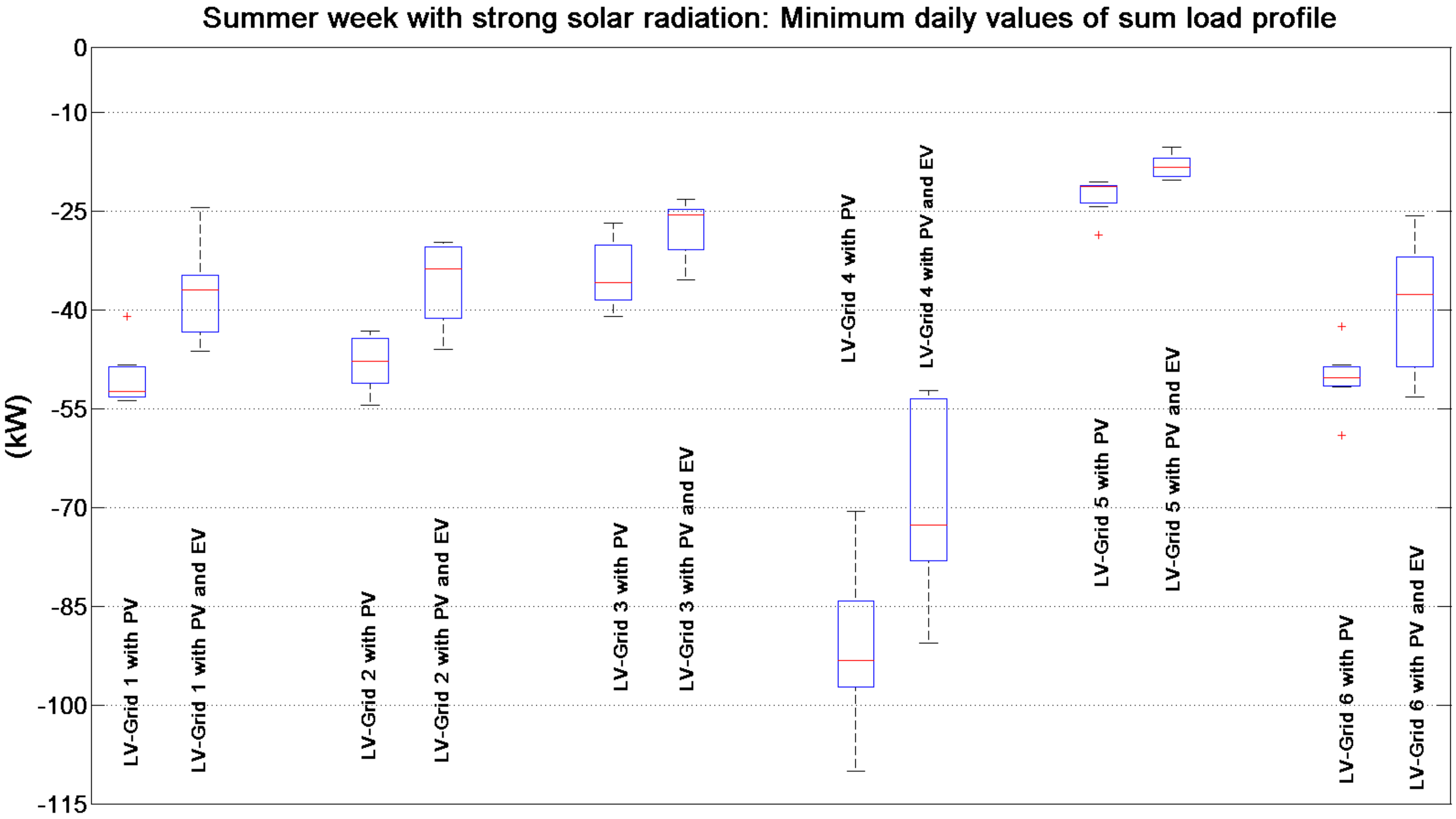

Figure 46: Impact of generation-based charging control on minimum daily values – the time spread is a week – during a summer week with strong solar radiation (own calculation and depiction)

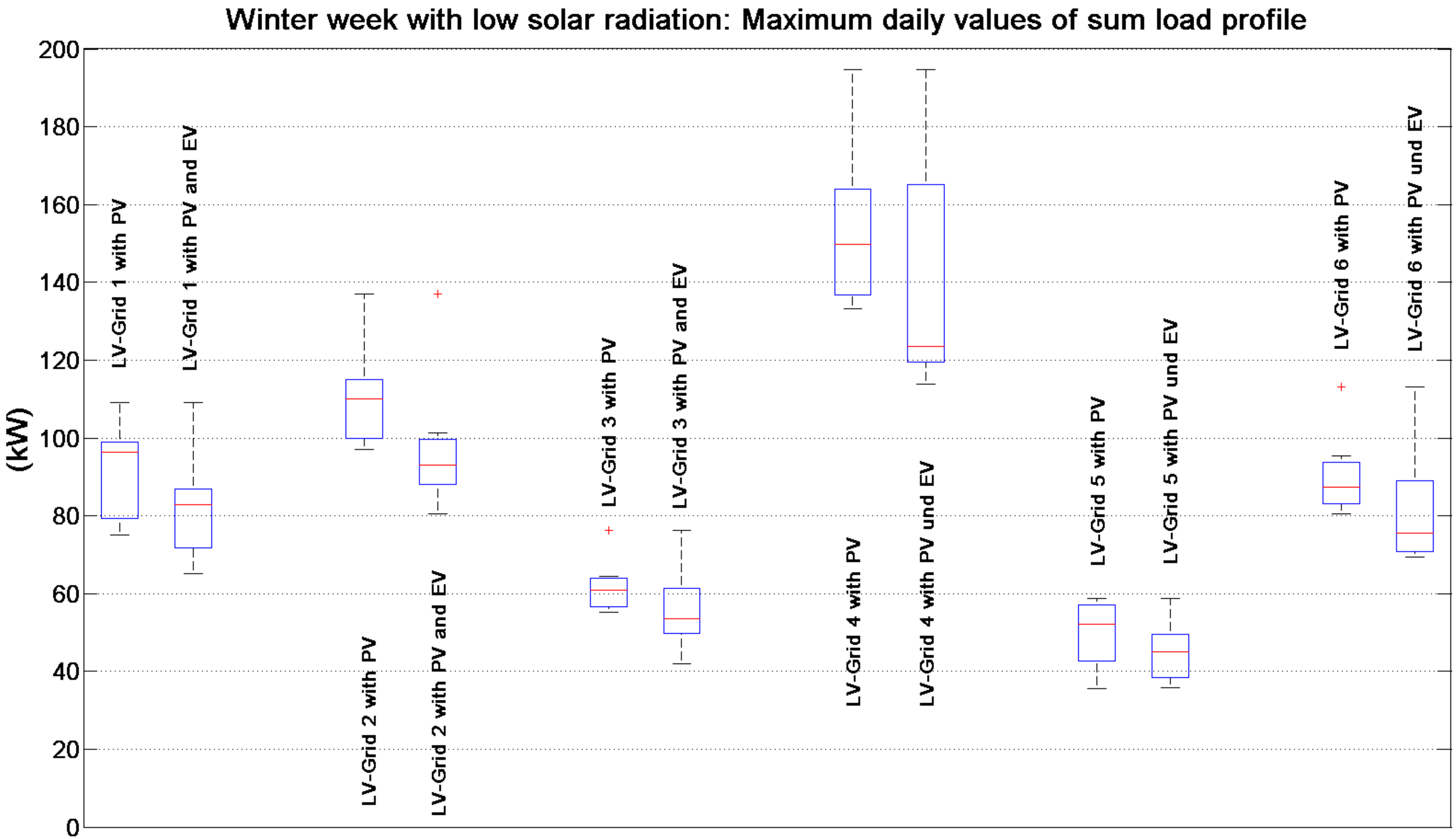

Figure 47: Impact of load-based charging and discharging control on maximum daily values – the time spread is a week – during a winter week with weak solar radiation (own calculation and depiction)

The reason for this grid friendly integration of EVs is the implementation of the mentioned scaled charging concept – low coincidence factor by charging of available vehicles at home from 0:00 a.m. to 06:00 a.m. (see also Figure 45) within an LV-grid. On the other hand, discharging batteries in the time frame from 07:00 p.m. to 09:00 p.m. cannot diminish the occurred maximum power in the analysed LV-grids. The reason is the appearance of maximum consumed power in times beyond the time slot from 07:00 p.m. to 09:00 p.m., which is also a result of implemented additional loads (EVs, 40 % penetration rate).

The estimation of possible revenues due to the discharging of vehicles in the time spread between 07:00 p.m. and 09:00 p.m. is based on consideration of each measured household load profile [ADRES, 2011] within this time frame. The evaluation does not take into account charging costs and derives potential revenues as a function of battery investment costs. Revenues of the V2G concept are derived based on the addition of revenues due to household electricity demand covered by discharged electricity, surplus electricity that is fed into the LV-grid and battery degradation costs due to additional discharging. The average household electricity price is stated as 19.56 €/kWh (average price for 2011, see [Eurostat, 2012]), which is comprised of the electricity price, network charges, taxes and surcharges. The electricity price is around 40 % of the total household electricity price, while network charges, taxes and surcharges make up the rest (60 %) of the household electricity price ([E-control, 2013]). As the average wholesale electricity price for the economic assignment, the value 51.80 €/MWh is assumed (average electricity price on EXAA for 2011, see Figure A.14 and [EXAA, 2012]).

Figure 48 depicts potential revenues of the V2G-concept associated with assumed battery investment costs and mentioned electricity prices. Positive revenues can be reached 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 50 €/yr can be reached per vehicle and with a battery investment cost of 500 €/kWh. Due to a successful realisation 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 needed DC/AC converter.

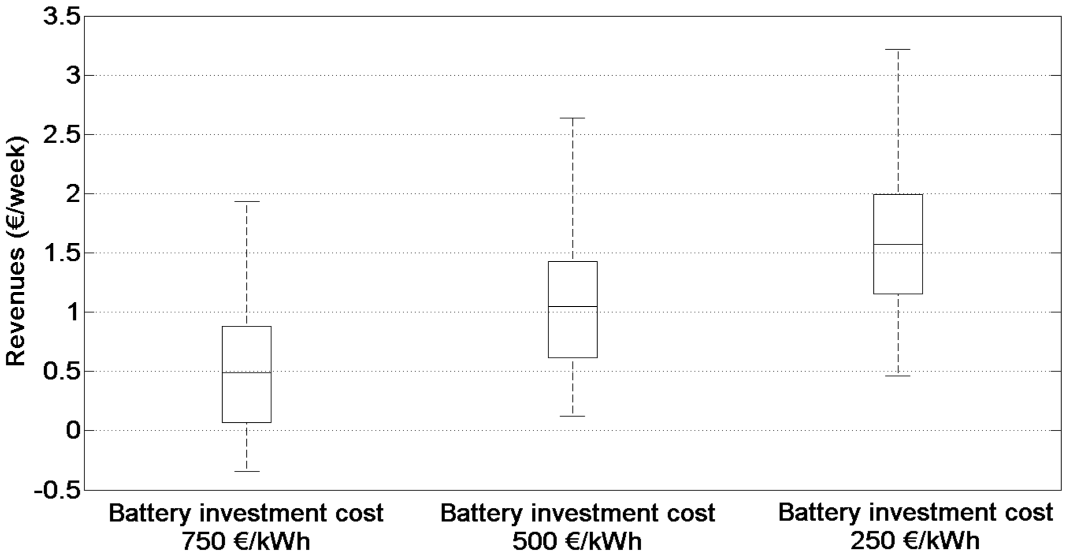

Figure 48: Revenues due to discharging EVs from 07:00 p.m. to 09:00 p.m. for different battery investment costs (own depiction and calculation)

Figure 49 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 round 39 % (case: battery investment cost is about 500 €/kWh).

In summary, it can be stated that the V2G-concept in regard to the covering of the household load profile is not able to cover all the costs accrued, because of the high level of battery degradation costs due to battery discharging.

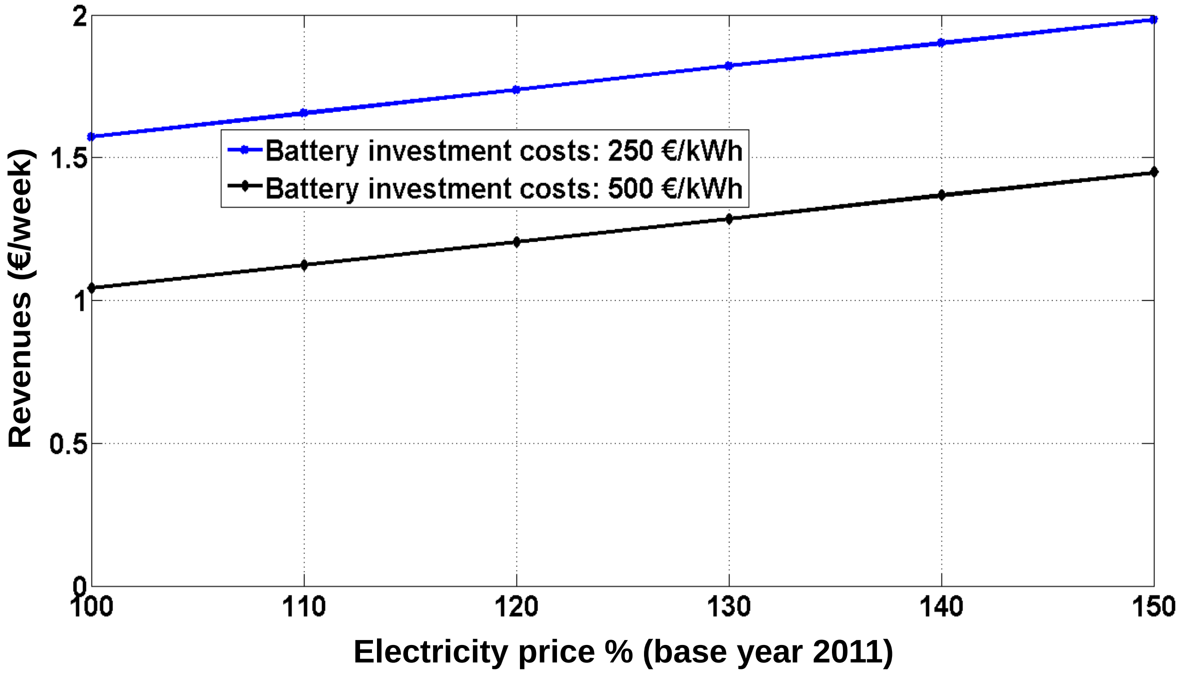

Figure 49: Discharging revenues based on variation of battery investment costs and average day-ahead electricity prices [EXAA, 2012] (own depiction and calculation)

5.4 Reusing of batteries – second life

Figure 50 depicts battery capacity losses due to automotive use for all analysed vehicle categories (automotive lifetime is 10 years). The batteries with 16 kWh, 24 kWh and 48 kWh show average capacity losses of about 12 %, 9 % and 6 % as from installed respective capacity. The outcomes are determined based on the laboratory investigation of [Peterson, 2009] (see also chapter 4.4.2) and used driving patterns (see chapter 4.5). Generally, the results indicate the remaining capacity range for second-life usage. Due to uncertainty in the battery lifetime, the results for a second-life application take into account lifetime variations.

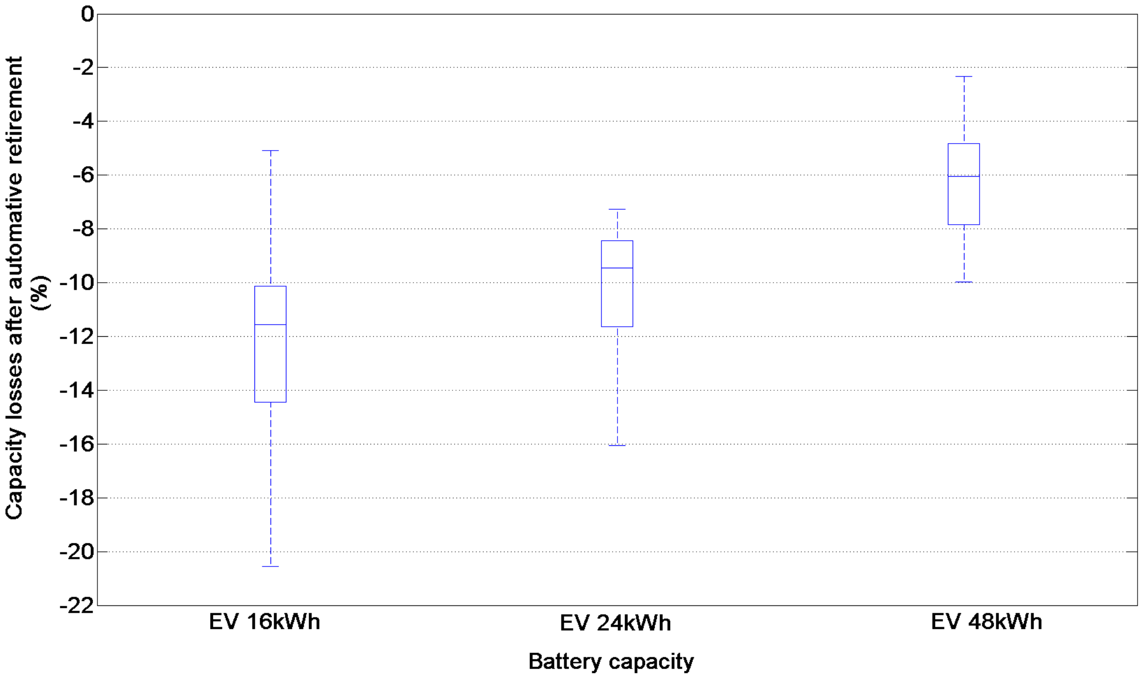

Figure 50: Capacity losses due to automotive use (assumed vehicle lifetime is 10 years) (own calculation and depiction)

Table 6 illustrates the calculated contribution margins of Li-ion batteries in the described second-life application (combined participation in wholesale electricity and balancing energy markets, see chapter 3.5). As expected, the margins, due to the participation of the batteries in the wholesale electricity and manual FRR market, are lower than those in the automatic FRR in the Austrian control zone (lower activation number of manual FRR and more attractive capacity/balancing energy prices on the automatic FRR market, see chapter 2.1.1).

Table 6: Revenues of reused Li-ion batteries (different capacities) in analysed concept for second-life usage

Revenues (€/yr)	Li_ion	Li_ion	Li_ion
	24 kWh	48 kWh	100 kWh
Day-ahead and automatic FRR markets	535	649	1,986
Day-ahead and manual FRR markets	299	389	1,215

Based on the results, the disposal value of a Li-ion battery (original investment cost =

1,000 €/kWh) as a function of its lifetime is compared to the net present value of a lead-acid battery, which provides the same application (capacity: 100 kWh, operation range between 10 % and 80 % of charging state). The investment costs for lead-acid batteries are between 50 €/kWh and 100 €/kWh with a lifetime of 12 years [Hadjipaschalis, 2008]. The costs for a hybrid inverter (AC/DC and DC/AC inverter) are neglected for both battery technologies. The dotted line in Figure 51 represents the disposal value (net present value) of the second use application based on the revenues for the year 2020, repurposing costs of about 250 € [Neubauer, 2011] and battery lifetime variation. According to [EMST, 2011], the battery investment costs would be round 370 €/kWh in 2020. The solid line in the same figure represents the present value (interest rate = 7 %) of using the described lead-acid battery for the same purpose, but with different investment costs (100 €/kWh or 50 €/kWh).

The results conclude that the use of Li-ion batteries after their automotive retirement is reasonable if a lifetime of more than four or seven years can be achieved (see Table 7).

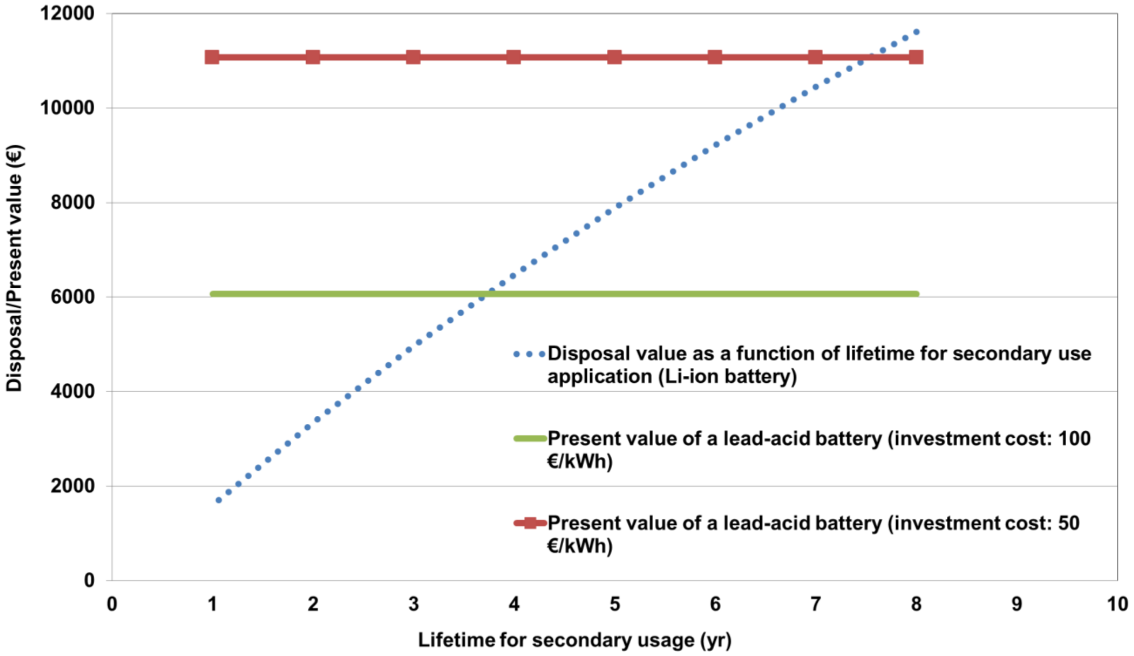

Figure 51: Comparison of the disposal value of a vehicle battery (Li-ion, 100 kWh) in second use with the net present value of a new battery for the same application (application: participation in the wholesale electricity and automatic FRR markets) (own depiction and calculation)

Table 7: Minimum lifetime of a reused battery for second-life concept in comparison to the reference technology (lead-acid battery)

Investment cost of lead-acid battery (€/kWh)	Minimum lifetime of used battery (Li-ion) in second-life concept (years)
100	> 4
50	> 7

6 Conclusions

The considered business cases for analysing the implementation of EVs in an electricity system are subdivided into two prime groups:

- The first category refers to the mobile lifetime of batteries and consists of different charging (G2V) and discharging (V2G) strategies that are subdivided into the following:
  - Uncontrolled charging strategy
  - Controlled charging/discharging concepts
  - Intelligent charging/discharging strategies
- The second classification takes the reusing of batteries after their automotive retirement into account (second-life concept).

The identification of an efficient way to implement EVs in an electricity system is the aim of the creation and analysis of possible charging/discharging strategies. The goal of the assessment of the second-life concept is given in the economic calculation of the minimum remaining battery (Li-ion battery) lifetime needed for reusing purposes.

The considered charging and discharging strategies are as follows:

- Market-based charging/discharging strategy: participation in frequency reserve markets
- Generation-based charging/discharging strategy: integration of electric vehicles in a fictional balancing group with various generation structures
- Generation- and load-based charging/discharging strategy: charging at home if PV generation is available during the day or from 00:00 a.m. to 06:00 a.m., discharging of EVs at home in times of high electricity demand from 07:00 p.m. to 09:00 p.m.

The participation of EVs in frequency reserve markets is conducted from an electricity system's point-of-view. Without consideration of the competitive situation of EVs with other providers of positive frequency reserve restoration (FRR), revenues are obtained between 45 € and 119 € per vehicle and year (participation in positive automatic FRR market). The costs incurred for the communication infrastructure and DC/AC converter are not considered in the estimation of the above revenues. The consideration of major competitors ("pumped hydro energy storages"; main supplier of positive FRR) shows that degradation costs of Li-ion batteries[31] are much higher than the marginal costs of pumped hydro energy storages. On the other hand, the establishment of an international cross-border balancing market based on a common merit order will result in higher competition between the FRR suppliers and a reduction of offered balancing energy prices on an international cross-border balancing market. Therefore, the realisation of participation of EVs in positive FRR markets cannot be recommended in the current national market structure – not beneficial on the contrary to pumped hydro energy storages – and also in the future international cross-border balancing market[32].

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[31] Without consideration of costs for a converter, control and communication system.

[32] In comparison, the disadvantage of EVs for energy delivery – high degradation cost – remains and makes successful participation of EVs in the future common balancing energy market unfeasible.

Generally, the participation of EVs in negative manual/automatic FRR markets (times with existing surplus electricity within a control zone) with the assumed power and balancing energy prices obtains a spread of revenues between -87.6 € and 70.80 € per vehicle and year[33]. From a competition point-of-view, EVs are able to provide negative FRR. However, even other small suppliers – like heat pumps – can also do the same with technological advantages. The stationary installation and thermal inertia of buildings are beneficial for the estimation of available reserve capacity of heat pumps in comparison to EVs. The mentioned properties of heat pumps enable high flexibility in the provision of different balancing products and therefore can easily contest EV shares in the negative FRR markets.

Therefore, it can be stated that the covering of costs incurred (organisation and communication expenditure) due to the participation of EVs in negative FRR markets with consideration of dispatch probability (1.34 % for negative manual FRR and 17.74 % for automatic FRR), alternative/future competitors and future establishment of an international cross-border balancing market seems to be impossible or very difficult.

Then, two different approaches to maintaining a balance between electricity generation and consumption regarding the integration of EVs in a fictional balancing group are analysed and subdivided into the following:

- Combined charging and discharging concepts for the implementation of EVs within the balancing group
- Charging concept for the implemented EVs within the balancing group only.

The combined charging and discharging concept for maintaining a balance between electricity generation and consumption of the created fictional balancing group results in higher cost incurred than in the charging-only concept (a difference of about 100 %). The reason is the high degradation costs of Li-ion batteries[34]. Despite the assumed low battery investment cost of 500 €/kWh, the regarded battery degradation costs cannot be covered by revenues due to the selling of discharged electricity on day-ahead or intra-day markets.

In case of utilization of charging concept only, the charging costs (determination of charged electricity with electricity prices on day-ahead or intra-day markets) will be covered by vehicle users. On the other hand, the use of EVs (controllable devices) results in cost saving for non-consumed balancing energy. The saved balancing costs are between 32 € and 150 € per week.

Therefore, 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. The saved balancing costs can be spent and used for the control infrastructure needed for charging EVs.

The economical assessment of a combined generation- and the load-based charging/discharging strategy is comprised of the following:

- Determination of the possible diminishing of the transformation station dimension from a distribution system operator's point-of-view.

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[33] Without consideration of costs for control and communication system.

[34] Without consideration of costs for DA/AC inverter.

- Estimation of possible revenues due to discharging vehicles within the time spread of 07:00 p.m. and 09:00 p.m.

Despite a penetration rate for EVs of about 40 % in LV-grids (the same number of PV units as EVs are also integrated), the combined generation- and load-based strategies do not affect the dimensioning of the transformation station. On the one hand, generation-based charging (from PV electricity generation) cannot store peak PV electricity generation (location: home) because of the non-availability of EVs during the times of peak PV electricity generation. On the other hand, the high penetration ratio of EVs (higher number of existing loads in LV-grids) does not increase the maximal load at the transformation station, because of possible charging from 00:00 a.m. to 06:00 a.m. and consideration of a low coincidence factor by charging. The discharging from 07:00 p.m. to 09:00 p.m. reduces the sum load of the transformation station but does not affect the maximum occurring value of the sum load profiles of analysed LV-grids.

The load-based discharging of EVs between 07:00 p.m. and 09:00 p.m. obtains positive revenues for any cases (driving patterns, household profile, availability at home and strength of solar radiation) from battery investment costs of 500 €/kWh downwards. The yearly revenues potential is given at around 50 € per year and vehicle (battery investment cost of 500 €/kWh). Due to a successful realisation 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 needed DC/AC converter. The realisation of the V2G concept in regard to the covering of the household electricity load profile is not able to cover all the costs accrued from the high level of battery degradation due to battery discharging.

Despite choosing an application for battery reusing, which shows high revenue potential, a long second lifetime of more than four years is needed to inspire an investment in this further application. The reaching of the mentioned minimum lifetime for the use of a battery after its mobile retirement depends on the stability of Li-ion battery technology and the remaining usable battery capacity.

The various analysed discharging strategies are not realisable because of capacity losses due to discharging and the resulting high degradation costs. The calculated revenues are too low to cover the associated system costs (DC/AC inverter, investment for communication and control system). The reduction of battery investment cost at a low range of about 250 €/kWh does not change this statement. A successful economical realisation of the V2G concept could be reached in conjunction with a considerable reduction of capacity losses in battery technology.

Therefore, an efficient integration of EVs in Austrian 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. Therefore, the target function of charging strategies is oriented to the requirements of balancing group representatives and linked consumption/generation portfolios.

7 Outlook and suggestion for an efficient integration of EVs in the Austrian electricity system

The economical assessment of mentioned charging strategies in this work are generally based on analysing the potential revenues for involved stakeholders, whereby the revenues are derived for each one of the considered EVs with associated diving pattern. On the other hand, the impact of a high penetration rate of EVs on eight different LV-grids (located in rural and urban areas) is analysed in [Prueggler, 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 charging approach (see definition in chapter 2.2). This means that a comprehensive reinforcement of LV-grids will not be needed until the mentioned penetration rate of EVs is reached. An introduction of controlled charging concepts, more precisely, load- and generation-based charging strategies 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 obtains integration of a higher number of EVs in LV-grids without comprehensive reinforcement activities within LV-grids. Therefore, depending on the chosen charging concept – uncontrolled or controlled strategy – 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 is subdivided into two implementation stages (see Figure 52). The first stage is linked to a moderate penetration of EVs in LV-grids, whereby a reinforcement of grids due to the integration of EVs is not needed. The second implementation stage begins after the first and is defined by the comprehensive reinforcement of LV-grids due to the continuation of uncontrolled or controlled charging concepts. The second implementation stage can also be characterised by the introduction of more complicated intelligent charging concepts, which determine real-time charging strategies based on market information and current status in LV-grids.

The charging of EVs in the first stage, as shown in Figure 52, results in a more efficient usage of LV-grid reserves if load- and/or generation-based charging concepts are used. Intelligent charging also considers aside from market and local/global generation/consumption status, grid restrictions in the LV area (maximum degree of voltage and capacity utilization). The reusing of batteries after their automotive lifetime can be conducted in both implementation stages. The removed batteries from EVs can be utilized for various purposes, for example with their aggregation by different market participants like balancing group representative, distribution system operator and so on.

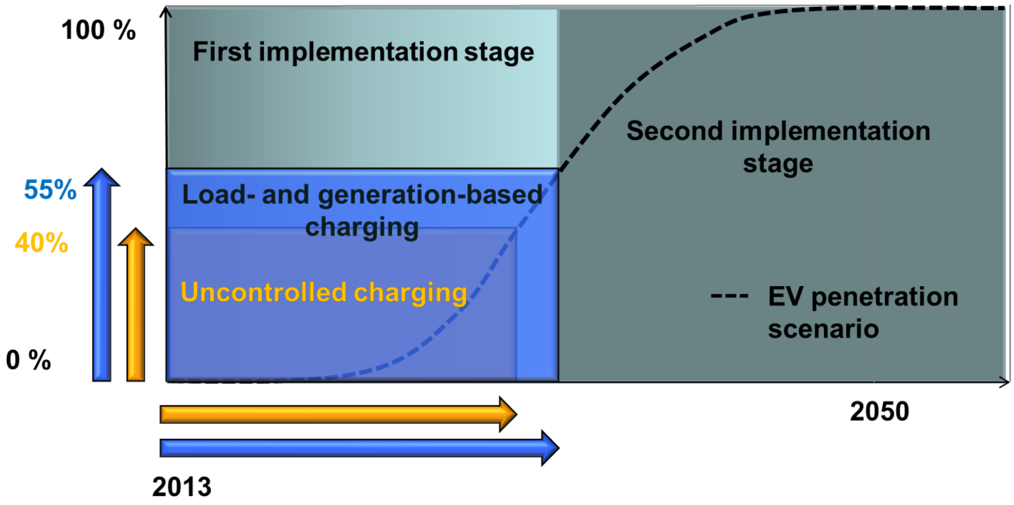

Figure 52: Implementation stages for e-mobility in the Austrian electricity system from market point-of-view and based on an analysis of the impact of EVs on selected LV-grids (Source [Prueggler, 2013], own adaptation and depiction)

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: The existing balancing group model in the Austrian electricity system allows a distinction to be made between physical delivery of electricity and equilibration of electricity and delivering businesses. Each market participator must join a balancing group. A matching of electricity generation and consumption must be set in each commercial balancing group. Every balancing group is represented by a balancing group representative responsible – among others – for data exchanges with other stakeholders and the initial financial risks of the balancing group according to the costs accrued for needed balancing energy.

  Calculation of the first clearing price for balancing energy is based on a progressive curve (see Figure 9) derived from the addition of a base electricity price and an auxiliary function as a function of control zone deviation. The derived clearing price can be positive or negative. A balancing group with deficit or surplus electricity pays or receives the clearing price multiplied by the amount of balancing group deviation if the clearing price is positive, respectively. A negative clearing price results in contrary cash flows.

  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, linked balancing energy costs and furthermore the amount of activated frequency restoration reserves and associated costs within the control zone. EVs are suitable equipment (existing flexibility, long periods of inactivity and no investment costs [purchase of EVs] for balancing group representatives) to be integrated in existing balancing groups based on a charging concept that also considers the deviation between electricity generation and consumption within balancing groups. Therefore, a new task for a balancing group representative can be the determination of 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 needed energy management system and associated communication infrastructure for EV charging.

According to the existing architecture in the Austrian electricity market, a balancing group representative is able to announce intraday changes of internal schedules (within the APG control zone) 15 minutes ahead of each quarter-hour to the balancing group coordinator [E-Control, 2010] [35]. A reduction of the mentioned time spread would increase the flexibility of the balancing group representative and support a more suitable (near to real-time) controlling of EV charging. The charging of EVs by a balancing group representative according to own requirements and the generation/consumption portfolio supports an effective integration of renewable technologies in an electricity system. In this conjunction, vehicles – if connected to a grid – can be charged in times of existing renewable surplus electricity (depending on the generation portfolio of the balancing group). In order to avoid a high coincidence factor by charging EVs, the balancing group representative must realise a scaled charging concept.

The implementation of EVs in an existing balancing group is based on current electricity market architecture. This means that a change or extension of the interaction between market participators or the integration of a new stakeholder for charging EVs is not necessary during the first implementation stage of EVs. Only the suggested reduction of the existing 15 minutes time spread regarding schedule changes needs an adaption of relations between affected stakeholders.

- 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. Development of smart grids in this stage occurs if the development of such technologies is more cost- and system-efficient than the actual electricity system design. For this stage (a high penetration rate of EVs in transportation), many previous studies mention the introduction of a new stakeholder in the electricity market model, which is mostly called the “aggregator” or “e-Mobility provider”. The duties of the aggregator are providing 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, 2010], [Galus, 2010], [Kempton, 2004], [Kristoffersen, 2010]). It can be stated, that an aggregator – whatever the control strategy might be – 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 (consideration of market rules) with consideration of driving patterns and the mobility needs of the controllable electric vehicles (see also definition of aggregator in [EU-Smart Grids, 2011]).

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[35] The balancing group representative can announce changes in cross-border schedules 45 minutes prior to the start of the full hour to the transmission system operator [E-Control, 2010].

A comparison between the roles of a balancing group representative and the tasks of an e-mobility aggregator (e-mobility provider) shows an obvious similarity between them. In the case of a high range of EVs in the transportation sector an enhanced form of balancing group representative can be established in the electricity market. Due to the assumed existence of mature smart grid algorithms/applications in this stage, distribution system operators are informed about the actual status in their own low and also medium voltage grids. Once an enhanced form of the balancing group representative is defined in the electricity system, coordination between times of controlled charging (provided by the enhanced balancing group representative) and local grid status (mainly LV-grid) must be conducted (intelligent charging). This is the main distinction from the first implementation stage. Due to a high range of existing vehicles, an efficient use of available grid (LV-grids) reserves, which can prevent or postpone LV-grid reinforcement, is more important and needs to be considered in controlled charging strategies.

For example, the energy management system of an enhanced balancing group representative, which defines charging strategies, must also consider grid restrictions depending on the actual grid status. Compliance with grid restrictions within a defined spread can be realised, on the one hand, with the provision of actual grid status by the distribution system operator to the energy management system. The direct access of the distribution system operator to the charging strategies of an energy management system can be mentioned as another approach in this conjunction.

From the complexity of the legal, economic and regulatory frameworks, the first approach (the provision of grid data to an energy management system) is easier to realise than the second suggested (intervention in the infrastructure of a third party) concept. However, compliance with grid restrictions, according to the first approach, will also be a task for the enhanced balancing group representative. Therefore, the distributed system operator is obliged to publish relevant grid data based on a non-discriminatory access for involved stakeholders, e.g. balancing group representatives.

In summary, explanation and discussion of tasks of implemented enhanced balancing group representatives suggests an extension of current interrelations between distribution system operators and balancing group representatives.

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Appendix

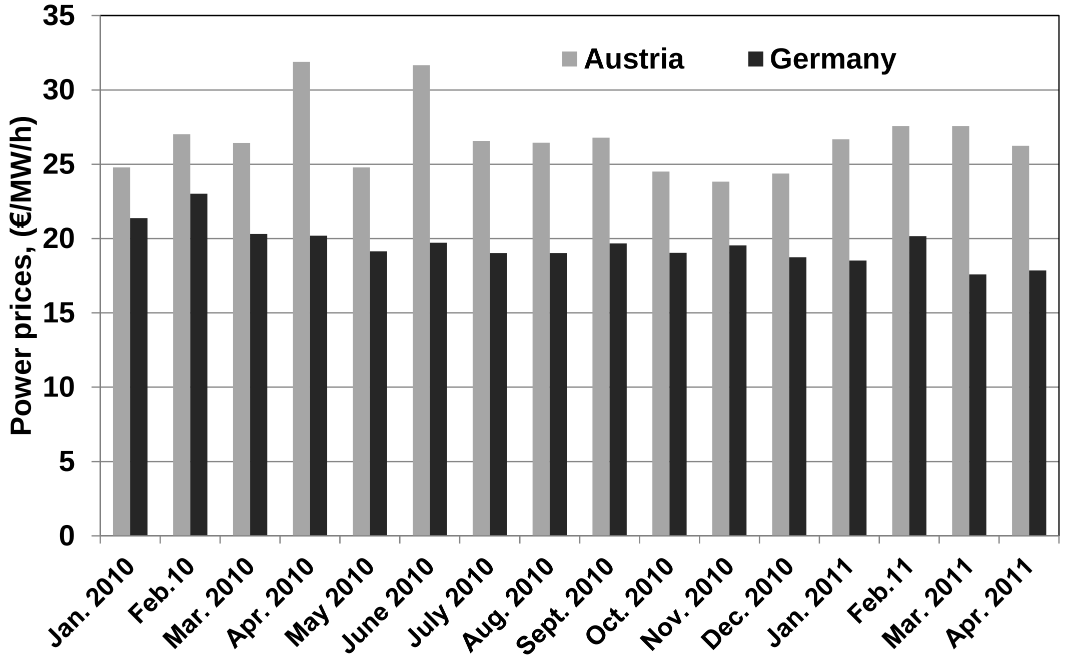

Figure A.1: Capacity prices of FCR in Austria and Germany (own depiction)

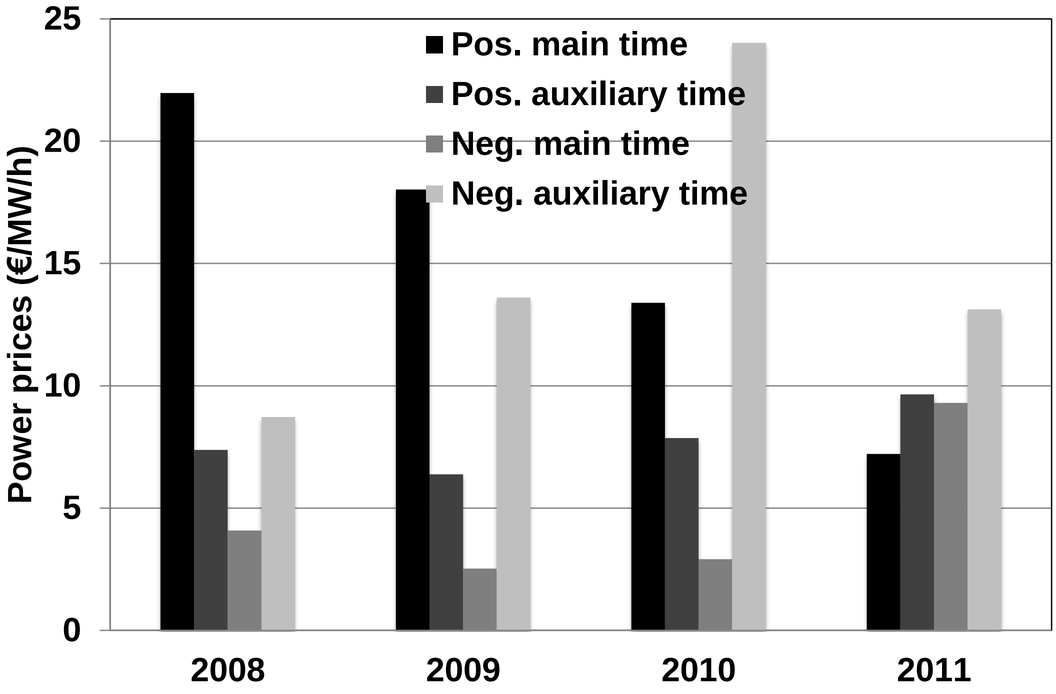

Figure A.2: Development of average power prices of automatic FRR (secondary control) on the German market from 2008 until 2011 (Source [Regelleistung, 2011], own depiction)

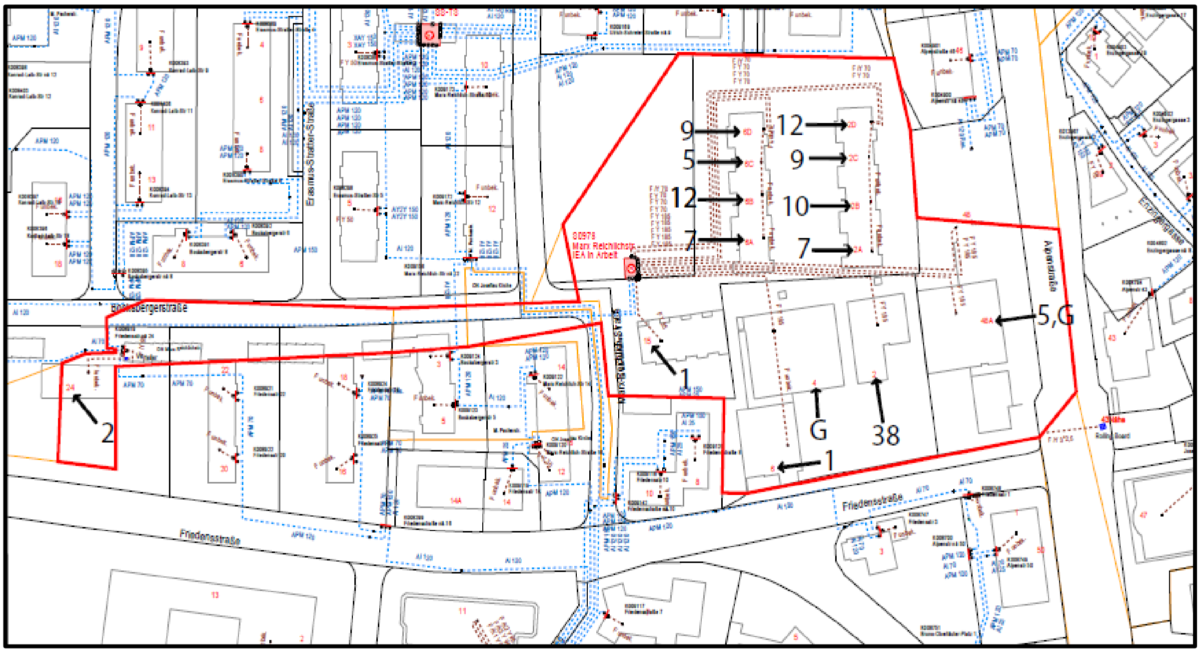

Figure A.3: Schematic diagram of the LV-grid number 5 in the Salzburg city with the estimated number of residents for each connecting point

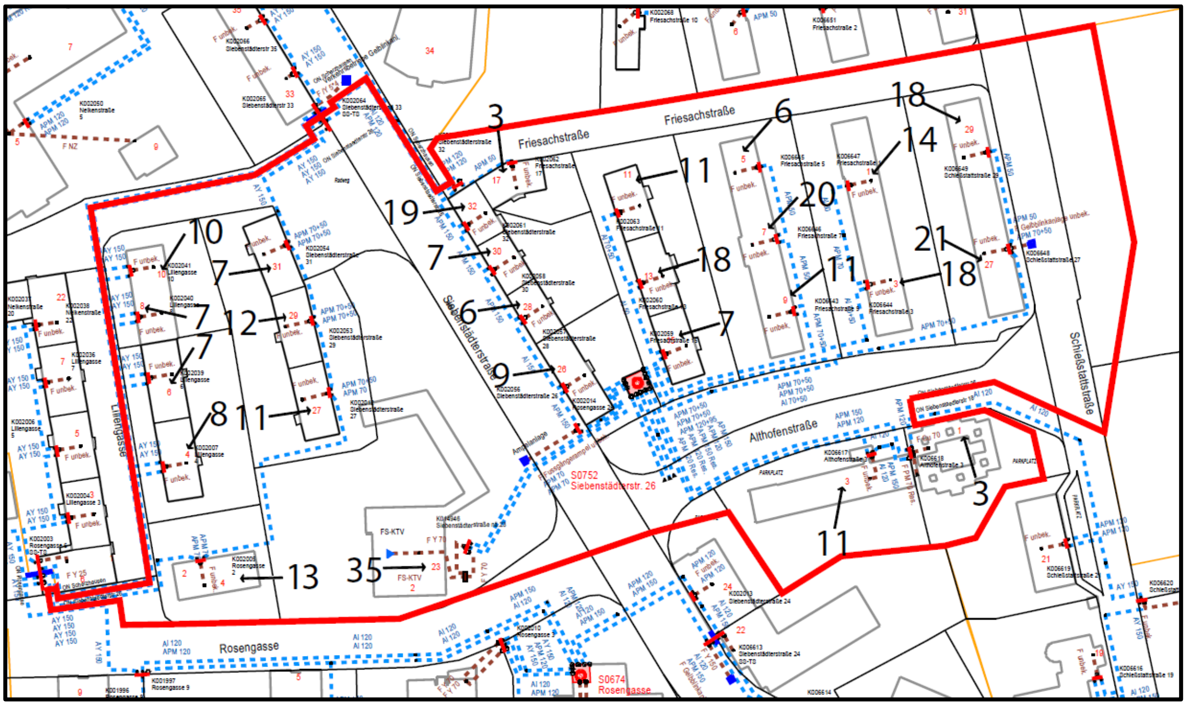

Figure A.4: Schematic diagram of the LV-grid number 4 in the urban area of Lungau (federal state of Salzburg) with the estimated number of residents for each connecting point

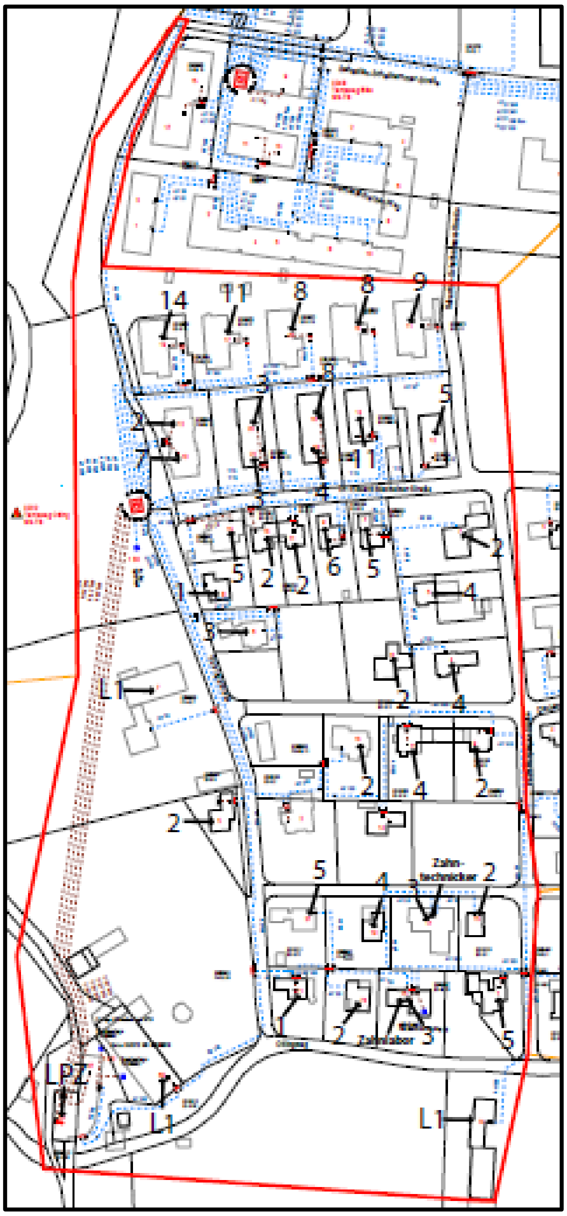

Figure A.5: Schematic diagram of the LV-grid number 1 in the urban area of Lungau (federal state of Salzburg) with the estimated number of residents for each connecting point

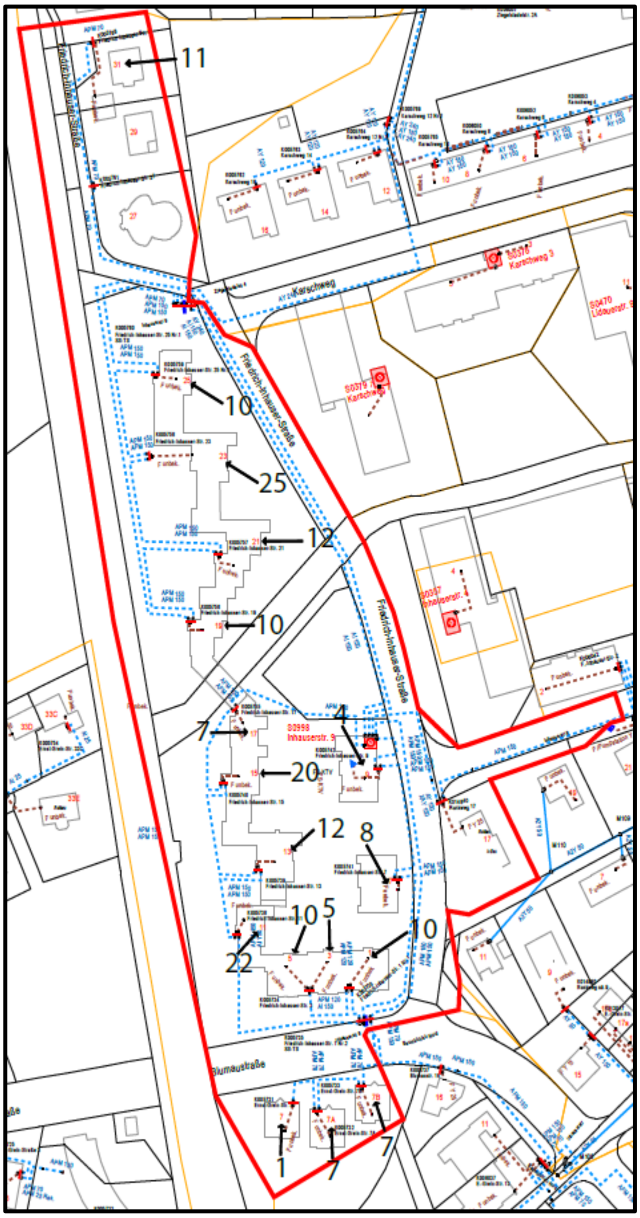

Figure A.6: Schematic diagram of the LV-grid number 6 in the Salzburg city with the estimated number of residents for each connecting point

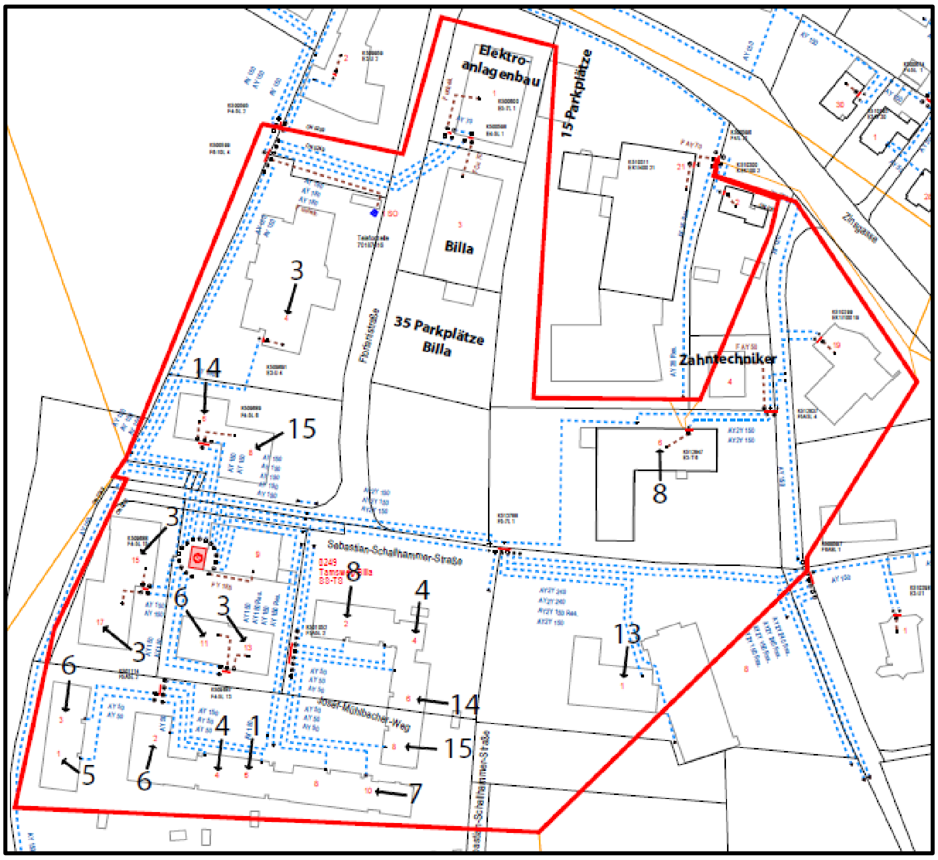

Figure A.7: Schematic diagram of the LV-grid number 3 in the urban area of Lungau (federal state of Salzburg) with the estimated number of residents for each connecting point

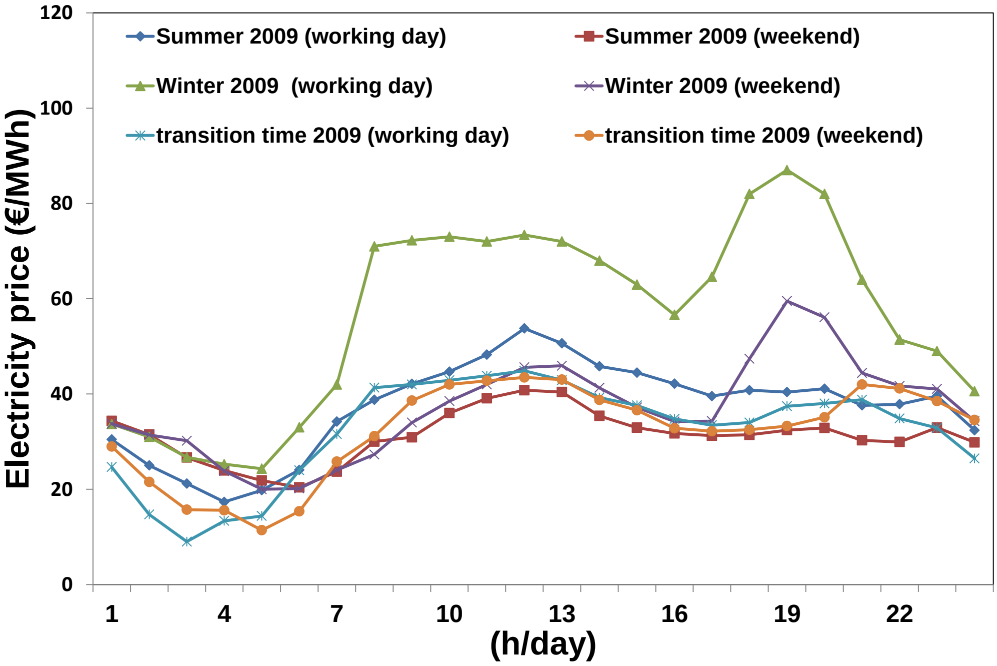

Figure A.8: Selected electricity price curves from 2009 (own depiction)

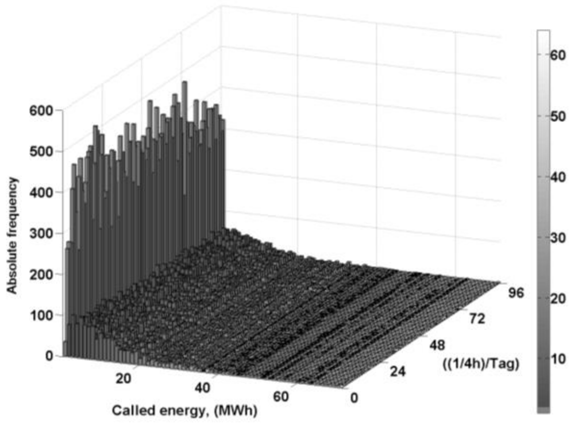

Figure A.9: Distribution of daily activated positive FCR in MWh (15 minutes resolution)

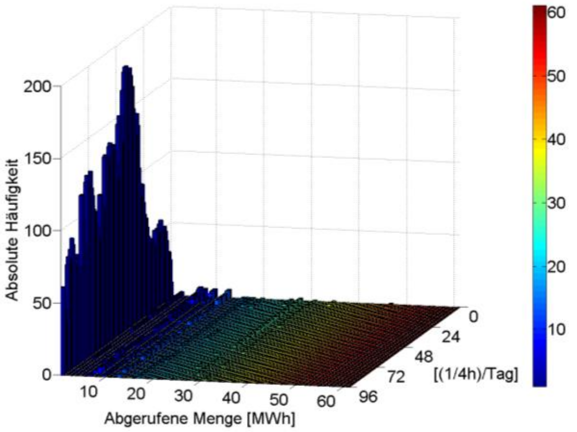

Figure A.10: Distribution of daily activated positive manual FRR in MWh (15 minutes resolution)

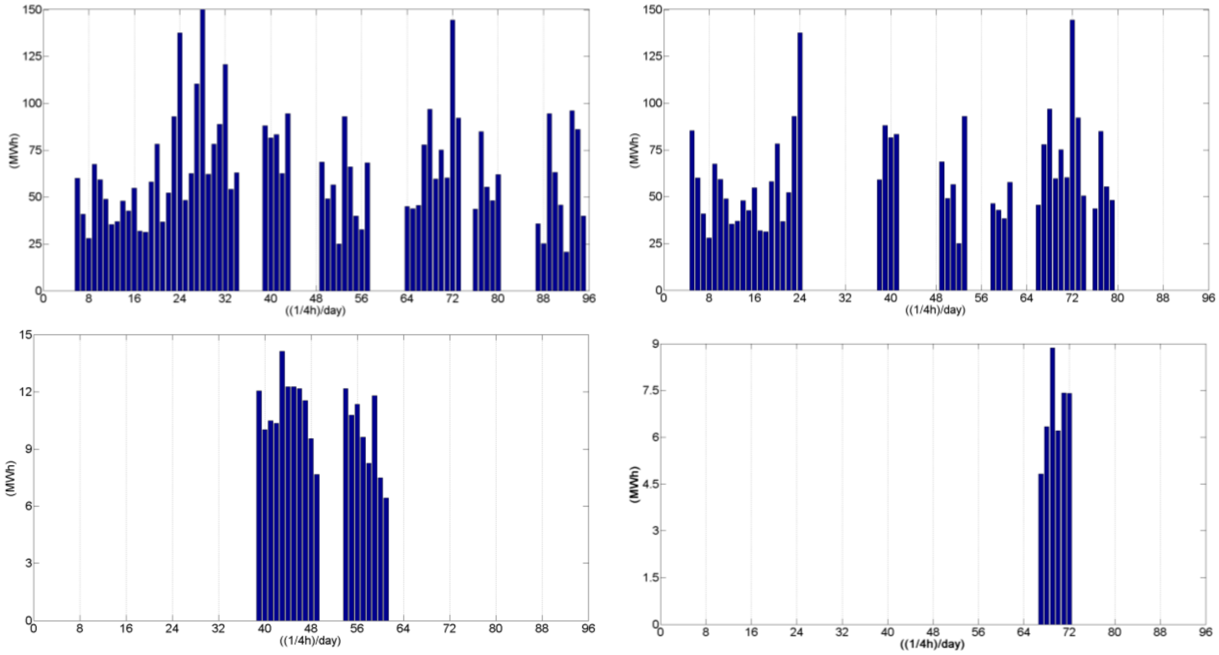

Figure A.11: Comparison of the modelled daily balancing energy scenarios (HEMAX: left column, HEMEAN: right column) of automatic FRR (upper row) and manual FRR (lower row)

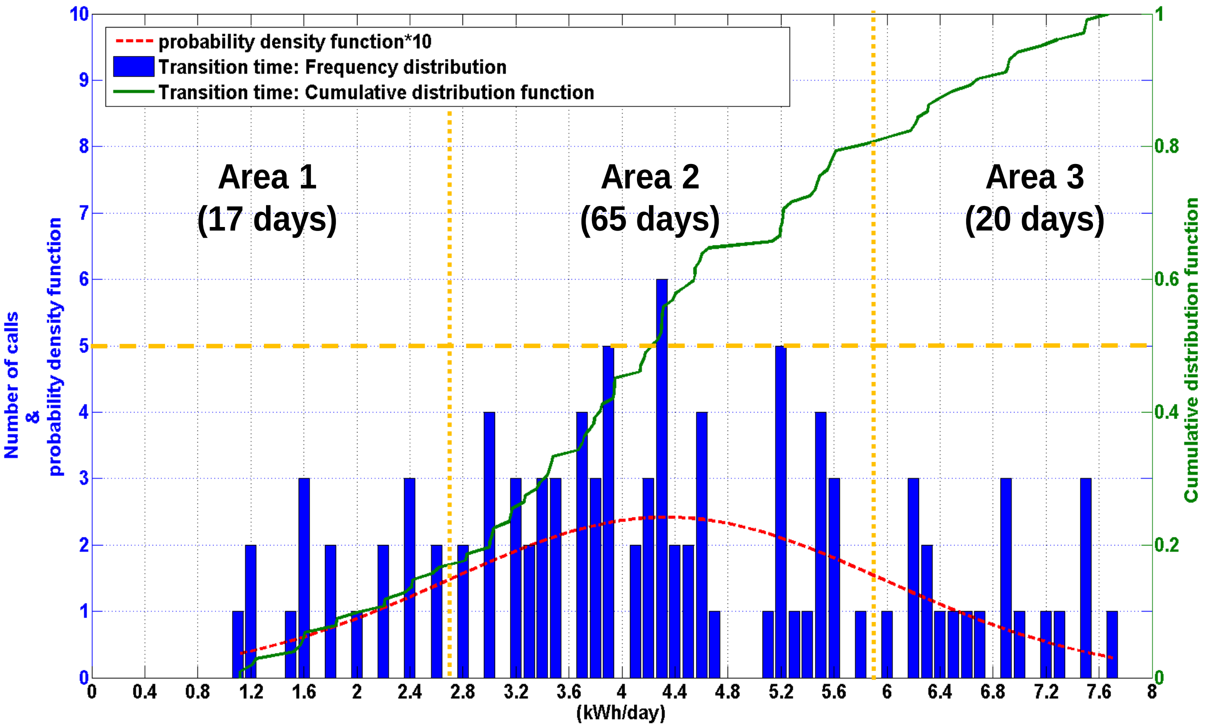

Figure A.12: Histogram, probability density function and cumulative distribution function of daily generated energy of a PV with an installed capacity of 2.7 kW_p during the transition time (own calculation and depiction)

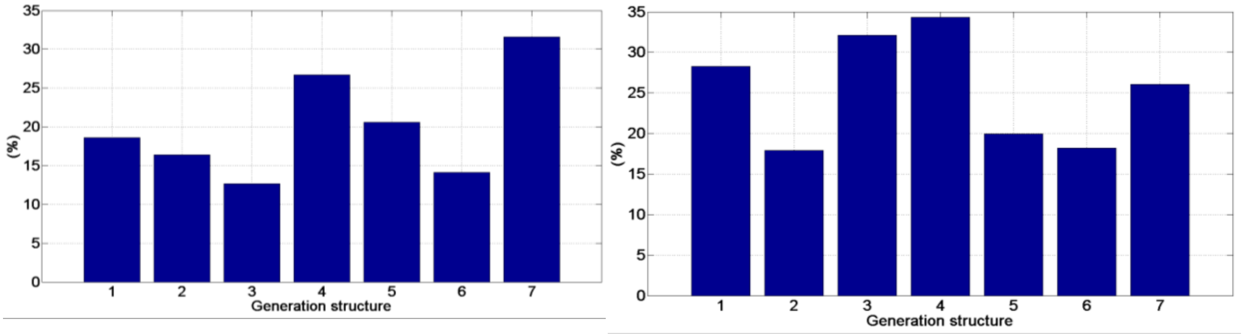

Figure A.13: Percentage declining of weekly deviation within balancing group according to generation structures (left: Implementation of EVs due to charging and discharging, right: Consideration of EVs only due to their flexible charging)

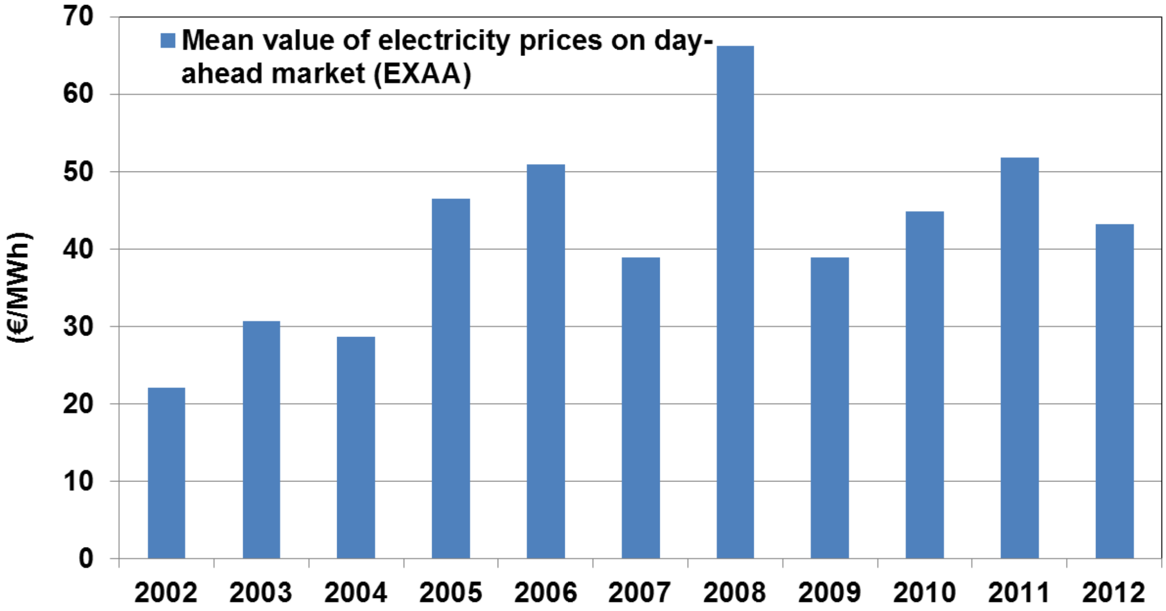

Figure A.14: Development of average wholesale electricity prices on the day-ahead market (EXXA)