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Integration of electric vehicles in a smart grids platform:

The case of Austria

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Ao.Univ.Prof. Dipl.-Ing. Dr.techn. Reinhard Haas

und

Projektassitent Dipl.-Ing. Rusbeh Rezania

Institut für Energiesysteme und elektrische Antriebe (E370)

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Fakultät für Elektrotechnik und Informationstechnik

von

Marvin Steinböck, BSc
0625448
3430 Tulln, Anton Bruckner – Str. 22a

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Dedicated to my family and all colleagues at VUT who made the study worthwhile

Kurzfassung

Ein steigender Anteil erneuerbarer Energieträger im Elektrizitätssystem geht mit einer zunehmenden Volatilität der Erzeugung einher. Eine Möglichkeit diese zu kompensieren und ein Gleichgewicht zwischen Erzeugung und Verbrauch herzustellen, besteht in der Verwendung von Elektrofahrzeugen als Puffer.

Diese Arbeit untersucht die Verwertungsmöglichkeiten der Anbindung von Elektrofahrzeugen an das Energienetz. Es werden die für eine erfolgreiche Integration erforderlichen Rahmenbedingungen ermittelt. Basierend auf einem Geschäftskonzept werden Geschäftsmodelle, die finanzielle Anreize für die Besitzer von Elektroautos schaffen, erstellt und bewertet. Die Rückspeisung von Energie ins Netz ist nicht vorgesehen, da sie eine zusätzliche Beanspruchung der Batterie zur Folge hätte.

Aufbauend auf einer Analyse des heutigen Elektrizitätsmarktes und der Märkte für Ausgleichsenergie, werden von der Integration betroffene Marktteilnehmer identifiziert und Geschäftsmodelle entwickelt. Letztere werden in Matlab implementiert um mit Hilfe von angenommen Szenarien, welche unterschiedliche Marktdurchdringungen von Elektrofahrzeugen aufweisen, die in den verschiedenen Geschäftsmodellen erzielbaren Erlöse zu untersuchen.

Sämtliche Berechnungen werden für das Jahr 2010 durchgeführt, um die Verwendung von Prognosen für Lastgänge und Preisentwicklungen, wie sie zum Beispiel für das Jahr 2025 erforderlich wären, zu vermeiden. Es zeigt sich, dass bei einer angenommenen Marktdurchdringung von 100.000 Elektrofahrzeugen (2,3 % des PKW-Bestandes in Österreich) durch gesteuertes Laden für den Besitzer eines Elektroautos jährliche Einsparungen bis zu 103 € erzielt werden können, da Strom in preisgünstigen Intervallen bezogen wird. Bei der Teilnahme an den Systemdienstleistungen Sekundär- und Tertiärregelung können Aggregator und Besitzer von Elektroauto gemeinsam zusätzliche jährliche Erlöse von bis zu 171 € lukrieren. Abhängig vom Geschäftsmodell treten mit steigender Anzahl der Elektrofahrzeuge Sättigungseffekte auf, die zu einer Abnahme der Erlöse pro Fahrzeuge führen.

Die erzielbaren Erlöse steigen je mehr Regelenergie (Regelzone APG) für Bezug (Lasterhöhung auf Anfrage) durch Elektrofahrzeuge angeboten werden kann. Das Bereitstellen von Regeldienstleistungen für Lieferung ist aufgrund der Kosten für das Vorhalten dieser Leistung nicht rentabel. Das Bereitstellen von Sekundärreglung ist gewinnbringender als das Bereitstellen von Tertiärregelung, da deutlich mehr Sekundärregelenergie abgerufen wird. Wenn die Anzahl an Elektroautos einen bestimmten Wert überschreitet, sinken die Erlöse je Elektrofahrzeug.

Abstract

An increase in the use of renewable technologies for power generation comes along with a rise in the volatility of generation. One option to compensate this and create equilibrium between generation and consumption is the use of electric vehicles as buffer.

This work focuses on application possibilities of the connection of electric cars to the power grid. The framework necessary for a successful integration is investigated. Based on a business concept, business models that create financial incentives for the owners of electric vehicles are drafted and analyzed. The injection of electricity back into the power grid is not allowed in any of the business models as it would increase battery wear.

Research on today's electricity market and the markets for control power is conducted in order to identify stakeholders that are affected by the integration of EVs (electric vehicles). Business models are created and implemented in Matlab. Assumed scenarios that vary in the market penetration of EVs are used to analyze the financial effects which the application of business models has on market participants.

In order to avoid projections of load curves and price developments, all calculations are performed for the year 2010. At a market penetration of 100,000 EVs (2.3% of passenger cars in Austria), controlled charging alone could result in annual savings of 103 € for the owner of an EV. The additional provision of ancillary services (secondary control and tertiary control) can increase the annual revenues generated by the aggregator and owner of EV together to 171 €. Depending on the applied business model, saturation effects that reduce the revenues per EV occur as the number of EVs is increased.

The achieved revenues increase as more control power for purchase (in the control area of APG) is provided by the use of EVs. The provision of control power for delivery, however, is not profitable since the involved procurement of control power is expensive. The revenues generated by the provision of secondary control power are greater than those resulting from the provision of tertiary control power. Revenues achieved per EV start to decrease once the number of EVs exceeds a certain point.

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Abbreviations

APCS	Austrian Power Clearing and Settlement
APG	Austrian Power Grid
BAU	Business-as-usual
BGR	Balancing group representative
CAM	Control area manager
CSA	Clearing and settlement agent
DG	Distributed generation
DSM	Demand side management
DSO	Distribution system operator
EC	European Commission
E-Control	Energie-Control GmbH
EEX	European energy exchange
EU	European Union
EV	Electric vehicle
EXAA	Energy exchange Austria AG
GUI	Graphical user interface
MAC	Media Access Control
OeMAG	Abwicklungsstelle für Ökostrom
OEV	Owner of electric vehicle
OTC	Over-the-counter
PV	Photovoltaik
RES	Renewable energy sources
SOC	State of charge
TSO	Transmission system operator
V2G	Vehicle to grid
VAT	Value added tax
VKW	Vorarlberger Kraftwerke

Definitions

Definitions specific to terms used in the thesis:

"Aggregator" is an entity that is not present in today's electricity market. In future he will contract owners of electric vehicles and manage the charging of their vehicles in a cost-efficient manner. A detailed description can be found in section 5.1.1.

"Ancillary services" shall mean the provision of secondary control services and tertiary control services. These are necessary for the operation of transmission and distribution grids.

"Control area" shall be a subsection of the European power grid. The interconnected grid is divided into control areas that are largely independent.

"Dynamic pricing" or "real-time pricing" shall mean a charging scheme where electricity prices change as often as hourly or sometimes even more often. In contrast to other time-based pricing schemes, prices are not known days or months ahead.

"Electric vehicle" shall mean a full-electric car. The term was chosen because most of the business cases could principally be applied to other electric vehicles such as electric motorbikes or electric buses as well. However, different driving patterns for these classes of vehicles and dissimilar capacities of the batteries would go beyond the scope of the thesis.

"End-user" in the context of market actors shall mean a customer buying electricity for own use. The end-user may also generate electricity using small-scale plants and thus distinguishes himself from a mere consumer.

"End-user" in the context of electric vehicles shall mean the owner of an electric vehicle who has a contract with an aggregator. The term must not be mistaken for "clients". "Clients" of an aggregator are end-users and one or more other actors in the electricity market.

"Infrastructure" shall mean the infrastructure of power lines, charging stations and communication. In a broader sense the interfaces needed to use this infrastructure are included in the meaning.

"Prosumer" shall mean an entity in the electricity market that is a final consumer of energy but also produces electricity which can be fed to the public power grid. The term symbolizes the trend of private consumers to become producers by installing PV (photovoltaic), cogeneration units or other devices. It is a portmanteau formed by contracting the words "producer" and "consumer". The term was coined by Alvin Toffler and is not restricted to the field of energy markets.(Toffler 1980)

"Time-based pricing" shall mean an umbrella term for pricing schemes where electricity prices change depending on the time the energy is consumed.

"Time-of-use pricing" means a time-based pricing scheme in which electricity prices are set for a specified time period on an advanced basis.

Definitions adopted from the Federal Ministry of Economics and Labour:

The following definitions are adopted from a report of the Federal Ministry of Economics and Labour.(bmwfij 2007) The explanations are shortened to eliminate information that is irrelevant for this work.

"Balancing energy" shall mean the difference between the amount of energy agreed in the schedule and the amount actually generated or consumed by a balance group in a defined settlement period.

"Cogeneration" shall mean the simultaneous generation in one process of thermal energy and electrical energy.

"Distribution" shall mean the transport of electricity on high-voltage, medium-voltage and low-voltage distribution grids with a view to its delivery to customers.

"Electricity undertaking" shall mean a natural or legal person or a commercial undertaking performing one or more of the functions of generation, transmission, distribution, supply and purchase of electrical energy with a view to profit, as well as performing commercial, technical or maintenance duties in connection with these functions.

"Generation" shall mean the production of electricity.

"Grid operator" shall mean an operator of a transmission or distribution grid with a nominal frequency of 50 Hz.

"Schedule" shall mean the document showing the volume of electrical energy fed in and withdrawn at certain locations within a grid, as a projected mean value within a constant time pattern.

"System operator" shall mean a grid operator having at its disposal the technical and organizational means to take any measures required to maintain the operation of the grid.

"Transmission grid" shall mean a high-voltage interconnected system with a voltage of 110 kV or above, serving the purpose of supraregional transport of electrical energy.

1. Introduction

Increasing awareness about global warming, the upcoming trend of sustainability and peaking oil prices in the near past, have led policymakers and the society to reconsider energy generation and consumption.

As declared in the so-called 2020-Targets, the EU aims to increase the share of RES (renewable energy sources) in gross final energy consumption to 20% by the year 2020. Put to national objectives, the share in Austria needs to be increased from 23.3% in 2005 to 34%. The share achieved in 2008 was 29%.(Bundesamt 2010)

In Austria the share of RES in electricity generation has historically been high. Hydroelectric power plants account for more than half of the electricity produced. However, the (economic) potential for large-scale hydroelectric generation is exploited. To meet the growing demand for electricity, restrict emissions and gain independence of supply, distributed generation will play a major role. In addition to small hydroelectric stations and biomass units, wind power and PV are gaining popularity. Even though wind and solar energy are favourable from an environmental point of view, they have significant drawbacks namely volatility and intermittence.(Pieper 2010) Fundamental physical laws require generation to be in balance with consumption at all times. Hence there is a need for balancing energy to compensate for volatility. Fluctuation of generation is also an issue since storage capabilities of electric energy are very limited. Today generation from photovoltaic is still insignificant. Countries, like Germany, that are home to vast wind farms face severe difficulties in coping with the volatility of this kind of energy source. These problems are likely to increase as the share of renewables grows.

The solution will be a mix of technologies and procedures. What can be said is that electric vehicles have a reasonable chance to be part of that solution. Provided an adequate infrastructure and communication interfaces, their batteries could be used to support system operators by providing ancillary services. Of course these services will not come free of cost. Battery life, comfort for the driver of the EV, and the required communication infrastructure (smart grid) need to be assessed. A large-scale integration of EVs in the electricity system would affect many stakeholders. Business models are a crucial step to achieve this integration.

1.1. Motivation

Actors in the electricity market have to comply with an abundance of rules to ensure that the balance between generation and consumption of electricity is sustained. Their roles and interactions are defined and supervised by the Federal Ministry of Economics and Labour and by approved private enterprises such as E-Control. Hence it makes sense to design a business concept that supports a widespread integration of EVs in the energy system. This business concept needs to take technical, economical and regulatory factors into account. Based on this business concept, business models can be created. These define the interactions between the OEV (owner of electric vehicle) and the rest of the electricity market. On the one hand it is vital to have business models that are fairly easily understood by the end-user. On the other hand additional interactions with the OEV can increase efficiency of the electricity system as a whole. In this work it is assumed that a so-called aggregator will act as mediator between the OEV and other stakeholders in the market. It is in his interest to offer business models that are attractive to end-users. This will be the case if comfort of the OEVs is respected and cost savings for the end-users can be achieved.

1.2. Scope and goals of this work

The objective of this work is to investigate the application possibilities of the connection of EVs to the power grid.

The current market is looked at and interactions among stakeholders are studied to find out what actors would be involved in the integration of EVs in the electricity system. A business concept is established to create a framework under which business models can be realized. Entities, the so-called aggregators, are foreseen to accomplish these business models. The aggregator offers his services in the form of energy contracts to OEVs. These comprise the provision of energy used for driving and the provision of ancillary services to the TSO (transmission system operator) and DSOs (distribution system operator). Taking into account the driving pattern of his clients, the aggregator controls the charging of his vehicle fleet. Four business models are designed to meet different restrictions of the communication infrastructure. These are implemented in Matlab and analysed using three scenarios which vary in the penetration of EVs. The focus lies on the investigation of financial effects business models have on stakeholders.

1.3. Outline of this work

The thesis is structured as follows:

1. Introduction: After explaining the motivation for the integration of EVs into the electricity system, a brief overview of the situation is given. The major parties are introduced and the importance of business models is stressed. The procedure to reach the goals of this thesis is described.

2. Background: The research focuses on the structure and functioning of the Austrian electricity market. At the beginning, a retrospect of the historic evolution of the electricity market is given. The vertical integration of utilities and their monopolistic supply is described. Negative consequences as well as diseconomies of scale are discussed. The effects of unbundling and liberalization are illustrated. The current market structure is analysed. Interactions among stakeholders are studied. Their roles and duties in the market for energy and for control energy are examined. The findings are illustrated in a figure which displays all major interactions. Future developments, in particular smart grids and the role of EVs, are looked at.

3. Database: The database used for the Matlab model is described. Most of the data was obtained from online databases and needed to be processed before it could be used. The database comprises load forecasts, load deviations, prices and the driving pattern. Depending on the type of data, median or mean operations were applied to attain representative values. The source and the dates of data values are listed. The data used to calculate parameter values is also discussed.

4. Methodology: A brief overview of the methodology is followed by a clarification of the framework of this work. Next, the Matlab model is discussed. The input parameters are defined and hints concerning their use are given. The procedure used in the Matlab model is explained. Finally the implementation and some exemplary functions are looked at.

5. Results:

   Business concept: The objective of the business concept is to reduce the complexity felt by the OEVs as stakeholders and thus enable them to participate in the electricity market. To implement business models in the market, certain entities are essential. After reasons for their necessity have been given, the interactions of these so-called aggregators with other market participants are discussed. A figure is used to visualize the role aggregators will occupy in the electricity market.

   A range of business models are constructed. They vary in their communication requirements and the provided ancillary services. The business models are analysed using a Matlab model. Scenarios are derived in order to examine the financial effects on involved stakeholders.

6. Conclusion: The results of chapter 5 are summarized and conclusions about the integration of EVs in the electricity system and the likely financial effects it will have on stakeholders are drawn.

2. Background

This chapter deals with the evolution of the electricity market in Austria. Following a historic retrospect, the present situation is analyzed. The roles of different stakeholders in the market are looked at in order to identify players that would interact with a future aggregator. Finally, we look ahead and an introduction to smart grids and the significance of electric vehicles is given.

2.1. Historic evolution of the electricity market

For the most part of the 20th century electricity undertakings were in the hand of the state. It was not until the beginning of the new millennium that utilities were liberalized and electricity markets were opened.

2.1.1. Nationalization after World War II

After the Second World War it was foreseen that a proper infrastructure is critical for economic and social development. The European social welfare states were interested in the nationwide development and provision of such infrastructure.(Hofbauer 2006) The second nationalization act of 1947 paved the way for the establishment of nationalized enterprises. One nationwide organization (Verbund), nine provincial organizations, five provincial capital organizations and a set of special purpose companies, so-called “Sondergesellschaften”, were founded.(Haberfellner 2002) Responsibilities of the enterprises were stipulated by law. The Verbund was in charge of the construction of large power plants and the transmission grid whereas other utilities were responsible for the provision of electricity in their areas and thus construct regional grids and power plants if needed. Electricity undertakings were vertically integrated, which means their value chain covered two or more of the fields: generation, transmission or delivery, and supply. As illustrated in Figure 1 most utilities generated, distributed and supplied electricity to their customers.

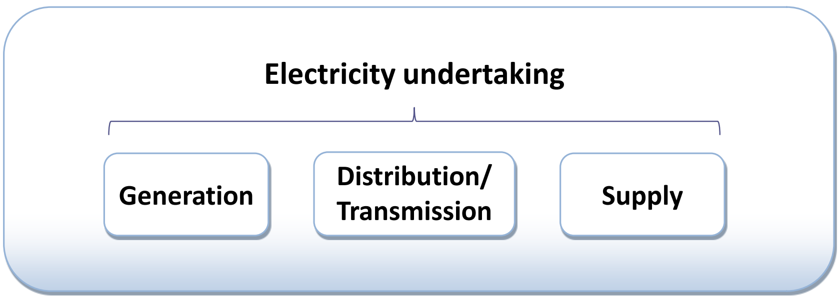

Figure 1: Vertically integrated utility

2.1.2. Market structure

The electricity market was dominated by vertically integrated utilities. They were owned by the state and had regional monopolies. As shown in Figure 2, consumers were not allowed to choose their supplier. For the benefit of society, utilities were assigned additional tasks in terms of safety of supply and environmental obligations. Prices were determined by the Federal Ministry of Economics and Labour. They covered not only costs for the generation and distribution of electricity but also costs for the fulfilment of those tasks that were in the public interest.(Hofbauer 2006) Since grid costs were included in that price, utilities had incentives to optimize the overall system consisting of production and grid infrastructure.(Brauner 2009a) Compared to other European countries electricity prices for businesses and industrial enterprises were relatively high. Electricity costs can account for up to 20 % of the total running costs of an enterprise, depending on the branch of trade. In order to support the competiveness of Austrian companies in a globalising environment, market-based pricing gained in popularity.(Haberfellner 2002)

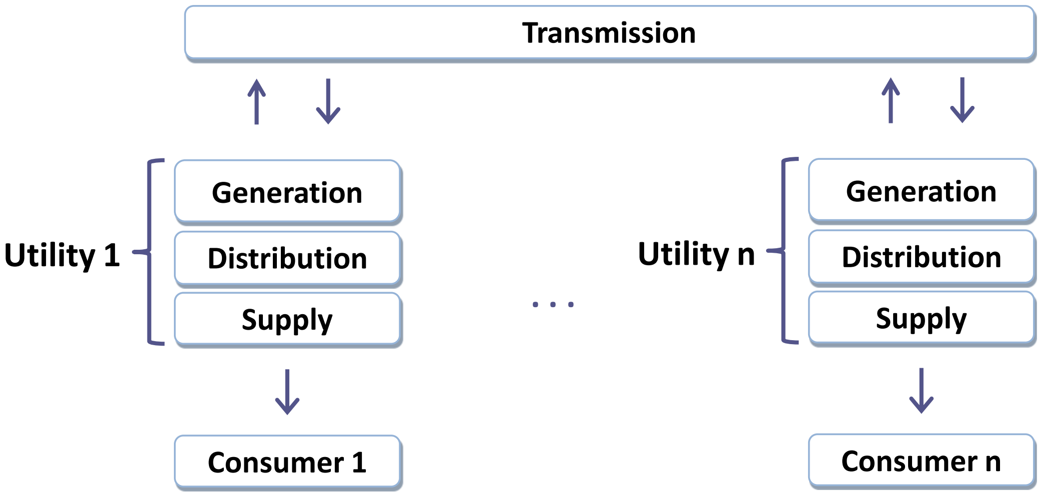

Figure 2: Consumers were bound to their utility

2.1.1. Liberalization process

For the most part of the previous century, electricity generation featured economies of scale. The idea of economies of scale is shown in Figure 3. The greater the electricity output of a power station was, the more profitable it could generate this electricity. However, in the 1980s, this assumed law was broken. The introduction of combined cycle power plants elevated the efficiency of smaller plants. In combined cycle gas turbine plants, the waste heat of the electricity generating gas turbine is used to create steam for the use in an attached steam turbine, which generates additional electricity. Furthermore, co-generation plants were gaining ground. They use the waste heat produced by electricity generation for other purposes such as district heating. Hence incentives for smaller electricity producers were on hand. In order to open the electricity market for so-called independent power producers, the regulatory framework needed to be changed.

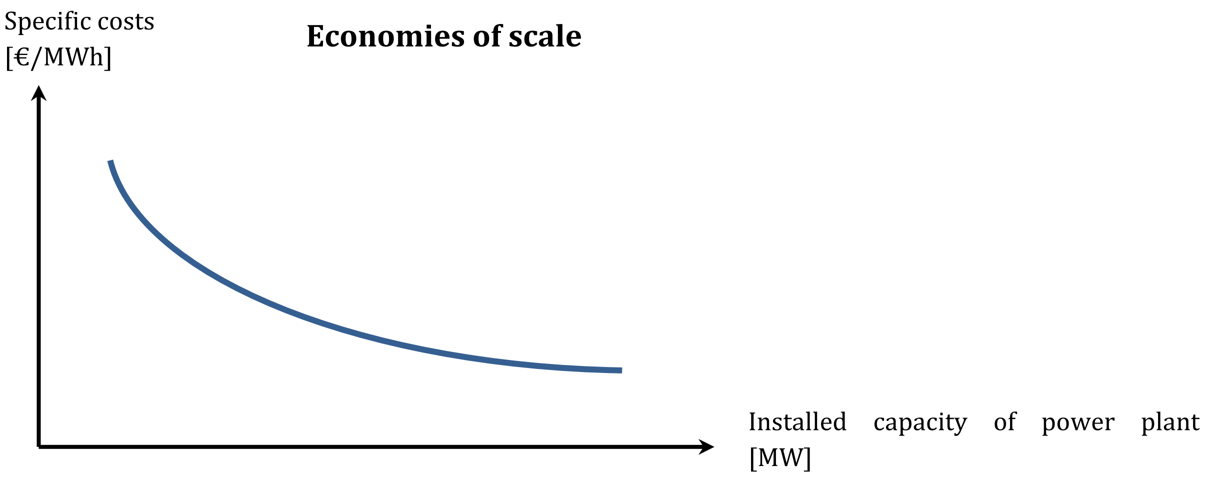

Figure 3: Economies of scale as they applied in electricity generation until the 1980s

Since electricity prices were not market-made but approved by a ministry, utilities had few incentives to generate and distribute the energy in a cost efficient way. The term "gold plated turbines" was coined to allude to the alleged habit of electricity undertakings to seize unnecessarily expensive hardware.(Haas 2010a) Moreover utilities were accused to have too much staff and overprice security of supply.

The EU directive 96/92/EG calls for a single European electricity market.(EC 1996) With the purpose of fulfilling this goal, the national electricity act was amended and a stepwise liberalization was initiated by the Austrian government. The following terms are often confused in their meaning since their implementations are closely linked. They are often part of a political reform process but cover different aspects of it.

Privatization

Corresponding with the second amendment of the second administrative penalty law in 1987, at least 51 % of formerly state-owned utilities must remain in public ownership. In 1988, 49 % of Verbund, the company in charge of the transmission grid, was privatized.(Verbund 2010) Most provincial utilities were partially privatized as well. The benefits of privatization are argued to be a more efficient provision of goods or services due to competition. However, to enable competition a further measure was required, being liberalization. Some perceive privatization as a prerequisite to liberalize markets because government enterprises could have unfair advantages and thus ruin competition. Nevertheless the majority of utilities' shares (at least 50 % plus one extra share) remained in public hands. The provincial utilities of Vienna and Tyrol were not privatized at all.

Liberalization

Liberalization refers to the opening of the electricity market for new participants. New generators can enter the market and consumers are allowed to choose their supplier. This is crucial for accomplishing competition. Beginning in 1999, a stepwise liberalization of the Austrian electricity market until 2003 was planned. Bigger consumers were able to choose their supplier earlier than smaller ones. As market participants argued that this would lead to distortion of competition, an amendment was abolished to introduce full liberalization in 2001. E-Control, a regulatory authority, was established in 2001 to supervise competition and provide consumers with price comparisons.(Haberfellner 2002)

Deregulation

Deregulation often goes hand in hand with liberalization. It aims at the reduction or simplification of regulations and government rules and thus promotes the operation of market forces. Nonetheless a certain amount of regulation is required to prevent market failures and the abuse of market power. In fact, the concrete formulation of a regulatory framework can be seen as fundamental for the functioning of markets and the efficient utilization of market forces.(E-Control 2003) In particular, enterprises having a monopoly such as grid operators need to be regulated.

Unbundling

As described in section 2.1.1, utilities used to be vertically integrated. In order to increase competition and admit new market participants, unbundling was vital. Unbundling means the separation of competitive segments from non-competitive ones. This is illustrated in Figure 4. Production, distribution/transmission and supply were separated. Utilities were split into these segments. Initially financial unbundling had to occur. Distribution and transmission are special in the way that they are considered natural monopolies. Economically it does not make sense to build a redundant power grid. Therefore network operators are exempt from competition. Their prices are set by a regulatory authority. Production and supply are competitive segments where competition is wanted from the government. The next step is legal unbundling, which is currently taking place. Independent enterprises that cover only one of these segments are formed. To enable fair competition, non-discriminatory grid access must be provided to all market participants. Additionally, cross-subsidization needs to be prevented. E-Control has been assigned with the supervision of this matter.

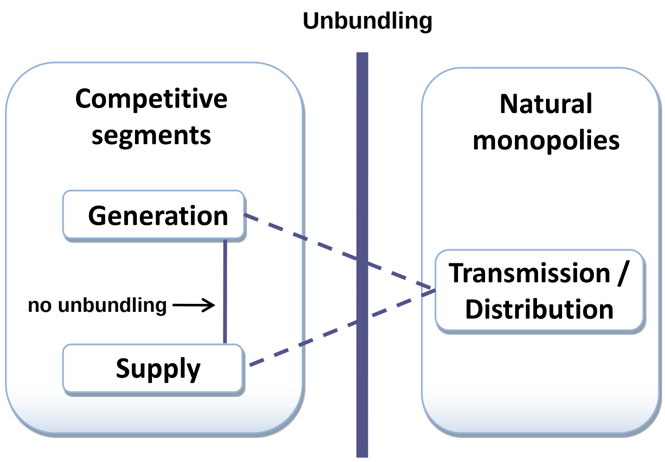

Figure 4: Unbundling (Haas 2010b)

2.2. Current electricity market

This subchapter focuses on the present state of the electricity market. After a discussion of the legal framework, market participants and their interactions are analysed. The functioning of the market for energy and for control energy is studied.

2.2.1. Legal framework

The legal basis of today's electricity market is determined by two core documents. On a European level it is the Electricity Directive for the Single European Market 2003 (2003/54/EC) of the European Parliament and the European Council.(APG 2010a, EC 2003) This directive was adopted in the national law. The legal framework in Austria is described by the Electricity Industry and Organization Act (ElWOG).

2.2.2. Market participants and interactions

Due to vast changes in regulation, the complexity of the electricity market increased significantly. In this section the entities in the market and their tasks are described. Their interactions are illustrated.

A description of the stakeholders and their tasks in today's electricity market follows:

"Producer" shall mean a commercial undertaking generating electricity. It can also mean a person generating electricity in a non-renewable way. Renewable generation conducted by individuals is not included in this term as owners of renewable distributed generation plants face different regulations. Hence producers own one or more power plants to physically produce electricity. Producers are free to choose where/if/when they sell their energy. If applicable, limited cross-border capacities or other bottlenecks may restrict their choice. They can sell energy via an energy exchange or over-the-counter (OTC). OTC encapsulates all trading not processed at an official market place, such as an energy exchange. In the context of energy markets, OTC-contracts basically means forwards. These are non-standardized bilateral contracts, including contracts made by telephone or via brokers. Most trading is done using this option.

Tasks:

- Can sell energy on an electricity exchange or OTC.
- Has to join a balance group or form one of his own. This balance group has to be supplied with a schedule of the forecasted generation. Mismatches result in payments by the producer.
- Is obliged to provide any required data, including generation schedules, to the grid operators and any other affected market participant.
- May offer ancillary services to the control are manager via a market maker auction and thereby generate additional revenue.

"Renewable distributed generator" shall mean a person or enterprise that generates electricity using renewable technologies. An example of a renewable distributed generator is a household that generates electricity via photovoltaic modules. In an electricity system without nameable storage capabilities, demand has to equal consumption at all times. Therefore it is necessary to feed excessive generated electricity from the house grid into the public one. To promote the use of RES, special feed-in tariffs are applied. These are coordinated by OeMAG (Abwicklungsstelle für Ökostrom AG). The subsidies are provided in the form of feed-in tariffs for a given period. They vary depending on the technology used. As of 2010, feed-in tariffs ranged from 5 c/kWh (renewable waste combustion) to 38 c/kWh (small-scale PV).(E-Control 2010a) Once the tariffs run out, the DG (distributed generation) may sell his produced energy to OeMAG at the market rate or try to find a supplier who offers a higher price.

Tasks:

- Produces electricity for own consumption or disposal.
- Has to join a balancing group and arranges a contract with OeMAG to receive a special feed-in tariff. Before that, grid admission has to be obtained from the distribution system operator.

"OeMAG" is the acronym for "Abwicklungsstelle für Ökostrom AG", the Austrian green power settlement agent. According to the Green Electricity Act §14 a private enterprise in terms of a private-public-partnership model was established. It shall process and commission green electricity.(OeMAG 2010)

Tasks:

- Commission new applications for subsidies.
- Purchase green electricity in line with national feed-in tariffs.
- Calculate the quotas of green electricity and allocate them to suppliers.

"EXAA" is the acronym of Energy Exchange Austria. It has become established as an European market for energy exchange.(EXAA 2010a) It shall be mentioned as an example of an energy exchange. The EXAA was founded in 2001 and is located in Vienna. Currently, it hosts about 80 trading companies that participate in the spot market.(EXXA 2010b) Electricity produced in Austria and sold on the spot market is traded via the EXAA or other energy exchanges. While some energy exchanges participate in the market for future contracts, the EXAA does not.

Tasks:

- Provide a trading platform for the day-ahead market (spot market) where producers can sell their energy and suppliers or electricity wholesalers can buy or resell energy.
- Provide a trading platform for European carbon emission allowances.

“Electricity wholesaler” shall mean a commercial enterprise or person that trades energy. He does not perform distribution or transmission functions. An electricity wholesaler often buys energy in huge amounts in order to achieve a good price. The energy is then sold to suppliers or other electricity wholesalers. Trading can be done via an energy exchange or directly with producers or suppliers. Producers and suppliers are usually risk averse and accept smaller profits if uncertainty is reduced in return.

Tasks:

- Buy energy via an energy exchange, directly from producers or from other electricity wholesalers.
- Sell energy on an energy exchange or via bilateral contracts to suppliers or electricity wholesalers.

“Distribution system operator” is an undertaking in charge of a regional distribution network. It has to ensure that energy is delivered in compliance with existing contracts between generators and consumers. It is responsible for making long-term investments and for maintaining the operability of its network.(E-Control 2010b) This last point has caused concern by policy makers as the liberalized environment induces DSOs to cut costs by reducing investments. Out of the set of load profiles announced by E-Control, the DSO has to assign appropriate profiles to consumers whose consumption is not measured frequently.

Tasks:

- Establish contracts with consumers to allow them access to the grid.
- Deliver electricity to consumers.
- If relevant, apply load profiles to consumers.
- Meter consumption without prejudice, check measurements for plausibility and attribute them to the responsible balancing groups. Transmit this data to the clearing and settlement agent.
- Create a special balance group to account for system losses and own consumption, e.g. a balance group for grid losses.

“Transmission system operator” is an undertaking similar to the DSO. It is in charge of the supraregional transmission network. It is responsible for the safe and reliable operation of the network and the transmission of electricity according to the instructions given by the control area manager. It must not discriminate any party (for the benefit of its associated enterprises).

Tasks:

- Ensure the operation of ancillary services.
- Transmit information of system utilization to the control area manager.
- Measure the energy exchanged at the borders of control areas.

“Supplier” shall mean commercial electricity undertaking that buys energy and sells it to consumers. The energy can be bought on an electricity exchange or purchased via bilateral contracts with wholesalers or producers. Since 2001 system operators have been obliged to grant non-discriminatory access to their networks to all suppliers.(E-Control 2010b)

Tasks:

- Deliver energy to consumers.
- Bill its clients for their consumed energy.
- Inform balance group representatives day-ahead of its customers’ consumption.

“Consumer” shall mean a private household or enterprise that purchases electric energy for its own use. These entities have to be granted grid access in order to receive electricity services. The price consumers have to pay for electricity is discussed in section 2.2.3. Since 2001 all consumers, may it be households or businesses, have the right to switch their supplier. Electricity consumers now have two separate contracts, one with the DSO for grid access and the other with a supplier for the delivery of energy. As of 2010, there are more than 130 suppliers in Austria. However, some offer their services only locally. System operators cannot be chosen. For each geographic location there is one responsible DSO.(E-Control 2010c)

Tasks:

- Conclude a contract with the appropriate DSO to obtain access to the power grid.
- Conclude a contract with a supplier.
- Pay suppliers for the consumed energy.

“Balance group representative” is the representative of a balancing group in front of other market players. A balancing group combines suppliers and consumers to a virtual group. Within this group supply and demand are balanced, thus fluctuations are evened out. Only the overall difference may cause additional payments. Formula (2.1) shows the calculation. In addition to all suppliers and consumers a few other market participants are forced to join a balancing group. There are a number of special balancing groups, for instance eco-balancing groups or those that account for the losses associated with distribution and transmission of electricity.

$$\Delta_{energy} = \sum_{supply} \left(E_{s,\,projected} - E_{s,\,is}\right) - \sum_{demand} \left(E_{d,\,projected} - E_{d,\,is}\right) \tag{2.1}$$

Δ_{energy} ... *required balancing energy*

$E_{d,\,projected}$ ... *scheduled energy demand according to load profiles*

$E_{d,\,is}$ ... *actual energy demand*

$E_{s,\,projected}$ ... *scheduled energy supply*

$E_{s,is}$ ... *actual produced energy*

Tasks:

- Draw up schedules of injected and withdrawn energy as well as schedules of transmissions to and from other balancing groups. Forward these schedules to the CSA (clearing and settlement agent) and the CAM (control area manager).
- Pay clearing and settlement fees to the CSA.
- Pay the CAM for required balancing energy and pass these fees on to balance group members.

"Control area manager" is an independent entity which is responsible for the supervision and regulation of power flows in a specified area. The European interconnected grid is divided into a large amount of control areas. These are to a great extent independently operated. Since January 2011 there are two control areas in Austria. They are operated by the transmission grid operators APG AG and VKW[1]-Übertragungsnetz AG. In other words, both transmission system operators in Austria are at the same time CAMs. All power lines that cross the border to neighbouring control areas are equipped with power meters which transmit their readings online to the respective CAM. The CAM calculates in advance how much electricity will need to cross the border in order to comply with the supply contracts. Power stations within the control areas are operated so they fulfil these schedules.

Tasks:

- Manage schedules with other control areas.
- Ensure a physical balance between supply and demand in the system.
- Designate a clearing and settlement agent and provide it with all information required.
- Insert the relevant (week-ahead) bids obtained from market makers in the (day-ahead) merit order list.
- Cooperate with the CSA and market makers to organize and dispatch control reserve energy in accordance with the merit order list.
- Meter power flows that cross the boundaries. Provide this data to CSAs and other system operators.
- Identify bottlenecks in the transmission network and take appropriate measures to prevent or handle them.

"Clearing and settlement agent" also called "balancing group coordinator" is an independent entity that assists the CAM by calculating the balancing energy of participants in the Austrian electricity market.(APCS 2010a) In order to do so, the CAM has to provide the CSA with the metered data so that deviations from schedules and load profiles can be

[1] Vorarlberger Kraftwerke

determined. Producers may offer day-ahead ancillary services. The bids are ranked to create a merit order list. This list is sent to the CAM who dispatches balancing energy if required. Each CAM designates one CSA. In Austria there are two CSAs: APCS (Austrian Power Clearing and Settlement) AG designated by APG (Austrian Power Grid) AG and A&B[2] AG designated by VKW-Übertragungsnetz AG. As a settlement agent, the CSA calculates the prices of balancing energy, charges the appropriate parties and pays the producers whose bids have been accepted.

Tasks:

- Collect bids for ancillary services and create a merit order list.
- Forward the merit order list to the CAM.
- Calculate the difference between the BGRs' forecasts and the metered data.
- Allocate the fees for balancing energy (secondary and tertiary control reserve) to the respective BGR.
- Allocate the fees and payments for primary control reserve to the producers.

"Market maker" shall mean an entity that was introduced to ensure liquidity on the market for tertiary control energy. The CAM defines the tendered power. Currently this is 100 MW for increasing generation (or reducing load) and 150 MW for trimming down generation (or increasing load).(APCS 2010b) Registered market makers, may it be producers or large consumers, can make bids in weekly auction for the tendered power on an internet platform. The day is separated into 6 time periods for which bids are accepted. The first bid a market maker places in a period has to be in the range of 10 MW to 50 MW. Further, bids in the same time period must be between 25 MW and 50 MW each. Bids can be varied in steps of 1 MW. All bids that were placed by a specified date are ranked and forwarded to the CAM, who will insert the best bids according to their price in the (day-ahead) merit order lists, which he receives from the CSA. The energy prices of market maker bids may be adjusted whereas the volume of the bids must not be changed.(APCS 2009a)

Tasks:

- Hold weekly auctions for the procurement of tertiary reserve energy.
- Rank bids according to their price and forward them to the CAM.

"E-Control" is the regulator of the Austrian electricity market (and gas market). As such it has to be politically and financially independent. It was established in 2001 and is a 100 % state-owned enterprise, whose interests are managed by the Federal Ministry of Economy, Family and Youth. Its primary objective is to strengthen competition on the Austrian electricity market and to ensure this does not compromise sustainability or security of supply.(E-Control 2010d) E-Control's duties are twofold. On the one hand, it sets the framework by establishing market rules for competition and regulating network tariffs. On the other hand, it exercises market oversight by combating competition violations and tracking and analyzing market development.(E-Control 2010e)

[2] Ausgleichsenergie und Bilanzgruppen-Management

Tasks:

- Set a regulatory framework.
- Supervise interactions on the electricity market.
- Take measures to increase competition, e.g. provide consumers with price comparisons.
- Study market development.

Markets players may fulfil a couple of the roles described above. Vertically integrated electricity undertakings often have subsidiaries that occupy the roles of different market actors. In Austria the TSO functions as CAM. A private household may not only consume energy but also generate electricity via solar panels. In this case he is both, a consumer and a renewable distributed generator.

Figure 5 shows the stakeholders described above and illustrates their interactions. Further, this graphic will help to understand where the aggregator, which will be introduced in section 5.1.1, fits in and what his interactions with other market participants are.

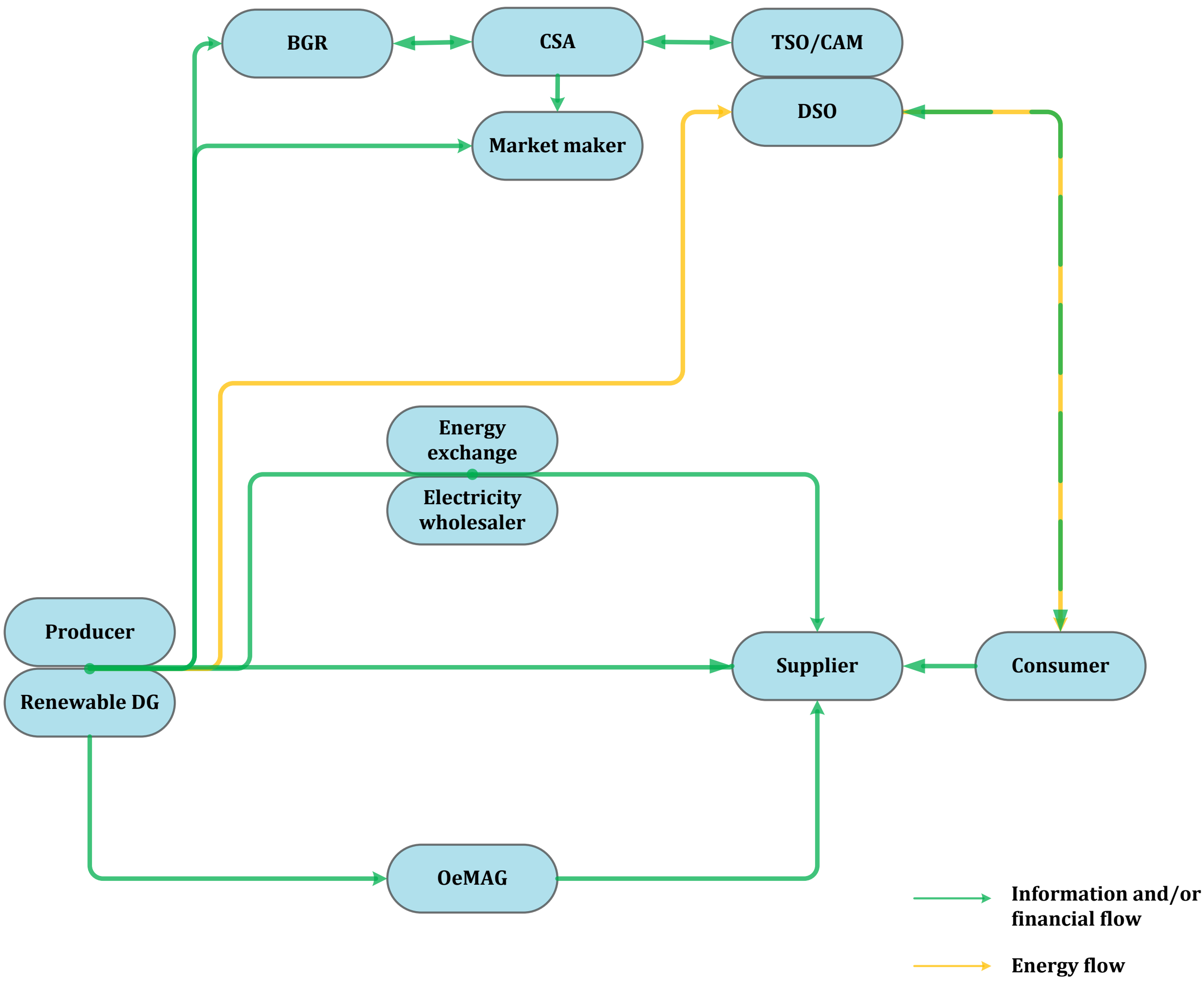

Figure 5: Interactions of stakeholders in today's electricity market

2.2.1. Functioning of the market for energy

This section describes the functioning of the market for energy. It explains the stages most energy has to pass in order to get from the production site to the point of consumption. The vast majority of electric energy is traded on this market.

Electricity is generated by producers or renewable DGs. Most renewable DGs are contracted by OeMAG to receive financial compensation for the electricity they feed into the public grid. The total produced green energy is proportionally allocated to suppliers (according to the quotient of supplied energy to totally supplied energy), who have to cover the associated costs. They sell their energy OTC and/or via electricity exchanges. In a functioning market, as is the case in Austria, 80 – 85 % of all electricity is traded via long-term contracts weeks to years prior to delivery. 15 – 20 % are traded on the spot market (days to weeks ahead). Only about 2 – 5 % are traded on the market for control energy, which is described in section 2.2.2. In the case of perfect consumption forecast, prices on the three market segments would be the same.(Haas 2010c)

Before energy reaches the consumer it may be bought and sold a couple of times. In this process energy is traded only virtually. Suppliers buy energy from energy exchanges, wholesalers or directly from producers. They sell energy to consumers.

Physically, electricity is fed into the power grid at certain points and extracted elsewhere by consumers. In order to transport electric energy from where it is produced to where it is consumed, a power grid is needed. There are two kinds of grid operators. The TSO is in charge of the high-voltage transmission network, which is used to transport electricity over long distances. The DSOs operate mainly low-voltage and medium-voltage distribution networks, which are needed to transport electric energy from a power plant to the transmission grid or from the transmission grid to the consumer. The costs associated with the operation of these networks and a financial compensation for transmission losses are billed to the consumer via a contract with the DSO.

The power grid is considered a natural monopoly with the consequence that the consumer may not choose his DSO. To prevent DSOs from charging unreasonable prices, tariffs that are approved by E-Control are employed.(E-Control 2010f) Benchmarking is exercised to prove the reasonability of operation costs of the networks. Consumers may choose their supplier. To assist them by doing so, E-Control publishes price comparisons.

As said, there are two segments of the market for (non-control) energy. They differ in the time horizon and shall be discussed now.

Long-term market

Trading is done months to years ahead of the point of fulfilment. This segment is used by producers, wholesalers and suppliers to hedge or speculate. The liberalization of the energy market went hand in hand with increased uncertainties for market participants. Suppliers face varying electricity prices and do not know how many clients they will have in a year's time. Due to reasons of planning, most enterprises are risk averse. Long-term contracts allow them to hedge against price fluctuations.

A supplier is physically short as he needs to buy electricity in order to supply his costumers. He may hedge by going financially long. He would do so by buying futures-contracts or forwards-contracts. He purchases the contract at an agreed price. The seller is obliged to deliver a certain amount of energy at a given date unless the contract is eliminated before. About 98 % of futures are eliminated before their expiry date.(Haas 2009c) This is done by financially fulfilling the contract. In the example above, the supplier would sell his future and thus close his (financial) long-position.

Winnings in a physical long position imply losses in the respective financial short position, and vice versa. The same mechanism may also be used to speculate and thus generate additional profits.

As already mentioned, there are two popular types of contracts used in the long-term market.

- Futures are traded at official market places such as energy exchanges. A prominent European market place for futures is the EEX (European energy exchange) in Frankfurt. Like the Austrian energy exchange EXAA, many exchanges do not participate in the futures market. Futures are standardized products. A major advantage of futures is that the credit worthiness of contracting parties is checked by the exchange.

- Forwards are non-standardized bilateral contracts between two parties. Contractors need to check their opposite's credit worthiness themselves. Forwards are not traded at official market places. Although one contractor may be an energy exchange.(Haas 2009c) Buyer and seller know each other or use a broker as mediator. A major advantage is that the specifics of the contract are agreed upon the two parties. Most forwards are fulfilled by physical delivery of the product.

Future and forward products differ in whether they are peak load or base load products.(E-Control 2010g)

Short-term market

On the spot market electricity is sold or bought days to weeks prior to delivery. Again, bilateral contracts are possible. Most energy exchanges participate in the day-ahead market. Here electricity is traded on the day before delivery. In a functioning market the prices of futures and forwards converge to the spot market price as time progresses.

2.2.2. Functioning of the market for control energy

In order to understand the functioning of the market for control energy, it is vital to know the underlying technical mechanism. After the technical measures to stabilize the electricity system have been examined, the provision and finally the cost allocation are looked at.

Physical aspect – Mechanism of frequency control

This subsection deals with the functioning of frequency control. Three mechanisms (primary, secondary and tertiary control) work together to keep the frequency at its nominal value of 50 Hz.

Production plants are operated so that they meet the forecasted demand. In reality there are always deviations between the projections and actual consumption. It is also possible that the planned production is not achieved because of failures in power stations. An imbalance between generation and consumption leads to a deviation in the frequency. If production is smaller than consumption, the frequency descends. The turbines of most generation units are optimized for a frequency of 50 Hz. Thermal power plants must be dispatched when the frequency falls below 47.5 Hz. Otherwise they might suffer permanent damage.(Brauner 2009b) Hence it is vital to keep the frequency stable around its nominal value.

When the frequency drops/rises, **primary control** is the first mechanism that takes action. Certain registered power plants automatically increase/decrease their power output rapidly by means of turbine speed governors in order to stabilize the frequency and prevent a greater deviation. Activating this reserve works almost instantly. If there is only a brief power surplus or deficit, primary control is sufficient to stabilize the system.(E-Control 2010h)

If the disturbance lasts longer, **secondary control** is initiated automatically. It is activated within 30 seconds and aims at freeing primary control. In contrast to primary control reserve, which is provided on an international level, secondary control takes place in the control area which caused the imbalance. Its goal is to eliminate the deviation and thus bring the frequency back to its nominal value.

If the disturbance cannot be resolved within 15 minutes, **tertiary control** is applied manually. It frees secondary control. Since the dynamic requirements of tertiary control are not as hard to meet as those for the other two mechanisms, many more power stations are capable of providing this kind of reserve. The available tertiary control reserve (minute reserve) has to be greater or equal to the capacity of the largest generation unit in use in the control area.

The timing of this process is shown in Figure 7. Figure 6 illustrates the functioning of frequency control.

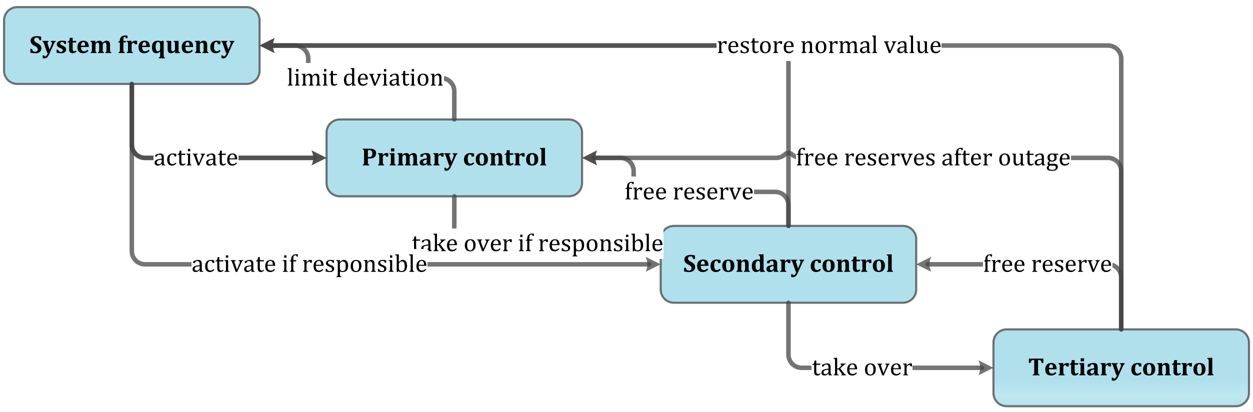

Figure 6: Frequency control in the ENTSO-E (ENTSOE 2009)

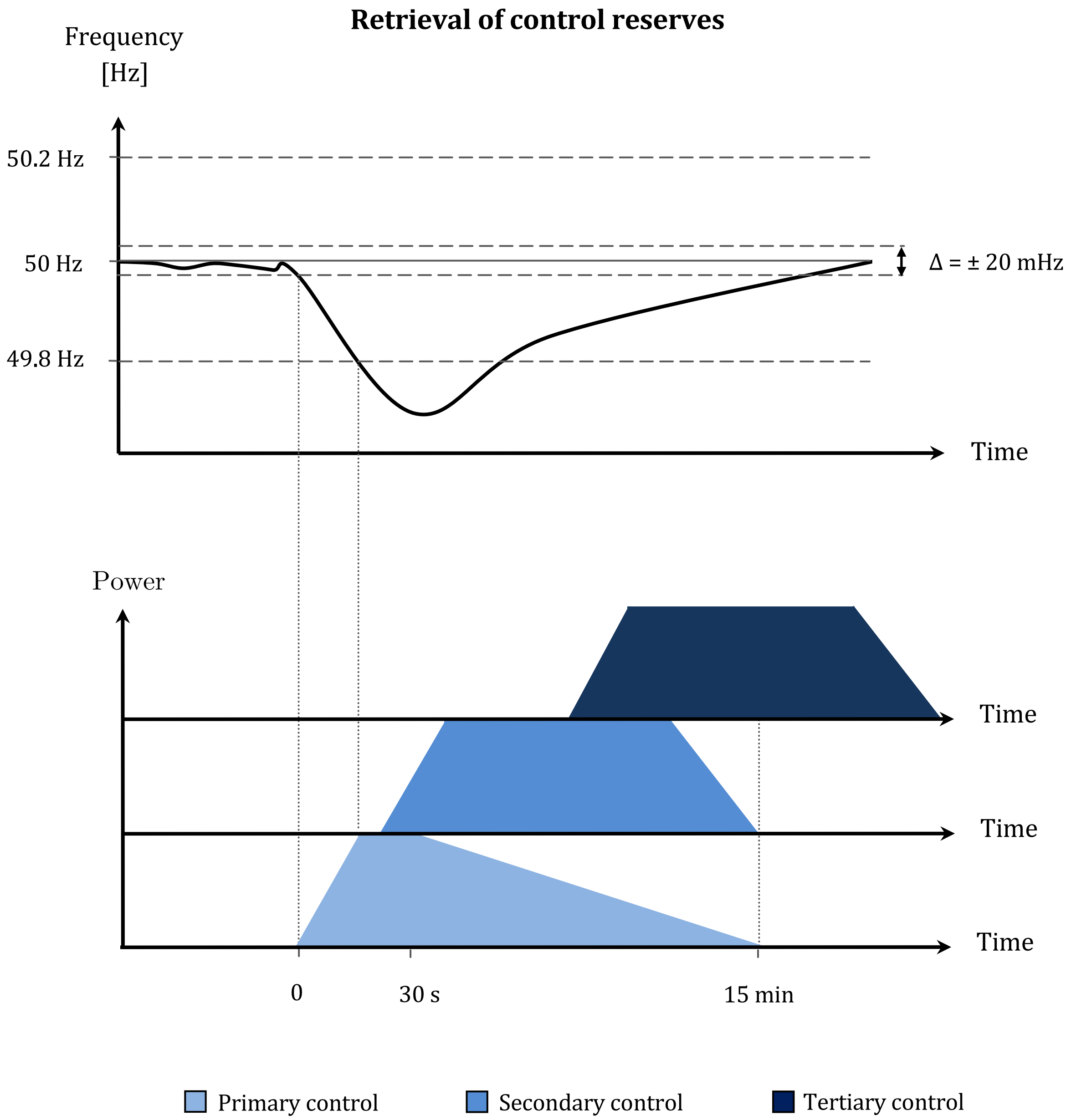

Figure 7: Retrieval of control reserves

Economic aspect – Provision of control reserve

Frequency control requires power plants to vary their power output if needed. This implies that participating generation units must not run at their nominal power output. Otherwise they would not be able to increase generation if needed. Keeping spare capacities is associated with a cost which explains why producers would not voluntarily participate in the provision of control reserve for free. Providers of control services must fulfil certain technical requirements. These are described in the technical organisational regulation TOR part E.(E-Control 2011a)

The required amount of **primary control** reserve is determined annually. For the year 2011 it is 76 MW.(APG 2011a) The provision is organized via weekly tender on an internet platform. Every Wednesday, the TSO in his capacity as CAM accepts bids for the following week. The bids are ranked according to their price. The cheapest ones are accepted until the required tendered amount is met. The internet platform grants public access to the results of auctions.(APG 2010b) In compliance with the UCTE Operation Handbook, primary control must be freed within 15 minutes. Bidders must be able to employ primary control power for up to 30 minutes in case that a repeated retrieval is necessary.(APG 2011b)

In the control area of APG **secondary control** reserve is provided by a single enterprise.(APCS 2010c) The amount of procured power is 180 MW for delivery and for purchase.(Kronberger 2003) In order to include market mechanisms in the provision of secondary control, an auction for the released secondary control energy is held in the consecutive week. Accepted bidders compensate the company, which has generated balancing energy by delivering energy during peak hours. Producers that have reduced their energy output in the course of providing balancing energy have to generate half of this energy during base load hours.(APCS 2009a)

Tertiary control is organized by the CAM via the CSA. The required amount of minute reserve (tertiary control power) is announced by the CAM. Stakeholders who meet the technical requirements and want to participate in the market for tertiary control have two options to submit quotes for the procurement and possible retrieval of control energy. Bids according to the specifications stated in Table 1 for delivery or purchase of control power are accepted in two auctions:

- Day-ahead: the CAM runs a web-based platform where bids for the next working day and holiday if applicable can be made. These have to be submitted by 16:00 o'clock. The CAM creates a merit order list.

- Market maker: If the CAM believes that the minute reserve raised on the day ahead might not cover the tendered amount, he orders the CSA to run a weekly auction. Stakeholders registered at the CSA may submit bids for the following week. Accepted bidders are allowed to alter the price of their bids. However, prices for delivery must not exceed the original price and prices for purchase must not be lower than the price offered originally. Changes must be made before the market closure of the day-ahead auction (16:00 o'clock). The CSA inserts accepted bids in the day-ahead merit order list.

The TSO has to ensure that retrieved control power is absorbed by the system for at least 15 minutes. He is obliged to retrieve offers in their full amount. Bidders must be capable of fulfilling retrieval orders from the TSO. Accepted bidders have to ensure that retrieved injection or withdrawal starts no later than 10 minutes after the TSO's request and before the end of the 15 minute interval. Bidders from other control areas must ensure that the inter-area transport of energy is approved by all involved TSOs.(APCS 2011b)

Producers can make bids for the following day to the CSA. The CSA creates a merit order list by ranking the bids according to their price. Accepted bidders are paid for the balancing energy actually procured. This list is forwarded to the CAM. Producers also have the option to participate in a weekly auction held by a market maker. The auction is held every Wednesday. Accepted bidders have to keep the agreed energy ready for the entire next week. They are paid for the provision of reserve energy and for the actual procured power. The auctioned amounts are 100 MW for delivery and 125 MW for purchase.(APCS 2010b) The bids accepted by the market maker are forwarded to the CAM, who inserts them into the merit order list. If tertiary control is applied, the CAM proceeds according to the merit order list. In today's electricity system hardly any tertiary control energy is released (see Figure 77) because most deviations can be eliminated by the application of primary and secondary control mechanisms.

Table 1: Specifications of bids for tertiary control power (APCS 2011c)

Time intervals	Power offered for delivery/purchase	Price restrictions
00:00 – 04:00 04:00 – 08:00 08:00 – 12:00 12:00 – 16:00 16:00 – 20:00 20:00 – 24:00	First offer: 10 MW – 50 MW Further offers from the same producer: 25 MW – 50 MW Offers can be varied in steps of 1 MW.	Day-ahead: $p_{delivery} \leq 3000$ €/MWh $p_{purchase} \leq 500$ € Market maker: $p_{delivery} \leq p_{EEX\ peak,\ last\ working\ day} + 80$ €/MWh $p_{purchase} \geq 0$ €

Financial aspect – Cost allocation

Clearing and settling is done by the CSA. The costs associated with primary control are carried by the producers. As only a few power stations participate in the provision of primary control, transfer payments fulfilled by the CSA are necessary.

In the control area of APG, secondary control is provided by Verbund. Injected and withdrawn control energy of a week are summed up separately. The compensation for retrieved secondary control energy is executed by exchange in kind. Compensation programs are run within the following two weeks. For delivery, the compensation program stipulates a delivery at constant power between 08:00 and 20:00 o'clock on working days. For purchase, the compensation program requires that half of the consumed energy has to be injected at constant power daily from 00:00 to 24:00 o'clock.(APCS 2009a) Charges and earnings resulting from the compensation programs are settled by the CSA, who forwards the charges to the BGR responsible for the deviation. The BGR allocates the costs to suppliers. In the end, these costs are carried by the consumers. The Verbund also receives a financial compensation for the provision of secondary control power. The respective contract between the Verbund and the TSO APG is not made public.

Tertiary control reserve is raised via auctions. Market makers receive a monetary compensation for the procurement of control power and a compensation in kind for the provision of balancing energy (retrieved control reserve).(APCS 2011d) Accepted bidders on the day-ahead market do not receive a compensation for the procured amount. The compensation in kind is comparable to the compensation program for secondary control energy. The CSA pays or charges the bidders and forwards the charges to the BGR.

In order to meet the product definition of current, transmission and distribution operators have to ensure that not only the frequency but also the voltage remains in its appropriate tolerance band. At the point of low-voltage withdrawal, the voltage has to be kept in a range of ± 10% of its desired value. This is achieved by applying voltage control to generation units, using voltage switches in transformers and connecting additional capacitors or inductances to the power grid.(Brauner 2009c) Voltage switches in transformers allow a stepwise variation of the voltage.

2.2.3. Electricity price

The price of electricity is made up of three components:

- Energy price
- Network charges
- Taxes and surcharges.

Each amounts to about one third of the total price.

Energy price

The energy price is the portion the supplier receives for his product. The energy price varies depending on the supplier and is determined by a client's consumption. Suppliers are free to set prices. Competition in the supplier segment is present and favourable for consumers. Switching one's supplier thus goes hand in hand with a change in the energy price.(E-Control 2010i) While the energy price offered by a supplier to private households is usually fixed, businesses and industrial enterprises have to bargain a price.(E-Control 2009b)

Network charges

Network charges are paid to the grid operators (TSOs and DSOs). They consist of three elements, which are all regulated by E-Control. The utilization charge compensates the grid operators for the costs associated with the operation, maintenance and expansion of their networks. They consist of a base charge and a consumption-based charge. The charges for grid losses are applied to financially compensate for the physical losses of energy inherent with transmission. The metering charges are paid to the grid operators to reimburse them for the costs associated with the installation and operation costs of metering devices.(E-Control 2010j)

Taxes and surcharges

Taxes and surcharges are called for by the state, provinces and municipals. Again, they are made up of three elements. The energy charge is applied to various forms of energy. The community levy is claimed by many communities to reimburse them for the use of public property. Each of the price components is subject to VAT (value added tax) of 20 %.(E-Control 2010k)

The latter two components cannot be influenced by the consumer. As switching one's supplier changes only the energy price, which makes up about one third of the total price, private households experience little incentives to do so. Exemplary compositions of the electricity price for a household and for a business are illustrated in Figure 8 and Figure 9. As some charges are fixed to absolute values, the shares vary slightly depending on the energy price.

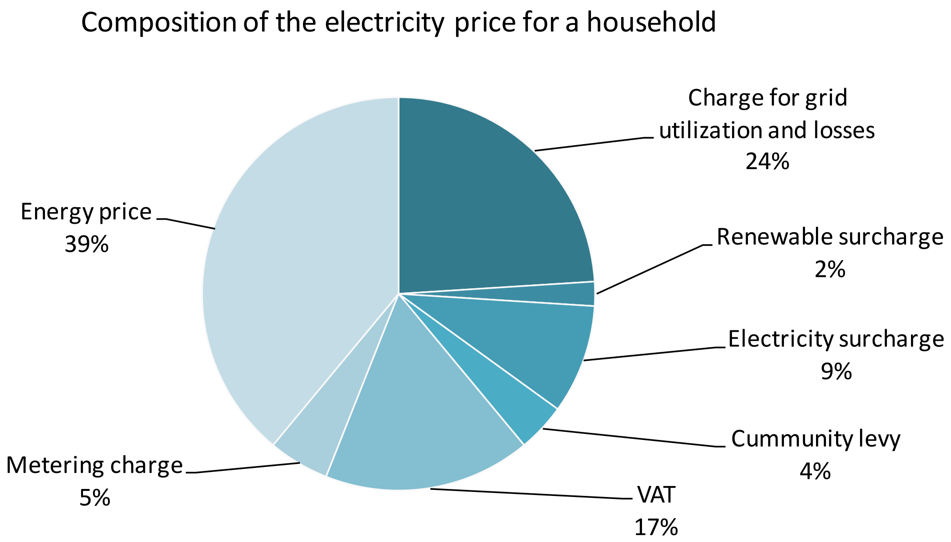

Figure 8: Exemplary composition of the electricity price for a household with a yearly consumption of 3 500 kWh (E-Control 2010l)

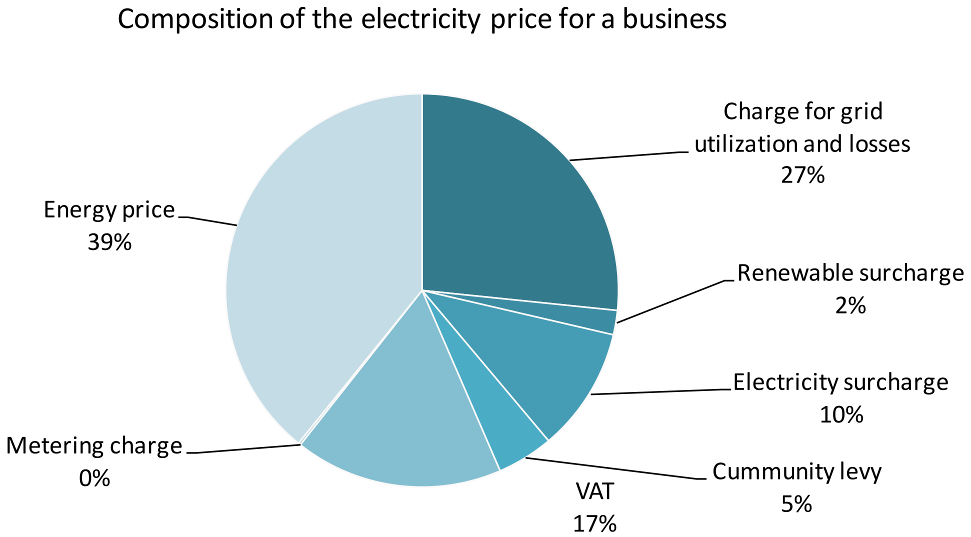

Figure 9: Exemplary composition of the electricity price for a business with a yearly consumption of 80 000 kWh. (E-Control 2009b)

2.3. Exciting prospects

Today's electricity system has evolved over a long time. In the past, generation was mainly centralized and supply had to satisfy demand. The trend to sustainability and the associated promotion of renewables, which are often distributed generation technologies whose energy output cannot be controlled in time, require new solutions to maintain system stability and reliability. An important and likely step to support this development is the introduction of technologies and financial instruments to increase the overall efficiency of the system by influencing the decision making of consumers and the management of their appliances. Smart grids, which are a prerequisite for the concepts drafted in chapter 5 and the role electric vehicles might play in the future are discussed in this subchapter.

2.3.1. Smart Grids

A smart grid, also known as intelligent grid, is an enhancement of today's power grid. It features an overlying communication network that facilitates bidirectional communication services. These allow generation units, network devices and consumer appliances to exchange data. It is an enabler for demand side management and has the potential to increase overall system efficiency.

There are numerous definitions of smart grids. The European Technology Platform SmartGrids understands smart grids as

> "[...] electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies."(SmartGrids 2006)

This definition was adopted and slightly modified by the national platform for smart grids.(E-Control 2010m) Commonly identified goals of smart grids are:

- Improving the connection and operation of generators and consumers.
- Further integration of consumers in the optimization of the electricity system. (DSM)
- Reducing environmental impacts of the system.
- Allowing more (renewable) distributed generation.
- Maintaining or improving system reliability and independence by locally self-healing networks.[3]

DSM

Demand side management aims to shift consumption in a way that benefits the electricity system. Figure 10 shows a load forecast for the control area of APG and the variation of load during the day. Consumption varies significantly during the day. Base load generation is provided by power plants that run for long periods and produce electricity at fairly low costs.

[3] "Self-healing" shall mean local networks keep operating even if failures occur in the superior grid.

Peak load generation, however, is expensive. Since the corresponding generation units run only a few hours a day, installation costs per MWh are high. Hence there is a point in flattening the demand curve. To do so, incentives for consumers are necessary. One option is time-based pricing. Electricity prices would be rather high during peak periods of the day and lower when there is little demand. This method requires the consumer himself or consumer appliances to be aware of the current price so that they can react. DSM would allow a greater integration of renewables as these pose intermittent generation, which can be forecasted only to a certain extent. A smart grid and smart consumer devices could accomplish this function. Further, the introduction of smart metering is necessary.

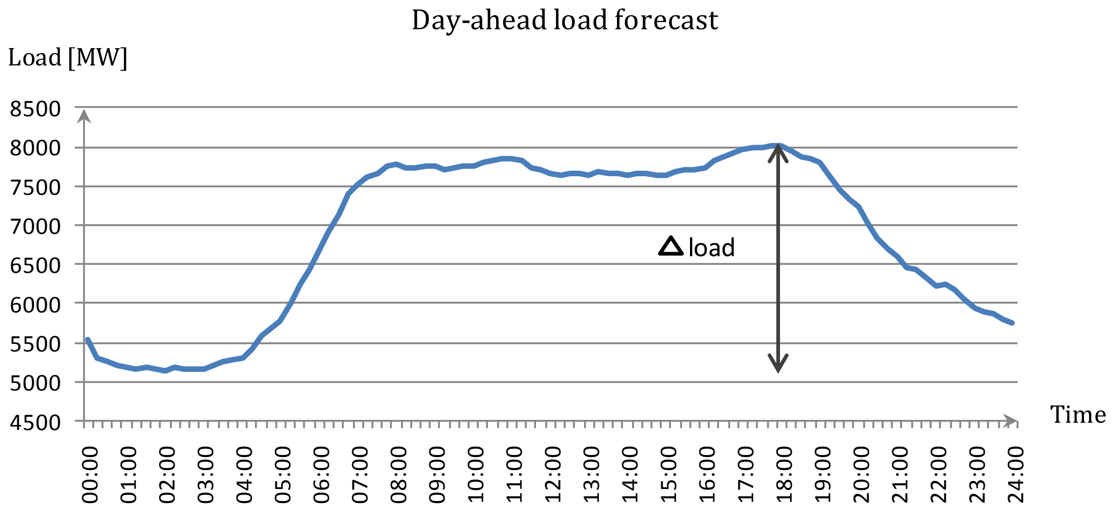

Figure 10: Day-ahead load forecast of the APG control area (2010/12/16), (APG 2010c)

Smart metering

In many cases electricity meters are read annually to determine a household's consumption of the last year. The introduction of smart meters would allow time-based pricing and increase awareness of one's energy consumption.(E-Control 2010c) Smart meters measure consumption in short intervals (e.g. minutes or seconds) and transmit these online to the DSO. Some smart meters are equipped with displays so that individuals are able to check their present consumption. This provides an opportunity to gain awareness of one's consumption and the changes a particular additional device causes. Major drawbacks of smart meters are the installation costs of the device and the required communication infrastructure. Privacy and data protection are also issues since precise consumption data is transmitted electronically.

Smart metering and the resulting awareness of energy consumption, together with likely price increases due to a boost in renewables and rising oil prices could encourage people to alter their energy consumption. In the field study MeRegio[4] households so far reacted to price signals by not only shifting their consumption to other times of the day but also by reducing their daily consumption.(Lutz Hillemacher 2011) E-Control commissioned Pricewaterhouse-Coopers to analyze the effects a large-scale introduction of smart meters would have in

[4] MeRegio is smart grids field study conducted in Baden-Württemberg, Germany. It is part of the E-Energy Project.

Austria. The results predict energy savings and a positive net benefit. (PricewaterhouseCoopers 2010)

2.3.2. The role of electric vehicles

If the amount of electric vehicles on the roads approaches 100.000, charging their batteries will become a major issue. The energy used and the power required for charging is much higher than that of mainstream consumer devices. This poses severe challenges for (distribution) power grids. However, it entails unique opportunities since DSM can be applied to electric vehicles. The most primitive way to charge an EV is to simply plug it in and let it charge. A smarter option is the practice of managed charging. This way, EVs could be used as controllable load and help to flatten the demand curve or provide ancillary services to the electricity system. Ideally EVs would be connected to chargers, may it be wireless or not, for most of the time they are not used for driving. Actual charging though would only occur when it is suitable for the electricity system or necessary for the owner of the electric vehicle (OEV). This would not merely help to flatten the demand curve, it would also allow a further integration of DG, which is often of intermittent nature. The extent up to which this can be achieved heavily depends on the management of charging. In addition to physical requirements that need to be met, economic incentives are necessary in order to convince OEVs to participate. One could go even further and exploit the storage capacities of EVs in both ways. Instead of merely charging EVs as needed, they could also be discharged and thus provide further ancillary services to the electricity system. The idea and the practice of connecting EVs to the power grid in order to allow electricity to flow from the vehicle to the power lines is called “vehicle to grid” (V2G).(UoD 2009) Discharging batteries and injecting energy into the grid increases battery wear. V2G is therefore not covered in this work.

A high penetration of EVs could challenge today’s grid infrastructure as it implies an increase in total load. The additional burden will depend on the number of EVs and on the charging behaviour.

3. Database

The database of the model comprises the following:

- Load forecast
- Load deviation
- Prices
- Driving pattern
- Battery properties

If not stated otherwise data is of the year 2010 as this is the most recent year for which complete data is available. The grid area of Tyrol was not part of the control area of APG until the beginning of 2011 and is therefore not included in the database.(APG 2011c) Since the current penetration of EVs today is far too small to realize the business concept designed in this work, data of the year 2025 would have been preferable. Although predictions for electricity prices for the year 2025 were accessible, the idea was rejected because of missing predictions of load curves and especially load deviations. A description of the used database follows.

3.1. Load forecast

Day-ahead load forecasts were obtained from the website of APG AG.[5] The enterprise is the TSO of the by far larger one of the two control areas in Austria. Online day-ahead load forecasts for the control area are available from January 1st 2010 onwards. Load forecasts comprise the total consumption within the control area of APG and underlying public grids, the consumption of pump storage plants and grid losses.(APG 2011c) Data for three weeks of the year was chosen. Each week is in a different period. For all 7 days of the week the data is available in intervals of 15 minutes. For working days and for weekend days in all three weeks average values for every interval were calculated. This was achieved by building the mean of the power over all working days or weekend days in the specified week for each interval. Table 2 shows the dates from which load forecast values were taken. Typical load curves of winter and summer days can easily be told apart as those of summer days have one peak whereas those of winter days have two. The prepared load forecasts are shown in Figure 11.

Table 2: Dates chosen for load forecast and price data

	Winter	Transition period	Summer
Working days:	18/1/2010 – 22/1/2010	20/9/2010 – 24/9/2010	19/7/2010 – 24/7/2010
Weekend days:	23/1/2010 – 24/1/2010	25/9/2010 – 26/9/2010	24/7/2010 – 25/7/2010

[5] Source of load forecast data: APG AG, http://www.apg.at/de/markt/last/lastprognose

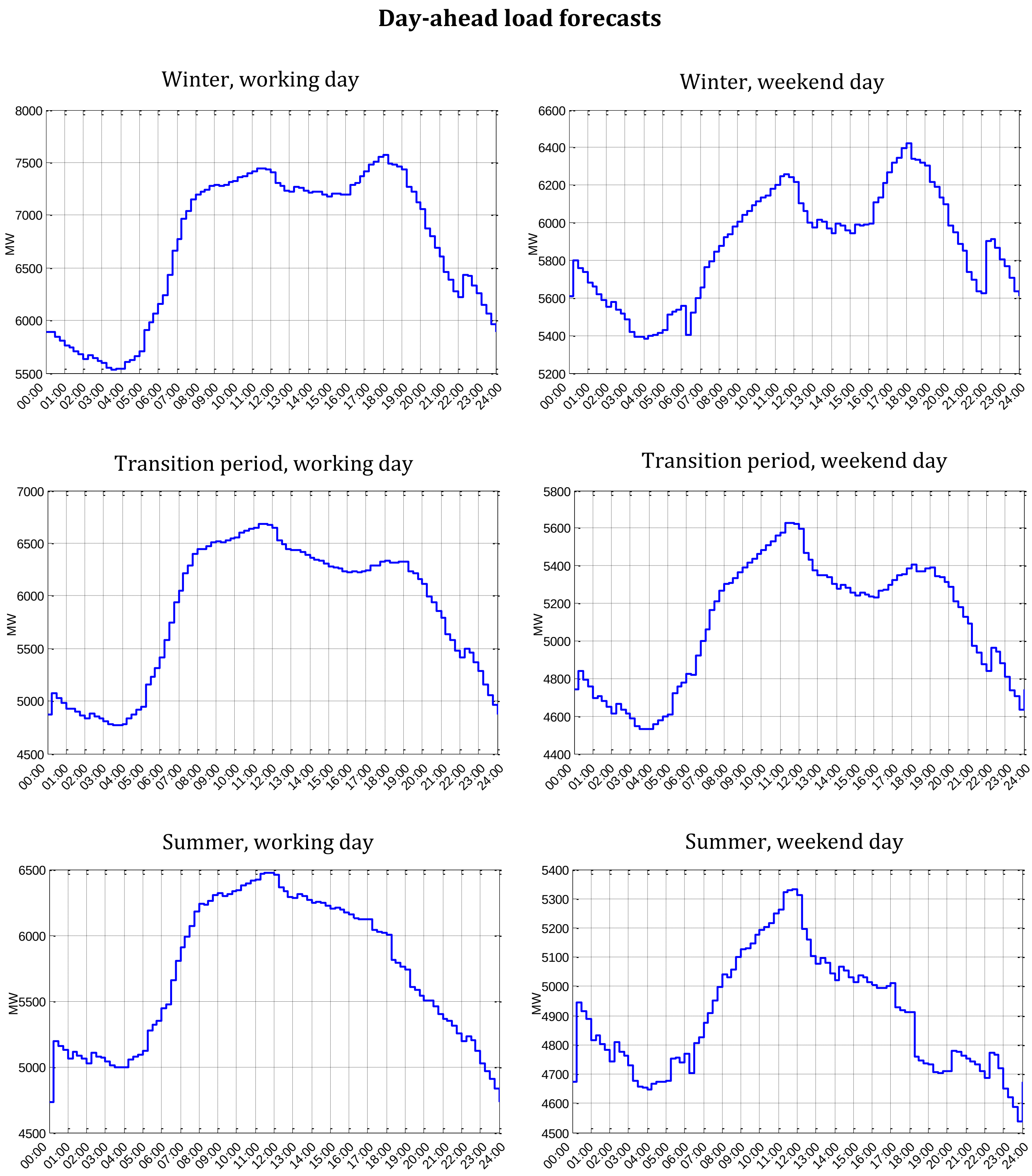

Figure 11: Load curves according to database (APG 2011c)

3.2. Load deviation

Load deviation is the sum of retrieved secondary control power, minute reserve and the unintended exchange of energy with other control areas of the synchronous are "Continental Europe".(APG 2011d) See Formula (3.1).

$$deviation = power_{secondary\ control} + power_{tertiary\ control} + power_{unintended\ exchange} \qquad (3.1)$$

An online database hosted on the TSO's website provides the data.[6] The delta of load within the control area is separated into total deviation and provided tertiary control power with a resolution of 15 minutes. The Matlab model requires the amount of provided minute reserve and provided secondary reserve. The latter is calculated by subtracting minute reserve from the total deviation. The unintended exchange of energy with other control areas in neglected. The sign of the values determines whether delivery or purchase is required to compensate the load deviation. The processing of data is similar to the one for load forecast. In the case of required secondary control energy median values were calculated. As tertiary control energy is retrieved very rarely, the median would be null. Therefore the values for minute reserve are obtained by calculating the mean for each interval. Working days and weekend days in different periods are looked at. Since fluctuations in load deviation are large in relative terms and significant for the output of the model, many sample days are used to compute average values. Table 3 shows the dates. The total load deviation is illustrated in Figure 12. A positive sign means that additional delivery is required. A negative sign means that load should be increased or generation decreased.

Table 3: Dates chosen for load deviation

	Winter	Transition period	Summer
Days:	1/11/2010 – 20/3/2010	21/3/2010 – 14/5/2010 15/9/2010 – 31/10/2010	15/5/2010 – 14/9/2010

3.2.1. Secondary control

As told in section 2.2.2, secondary control services are currently provided by a single enterprise. The compensation for retrieved secondary control energy compromises compensation in kind and a monetary one.

The procurement of energy is financially compensated. Since the respective contract is not made public costs are not available. For the model it is assumed that the price for procurement of secondary control power is the same as the one for tertiary control power (market maker option). Prices for delivery and purchase differ and vary over the year. It shall be referred to section 3.2.2.

The costs of retrieval are determined by the compensation programs. The costs and revenues resulting from the auctions for compensation programs are available on the website of the

[6] Source of load deviation data: APG AG, http://www.apg.at/de/markt/netzregelung/deltaregelzone

CSA, APCS AG.[7] Prices for secondary control energy for delivery and purchase are computed separately by building averages over several months for the periods winter, summer and transition period. The respective months are listed in Table 4.

Table 4: Months from which data for secondary compensation program is taken

	Winter	Transition period	Summer
Months:	January, February, November, December	April, October	June, July, August

3.2.2. Tertiary control

The costs that result the CSA from market maker auctions are accessible on his website.[8] The price for the procurement of minute reserve in the model is obtained by calculating average costs for each season. The selected dates are listed in Table 5.

The retrieval of tertiary control energy is compensated by an exchange in kind as explained in section 2.2.2.

Table 5: Dates from which data for minute reserve costs is taken

	Winter	Transition period	Summer
Days:	18/1/2010 – 14/3/2010 8/11/2010 – 31/12/2010	29/3/2010 – 9/5/2010 20/9/2010 – 31/10/2010	17/5/2010 – 11/7/2010 19/7/2010 – 12/9/2010

[7] Source of costs of compensation programs: APCS AG, http://www.apcs.at/balance_energy_market/statistics/2010/index.html

[8] Source of prices for procurement of minute reserve: APCS AG, http://www.apcs.at/balance_energy_market/statistics/2010/index.html

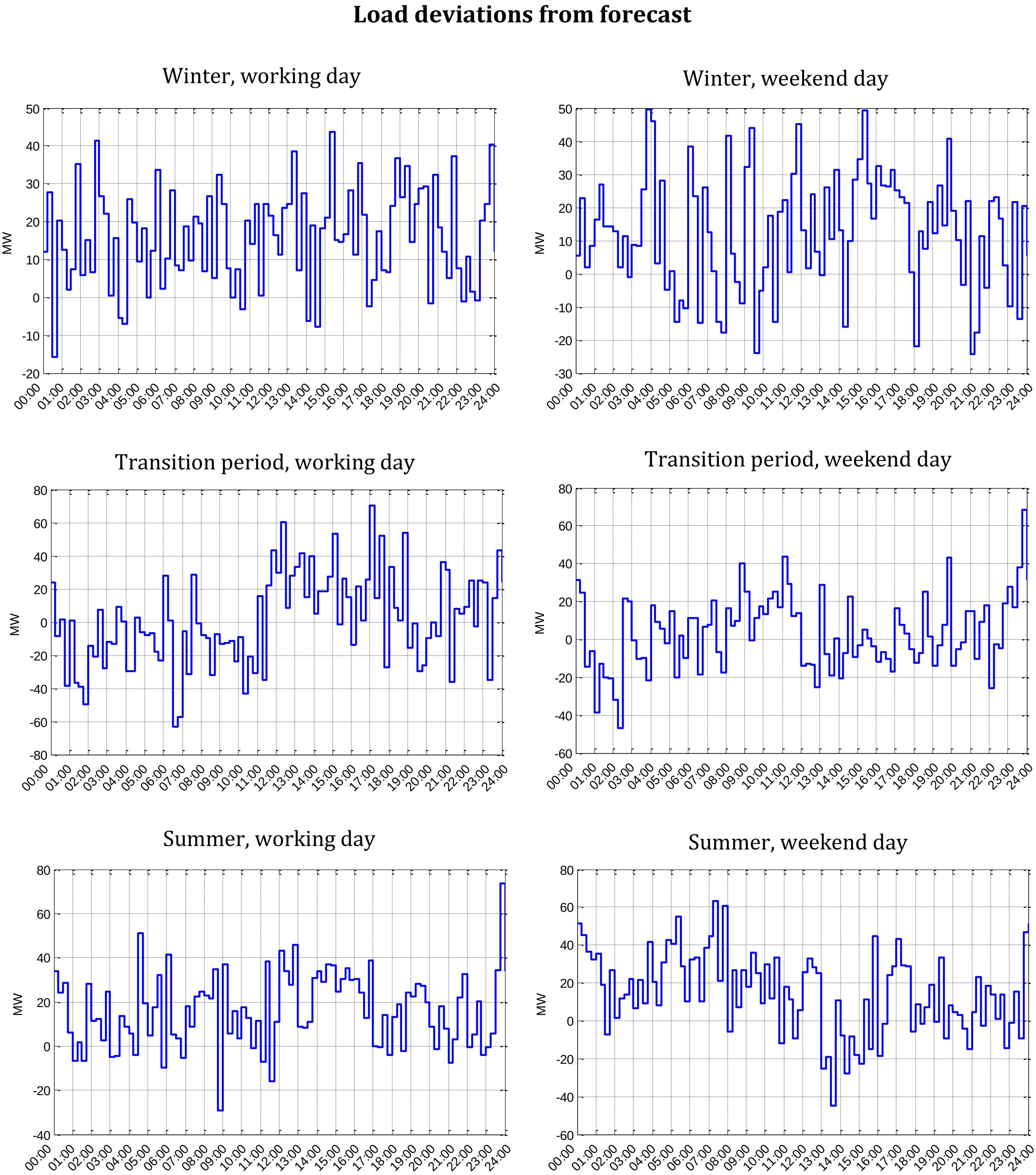

Figure 12: Load deviations from forecast (APG 2011d)

3.3. Prices

3.3.1. Spot market

Spot prices were obtained from the website of the Austrian energy exchange EXAA AG.[9] These spot prices are the day-ahead prices for (electric) energy in the German-Austrian supply area. As described in section 2.2.1, the most part of energy is traded outside official exchanges. In a functioning market, prices converge towards the spot prices. The majority of energy is therefore not bought at spot prices. Since prices of (bilateral) futures and forward contracts are not published, spot prices are used as database in this work. As time-based pricing is a key element of smart grids, the most detailed price information available was chosen, i.e. instead of using the prices of base and peak load products, the finest resolution was chosen.

Table 6 shows the product names of the respective time intervals. Average spot prices for working days and weekend days for winter, transition period and summer are computed. This is done by building the mean of the respective periods of the dates listed in Table 2. The resulting price curves are shown in Figure 14.

Table 6: Products on the spot market used in this work (EXAA 2010)

Product:	bEXAoff1	bEXAsun	bEXAearlyt	bEXAlunch	bEXAlatet	bEXAteatime	bEXAoff2
Time frame:	01^{00} - 05^{00}	05^{00} - 09^{00}	09^{00} – 11^{00}	11^{00} –15^{00}	15^{00} – 17^{00}	17^{00} - 21^{00}	21^{00} - 01^{00}

3.3.2. Aggregator markup

The energy component of the electricity price paid by OEVs consists of the energy price paid by the aggregator and the markup applied by the aggregator. See Formula (3.2).

$$p_{energy,\,OEV} = p_{energy,\,aggregator} + markup_{aggregator} \tag{3.2}$$

The markup of an aggregator is assumed to be similar to the one of suppliers. In order to obtain a concrete value for the markup, a supplier whose energy prices are in the middle field according to E-Control's price monitor was examined.(E-Control 2011d) Salzburg AG which offers an energy price of 7.085 c/kWh to households with an annual consumption between 1 000 and 5 000 kWh was chosen.(Salzburg 2011) Based on the data described in section 3.3.1 the average spot price of the year 2010 was calculated to be 4.4817 c/kWh. The resulting markup of 2.603 c/kWh is calculated according to Formula (3.3). This value is used in the model as markup of the aggregator.

$$markup_{aggregator} = markup_{supplier} = p_{energy,\,end-user} - p_{energy,\,supplier} \tag{3.3}$$

[9] Source of spot price data: EXAA AG, http://exaa.at/market/historical/austria_germany

3.3.3. Electricity price

The electricity price paid by OEVs (and other end-users) comprises not only the end-user price of energy as shown in Figure 8. It is therefore significantly higher than the price charged by the aggregator. The difference between the price charged by the aggregator and the actual price that has to be paid by the OEV is calculated by using the percentage values shown in Figure 8. These are taken from the website of the regulatory authority E-Control.[10]

3.4. Driving pattern

The data needed for calculating a driving pattern was provided by Herry Consult GmbH[11], an Austrian bureau for traffic planning. The resolution of the original data was 1 minute. Since the load forecasts and load deviations are given in intervals of 15 minutes, the resolution of the driving pattern was also reduced to intervals of 15 minute. The provided data was normalized by using the input parameter "maximum share of EVs driving at once". The parameter is explained later (see section 4.2.1). The resulting curve can be seen in Figure 13 and comprises data from multiple sources (see section 4.2.3). It shows the share of EVs that is driving in each interval.

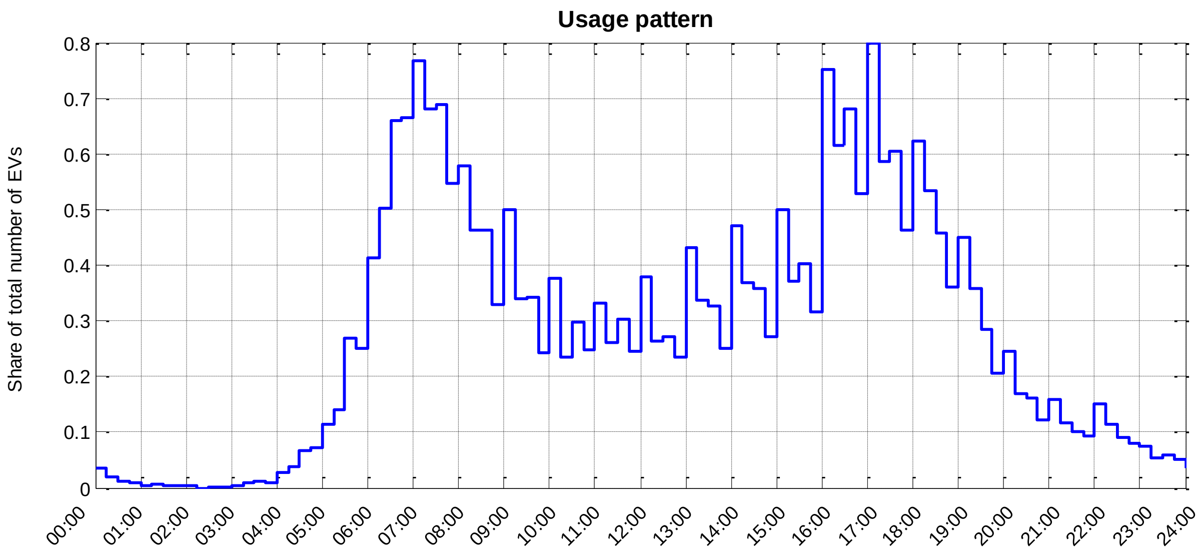

Figure 13: Driving pattern, parameter maximum share of EVs driving at once = 80 %

[10] Source of price composition: E-Control GmbH, http://www.e-control.at/en/consumers/electricity/electricy-prices/price-composition

[11] Source of data required for generating a driving pattern: Herry Consult GmbH, http://www.herry.at

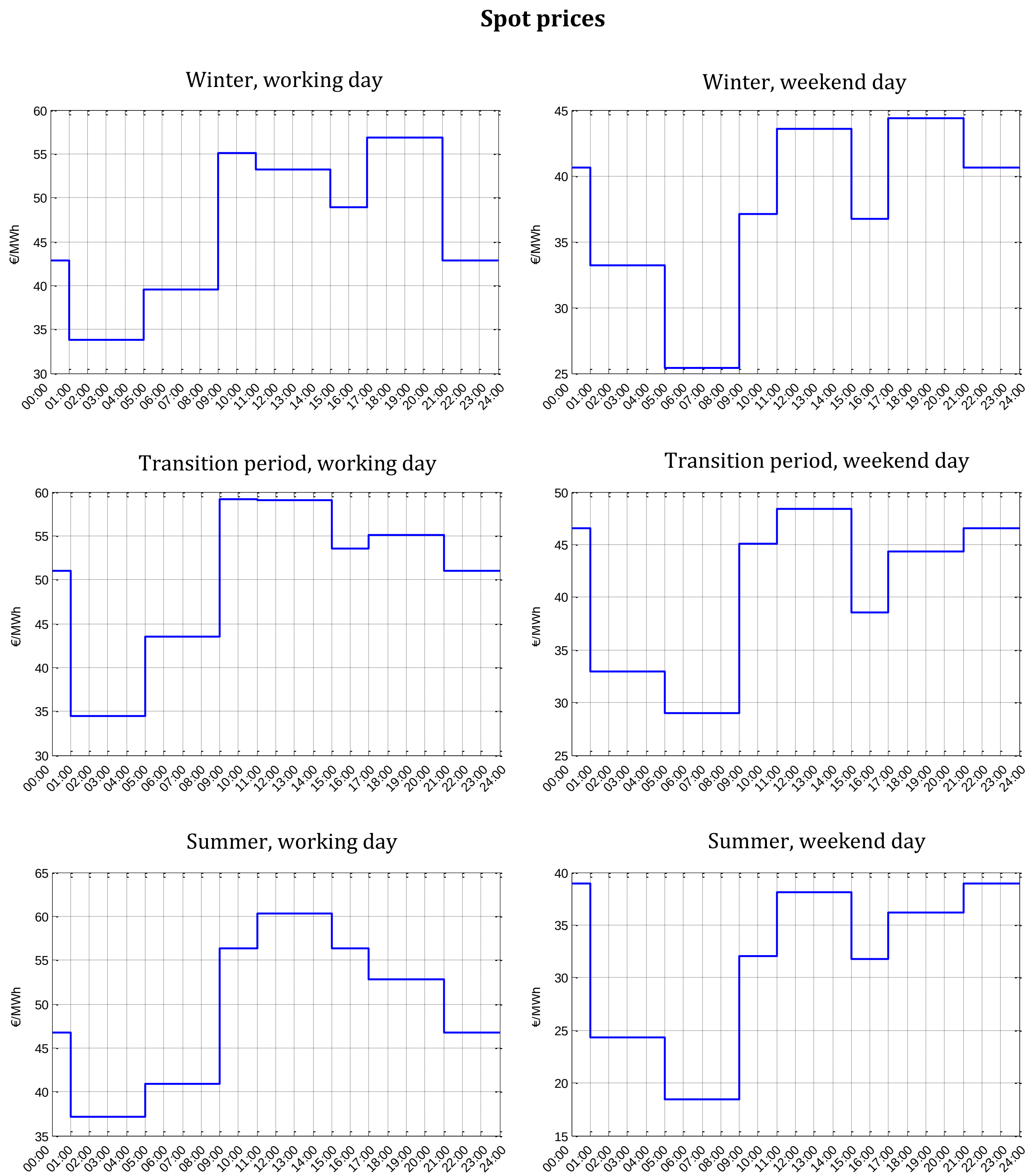

Figure 14: Average day-ahead spot prices of the year 2010 (EXAA 2010)

3.5. Parameters

Technical data was taken from the Nissan Leaf. The Leaf is a mid-size electric car produced by the Japanese car manufacturer Nissan. It's introduction to Europe started in 2011.(Haug 2011) The technical data of the car, except for the driving range, was obtained from a fact sheet that is available on the manufacturer's homepage.

Charging rate
The vehicle hosts a lithium-ion battery with a capacity of 24 kWh. The onboard charger permits a charging rate of 3.3 kW (Nissan 2010). This is also the charging rate used as input for the Matlab model. See section 4.2.1.

Battery capacity
The capacity used for calculations is lower than the one specified in the fact sheet. In order to consider the aging of batteries and the fact that an EV fleet will comprise not only new but also old vehicles, it is assumed that the average battery capacity is only 75 % of the original capacity. The idea behind this assumption is that people are likely to switch to a new battery when the capacity falls below 50 % of its nominal value. The aging of lithium-based batteries depends on the depth of discharge. They last longer the smaller the depth of discharge is.(Buchmann 2010) Keeping this in mind, the aggregator is assumed to exploit only 80 % of the battery's capacity. The value used for the input parameter capacity is therefore calculated in line with Formula (3.4).

$$battery\ capacity_{parameter} = 75\ \% \cdot 80\ \% \cdot battery\ capacity_{new\ vehicle} = 14.4\ kWh \qquad (3.4)$$

Driving range
The values for the driving range of the Nissan Leaf vary depending on the source. Nissan claims the range to be 100 miles.(Nissan 2010) According to the United States Environmental Protection Agency it is 117 km.(GCC 2010) Taking into account the aging of vehicles in the fleet, the average driving range is reduced to 75 %. This is the same factor applied in calculating the relevant value for the parameter battery capacity. The input parameter is therefore obtained using Formula (3.5).

$$driving\ range_{parameter} = 75\ \% \cdot driving\ range_{new\ vehicle} = 87.75\ km \qquad (3.5)$$

Daily driven distance
The average distance travelled by an EV per day could not be found in literature as such. It was calculated according to Formula (3.6) using values from different statistics.

$$distance_{daily\ driven} = \frac{ways_{per\ day} \cdot length_{way} \cdot persons_{per\ household}}{cars_{per\ household}} = 37.68\ km \qquad (3.6)$$

$ways_{per\ day}$ ... *average number of ways travelled by passenger car per day*

$length_{way}$ ... *average length of a way travelled by passenger car*

$persons_{per\ household}$ ... *average number of persons in a household*

$cars_{per\ household}$ ... $average\ number\ of\ passenger\ cars\ per\ household$

Since some of these values were not available for the whole of Austria, the biggest province, Lower Austria, was looked at. According to a reliable source (made anonymous by request), an average inhabitant of Lower Austria covers 1.5 passenger car ways per day. In 2008 the average distance of a passenger car way in Lower Austria was 15.7 km.(NÖ 2008) In the same year, on average 2.4 persons lived in a household in Lower Austria.(Statistik Austria 2009) The average daily driven distance is therefore 37.68 km.

Auctioned amounts of control power

The TSO determines the amount of control power that has to be procured. The values may differ between purchase and delivery. For the aggregator purchase means that in case of retrieval he has to increase the load by increasing the charging. Retrieval of delivery implies that he has to reduce the load by reducing the charging. The latter requires him to procure this control power by charging in each interval in which he participates in the procurement of control power. Otherwise he would not be able to reduce the charged amount in the requested interval. Table 7 lists the amounts of control power that have to be procured in the year 2011.

Table 7: Amount of control power to be procured (2011)

	Secondary control power (Kronberger 2003)		Tertiary control power (APCS 2010b)	
Type of control power:	Delivery	Purchase	Delivery	Purchase
Amount to be procured:	180 MW	180 MW	100 MW	125 MW

4. Methodology

First, the electricity market is analyzed. The focus lies on the structure of the current electricity market. Stakeholders are identified and their interactions are looked at. Regulatory and government authorities such as E-Control are the main source of information. Understanding the electricity market is essential for the next step.

A business concept is designed in order to establish a framework under which the widespread integration of EVs in the electricity market can take place. An aggregator functions as a mediator between the OEVs and other stakeholders in the electricity market. The previously conducted analysis of the market structure is necessary to identify where to place the aggregator in the electricity market. The aggregator, which may be some new enterprise or a spin-off of an electricity undertaking or telecommunication undertaking, offers his services to OEVs.

Next, business models are constructed. They based on the business concept and determine the control services provided by the aggregator. Further, they should create incentives for OEVs to participate in the electricity market. Four different business models which vary in their participation in the markets for control services are created.

For the business models designed in the previous step a Matlab model, consisting of functions that compute the revenues achieved by involved stakeholders, is derived. The model is used to study the economic effects business models have on the aggregator, OEVs and producers in terms of stakeholders.

Scenarios are drafted and used to analyze and interpret the effects business models have on market participants and the electricity system. Conclusions about the financial attractiveness of business models are drawn.

4.1. Framework

If not stated otherwise, the situation in Austria is described. It is important to note this, as electricity markets are immensely influenced and regulated by national policy.

As of today, the number of EVs on the roads is insignificant. Business models derived in this work require large fleets of EVs to be effective. The business concept and business models described are designed for a future situation which might be present by the year 2025.

4.2. Matlab Model

The created Matlab model implements four different business models:

- Business model A: The aggregator controls the charging of the EV fleet by ensuring that charging takes place when spot prices are the lowest. He does not provide ancillary services to the TSO.

- Business model B: The aggregator participates in the market for tertiary control. The share of tertiary control power he tries to provide is determined by the input parameter “tertiary procurement share” (see section 4.2.1). Apart from the procurement of tertiary control power, he charges when spot prices are low.

- Business model C: The aggregator participates in the market for secondary control. The share of secondary control power he tries to provide is determined by the input parameter “secondary procurement share” (see section 4.2.1). Apart from the procurement of secondary control power, he charges when spot prices are low.

- Business model D: This business model is a combination of model B and model C. The aggregator participates in both, the market for secondary control and the market for tertiary control. The aimed share of his contribution on the total required amount is determined by the input parameters “secondary procurement share” and “tertiary procurement share”. The priority lies on the provision of secondary control services because revenues generated here are generally higher than those generated in tertiary control services (see chapter 6). Hence procurement of tertiary control power only occurs, when the desired secondary procurement share could be reached.

A depiction of the model including the parameter groups is shown in Figure 15. All parameters used in the calculations can be modified using a GUI (graphical user interface). The database can also be changed by selecting different files to read the data from. The respective GUI is shown in Figure 74. A screenshot of all GUIs is illustrated in Figure 76.

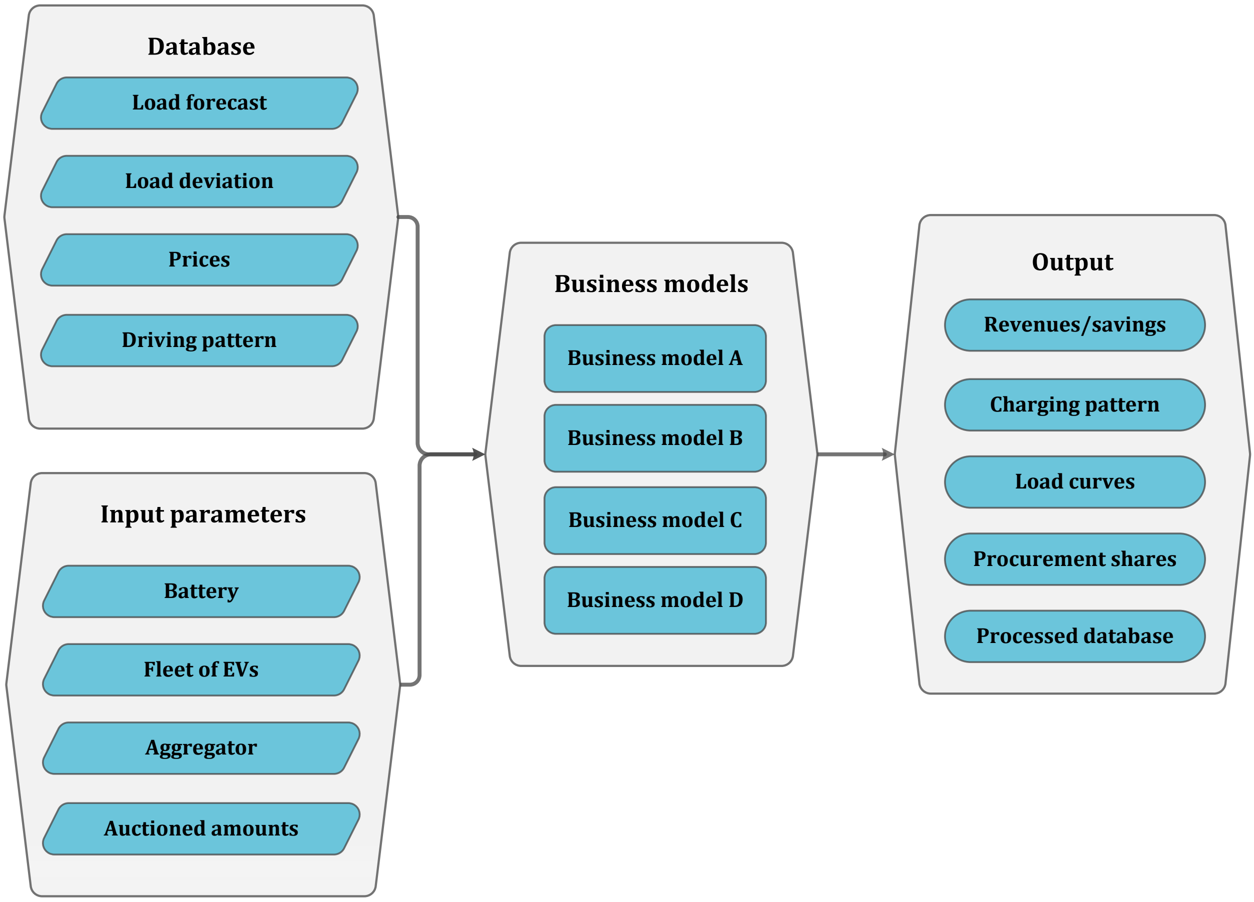

Figure 15: Structure of the Matlab model

4.2.1. Parameters

The parameters are grouped into four categories. A screenshot with all parameters and their default values is shown in Figure 73. The parameters are explained now.

Battery

"Capacity" shall mean the average share of the capacity that can be fully exploited. In order to maintain a certain lifetime of Li-Ion batteries, it is often advised not to fully discharge a battery. If the SOC (state of charge) should not be lower than x % at any time, then the actual battery capacity of an EV needs to be multiplied by 1 – x / 100 to obtain the value of the parameter "capacity".

"Maximum charging rate" shall mean the maximum charging rate available on average. The availability of charging stations and limitations in the charging rate they permit need to be considered as well. Standard household connections in Austria provide a power of 3.68 kW (230V · 16A). The maximum charging rate allowed by an EV is therefore not necessarily the relevant value for this parameter.

"Initial state of charge" determines the state of charge at midnight of each day. Due to the algorithms used in this model, the state of charge at 00:00 o'clock is the same for every day.

The parameter restricts charging possibilities and influences the results. However, the parameter can be chosen by the aggregator who will try to maximize his earnings. Sensitivity analyses for individual business models show that the influence of the initial state of charge is insignificant within a broad range. (See subchapter 5.3.)

Fleet of electric vehicles

"Number of electric vehicles" shall mean the total number of EVs, whose charging is controlled by the aggregator.

"Daily driven distance" is the average daily travelled distance of a car of the EV fleet.

"Driving range" is the average range an EV can travel when using the full capacity of its battery. Due to aging of the battery, battery capacity and driving range of a single EV will decrease over time. When choosing a value for this parameter, the age structure of the EV fleet must be taken into account.

"Plug-in factor" determines the average share of time a parked EV is connected to the power grid. Parked EVs can only be charged or used for the provision of ancillary services when they are plugged in. No values for the plug-in factor could be found in literature. The value is assumed to be 70 %. Sensitivity analyses are conducted to show the influence this parameter has on the results of the model.

"Maximum share of EVs driving at once" determines how many EVs are maximally driving at the same time. This parameter is used to normalize the driving pattern. It may also be used to consider that not all EVs of the fleet are used every day. No relevant values for this parameter could be found in literature. The value is assumed to be 80 %. Sensitivity analyses are conducted to examine the parameter's influence on the financial situation of the market participants.

Aggregator

"Secondary procurement share" is the desired quotient of secondary control provided by the aggregator and the total amount of required secondary control power (auctioned amount). Depending on other parameters, the aggregator might not have the capacities to reach the desired procurement share. The model calculates the actual procurement share which is smaller or equal to the desired one. The actual procurement share is the same as the share of secondary control energy provided by the aggregator to the amount of required secondary control energy. The reason is that in order to assure that balancing energy can be provided if requested it needs to be procured. The parameter is only relevant for those business models that allow participation in the market for secondary control services.

"Tertiary procurement share" is analogous to the previous parameter the desired quotient of tertiary control procured by the aggregator and the total amount of required tertiary control power (auctioned amount). It is only relevant for business models that allow participation in the market for tertiary control services.

"Smoothing factor" is used to smooth the charging pattern of EVs. The model computes a charging rate for each interval by considering the driving pattern, plug-in factor and the maximum charging rate. The smoothing factor reduces this charging rate by ensuring that a full charge of the battery would last at least the amount of hours assigned to this parameter.

Auctioned amount

"Secondary control power" shall mean the amounts requested by the CAM to be procured for secondary control services. Two amounts are auctioned, one for delivery (increasing generation or decreasing load) and one for purchase (reducing generation or increasing load). These parameters are only relevant for business models that allow the provision of secondary control services.

"Tertiary control power" shall mean the amounts requested by the CAM to be procured for tertiary control services. These parameters are only relevant for business models that allow the provision of tertiary control services.

4.2.2. Procedure of calculations

The finest resolution for which the CSA calculates prices and balancing energy is 15 minutes.(APCS 2011e) Consequently this is also the finest resolution used in the model. Calculations are executed for each 15 minute interval of the day. In order to reduce the processing time required by computers to run the model, average data values for specified days are used. For details about the utilization of mean and median methods see chapter 3. The calculations are executed for two representative days (working day and weekend day) in each period. The periods are winter, transition period and summer (see Table 8). Figure 16 illustrates the scheme.

Table 8: Periods of the year 2010

	Winter	Transition period	Summer
Dates:	1/1/2010 – 20/3/2010 1/11/2010 – 31/12/2010	21/3/2010 – 14/5/2010 15/9/2010 – 31/10/2010	15/5/2010 – 14/9/2010

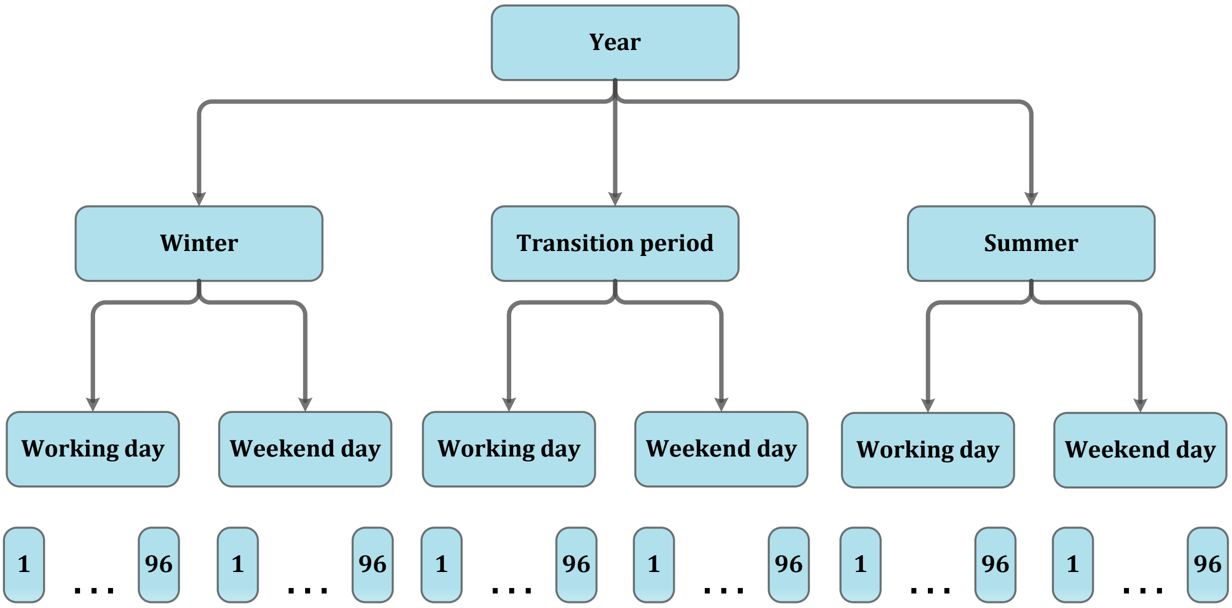

Figure 16: Calculations are performed for each 15 minute interval of selected days

4.2.3. Implementation of functions and business models

When the Matlab model is started, the main GUI (see Figure 75) opens. It allows selecting the database and changing parameters by pressing buttons that open the respective GUIs. The model is started by clicking "Calculate". The database is loaded and all parameters and variables are initialized. This step is only executed when the button is pressed the first time. If parameters are changed later on, the database is not reloaded. Next, the function "Calculation" is run. This function executes all other functions required to obtain the output of the model. The impacts of all four business models are computed in a single run of this function. The order in which calculations are executed is depicted in Figure 17.

Calculation of driving pattern, parking pattern and plug-in pattern

The database (see subchapter 3.4) together with the parameter "maximum share of EVs driving at once" (see section 4.2.1) and "daily driven distance" (see section 4.2.1) is used to obtain a driving pattern which describes how many EVs are driving in each 15 minute interval.

The data was given in accumulated amounts of driven kilometres for each minute of a day for 3,797 cars. In the first step the data was converted to a time resolution of 15 minutes.

$$pattern_{cumulated}(t) = data(15 \cdot t) \quad , \forall\, t > 1 \tag{4.1}$$

Next the difference in the accumulated amount between two intervals is calculated to determine the driven distance in each interval. The treatment of the first interval is different since no subtraction is required.

$$pattern_{delta}(t) = pattern_{cumulated}(t) - pattern_{cumulated}(t-1) \quad , \forall\, t \geq 2 \tag{4.2}$$

In order to obtain the absolute values of driven kilometres per day by a single car, each element of the vector has to be divided by the amount of cars studied in the survey.

$$pattern_{absolute}(t) = \frac{pattern_{delta}(t)}{number\ of\ cars} \quad , \forall\, t \tag{4.3}$$

This vector still contains absolute values. It is normalized by dividing by its maximum value and multiplying with the parameter "maximum share of EVs driving at once".

$$pattern_{driving}(t) = \frac{pattern_{absolute}(t)}{maximum(\ pattern_{absolute}\ )} \cdot maximum\_driving\_at\_once \tag{4.4}$$

This way the maximum number of EVs driving in the same interval is defined by the input parameter.

The parking pattern describes how many EVs are parked in each 15 minute interval. It is computed according to Formula (4.5).

$$pattern_{parking}(t) = 1 - \ pattern_{driving}(t) \tag{4.5}$$

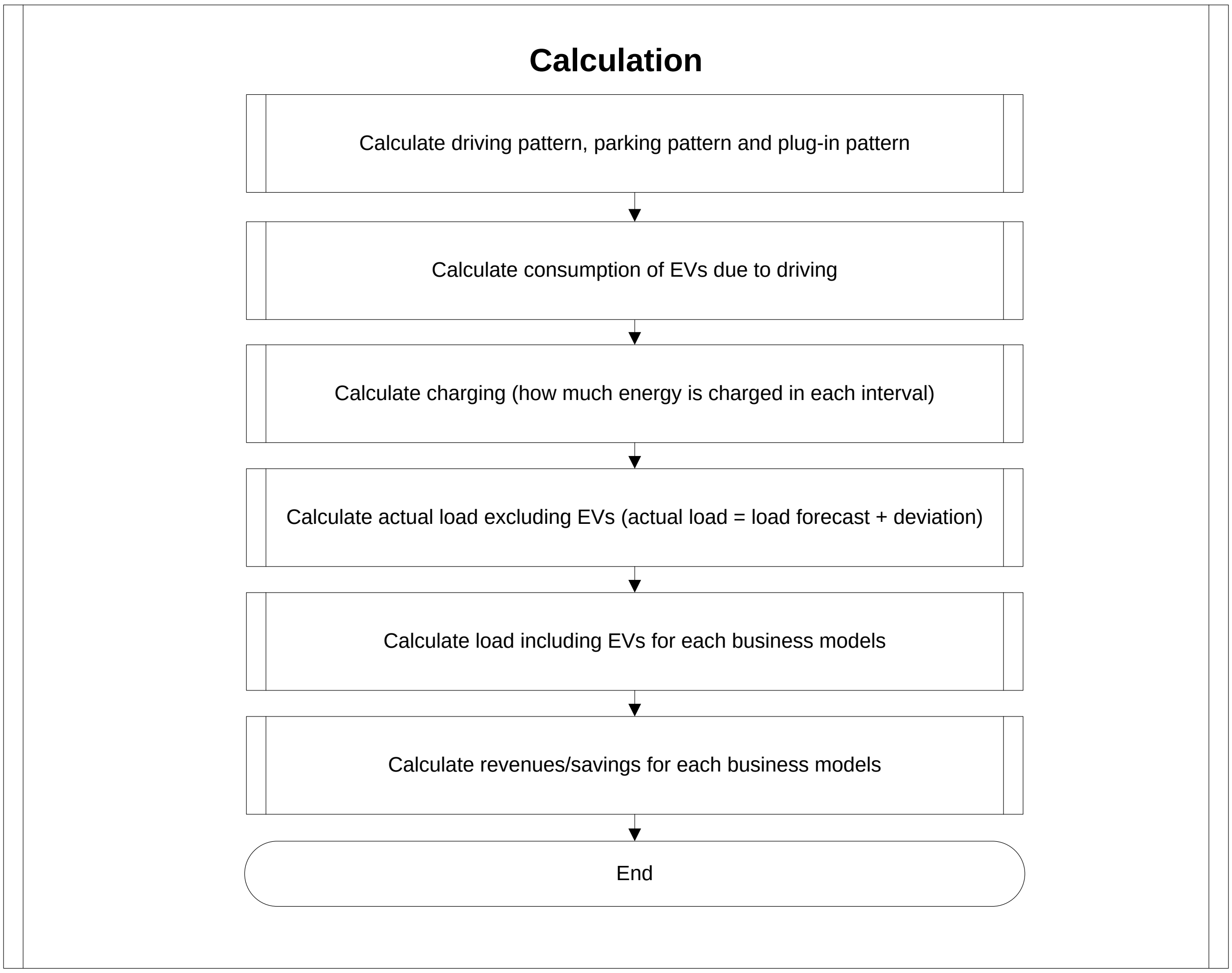

Figure 17: Depiction of the Matlab function "Calculation"

The plug-in pattern describes how many EVs are parked and plugged-in in each 15 minute interval of the day. The pattern is indexed with "available" as it determines the percentage of EVs available for charging. It is calculated according to Formula (4.6).

$$pattern_{available}(t) = plugin\ factor \cdot pattern_{parking}(t) \tag{4.6}$$

Calculate consumption of EVs due to driving

The energy consumption in each 15 minute interval is obtained by the use of Formula (4.7).

$$EV\_consumption_{due\ to\ driving}(t) = \frac{pattern_{driving}(t)}{maximum(\ pattern_{driving}\ )} \cdot EV\_consumption_{daily} \tag{4.7}$$

Based on the number of EVs in the scenario and the specific energy consumption the daily consumption was computed according to Formula (4.8). The specific energy consumption is the quotient of the parameters "driving range" (see subchapter 3.5) and "battery capacity" (see subchapter 3.5). For this calculation the full capacity of the battery is used.

$$EV\_consumption_{daily} = distance_{daily\ driven} \cdot number_{EVs} \cdot consumption_{specific} \tag{4.8}$$

Calculation of charging

The calculation of a charging pattern is the key function of the model. The corresponding illustration is shown in Figure 18. The output includes forecasted and actual charging patterns for each day and all four business models. Forecasted charging patterns consider the procurement of control services where applicable. Actual charging patterns consider not only the procurement but also the provision of control energy and can therefore differ significantly from forecasted ones. All of the following procedures are executed for a working day and a weekend day of each season.

The maximum chargeable amount of energy is calculated for each 15 minute interval. The amount is restricted by the percentage of EVs connected to the power grid, the total number of EVs and the input parameter "maximum charging rate" (see section 4.2.1). The factor 0.25 is necessary to convert the charging rate which is given in MW to energy (MWh) maximally charged in each quarter of an hour interval.

$$chargeable_{max}(t) = pattern_{available}(t) \cdot number_{EVs} \cdot 0.25 \cdot maximum\ charging\ rate \tag{4.9}$$

Next, the physically possible maximum chargeable amount of energy in each interval is modified using the input parameter "smoothing factor" (see section 4.2.1). The parameter is internally called "full load hours" which reflects its meaning. A maximum chargeable amount of energy per interval is defined so that the time in hours required for charging the battery from 0 % to 100 % equals the number stored in the variable "full load hours". This amount is used as upper limit for the maximum chargeable amount calculated in Formula (4.9). It is computed according to Formula (4.10). The factor 4 is needed to convert hours into 15 minute intervals. The division by 0.8 takes into account, that the parameter "battery capacity" is only 80 % of the true value of the battery capacity (see 3.5) since it is not the full capacity that is exploited.

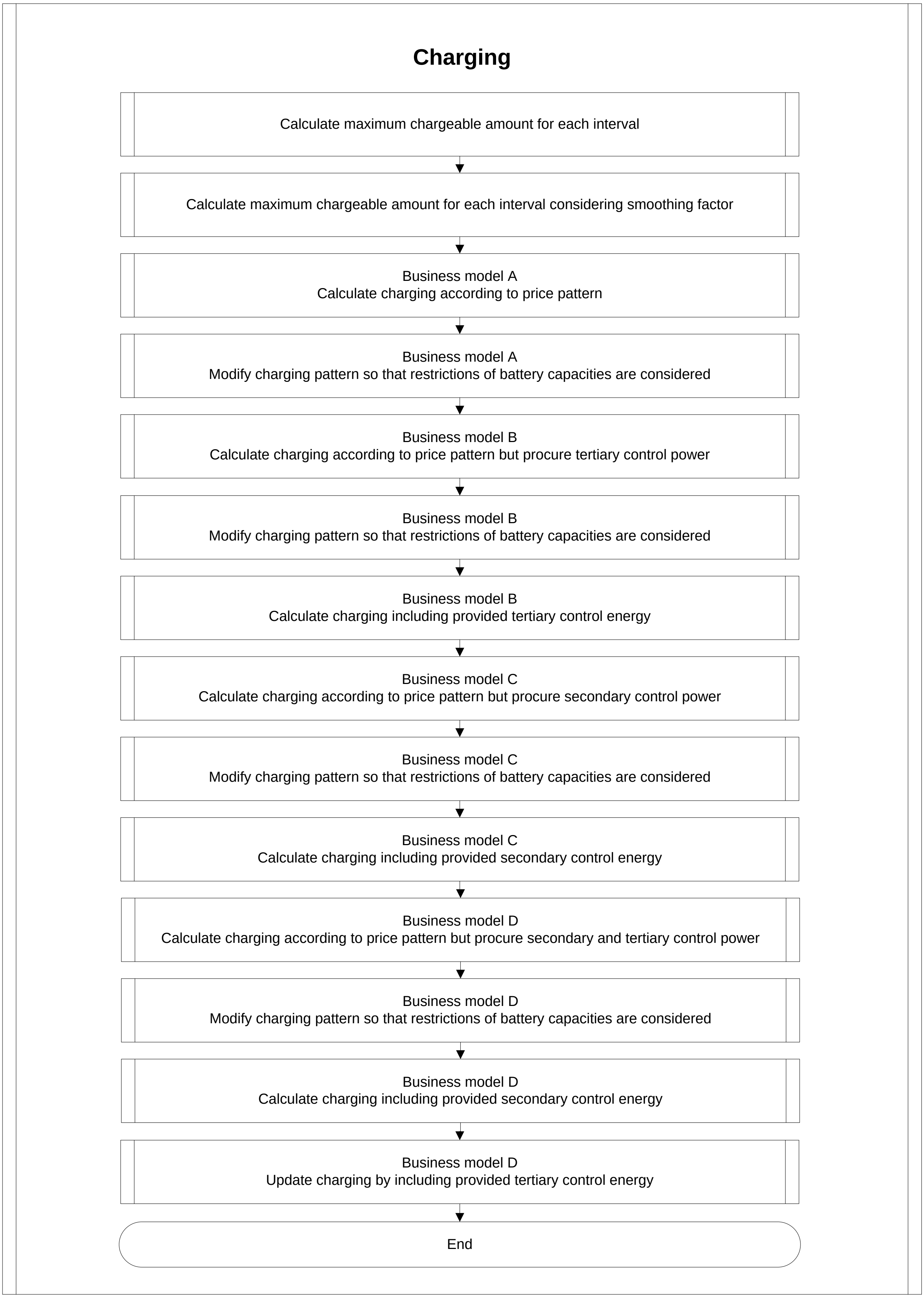

Figure 18: Depiction of the Matlab function which calculates a charging pattern

$$chargeable_{max,\,upper\ limit} = \frac{\frac{battery\ capacity}{0.8}}{4 \cdot full\ load\ hours} \tag{4.10}$$

The charging of business model A is calculated in two steps. First, the charging is calculated without taking into account the battery capacity. The procedure is illustrated in Figure 19. Secondly, the charging pattern attained before is modified considering the restrictions caused by the finite battery capacity. An illustration is shown in Figure 20. In this context the term battery capacity means the fully exploited capacity which is 80 % of the total capacity.

The charging of business model B is calculated in three steps. The first two are similar to the ones of business model A but differ in the procurement of control power that occurs in business model B. After these two steps the forecasted charging pattern is calculated. The retrieval of control energy is examined to obtain the actual charging pattern and the tertiary control energy provided by the aggregator and producer. The function that executes this last step is illustrated in Figure 21.

The procedure for business model C is analogous to that of business model B. The only distinction is that secondary instead of tertiary control power is procured.

The charging of business model D consists of four steps. In the first one the charging including the procurement of secondary and tertiary control power but disregarding battery capacities is calculated. Next the charging pattern is modified taking into account the restrictions caused by the battery capacities. Next, the retrieval of secondary control energy and tertiary control energy are computed.

Calculate actual load excluding EVs

The input data contains the information needed to calculate the forecasted load curve for the control area of APG (see subchapters 3.1 and 3.2). Further, it comprises the load deviations. Adding these two results in the actual load curve for the control area.

$$load_{excluding\ EVs,\,actual} = load_{excluding\ EVs,\,forecast} + load\ deviation \tag{4.11}$$

Calculate load including EVs

It needs to be distinguished between the forecasted and actual load curves including EVs. The load curves derived solely from the respective input data excluding EVs. The load curves including EVs can be obtained by adding the charging pattern to the load curve. The charging patters depend on the business model and scenario. Since actual charging can differ from the forecast one due to the provision of control energy, forecasted and actual charging patterns exist. The two load curves including EVs are computed according to Formula (4.12) and (4.13).

$$load_{including\ EVs,\,forecast} = load_{excluding\ EVs,\,forecast} + charging_{EVs,\,forecast} \tag{4.12}$$

$$load_{including\ EVs,\,actual} = load_{excluding\ EVs,\,actual} + charging_{EVs,\,actual} \tag{4.13}$$

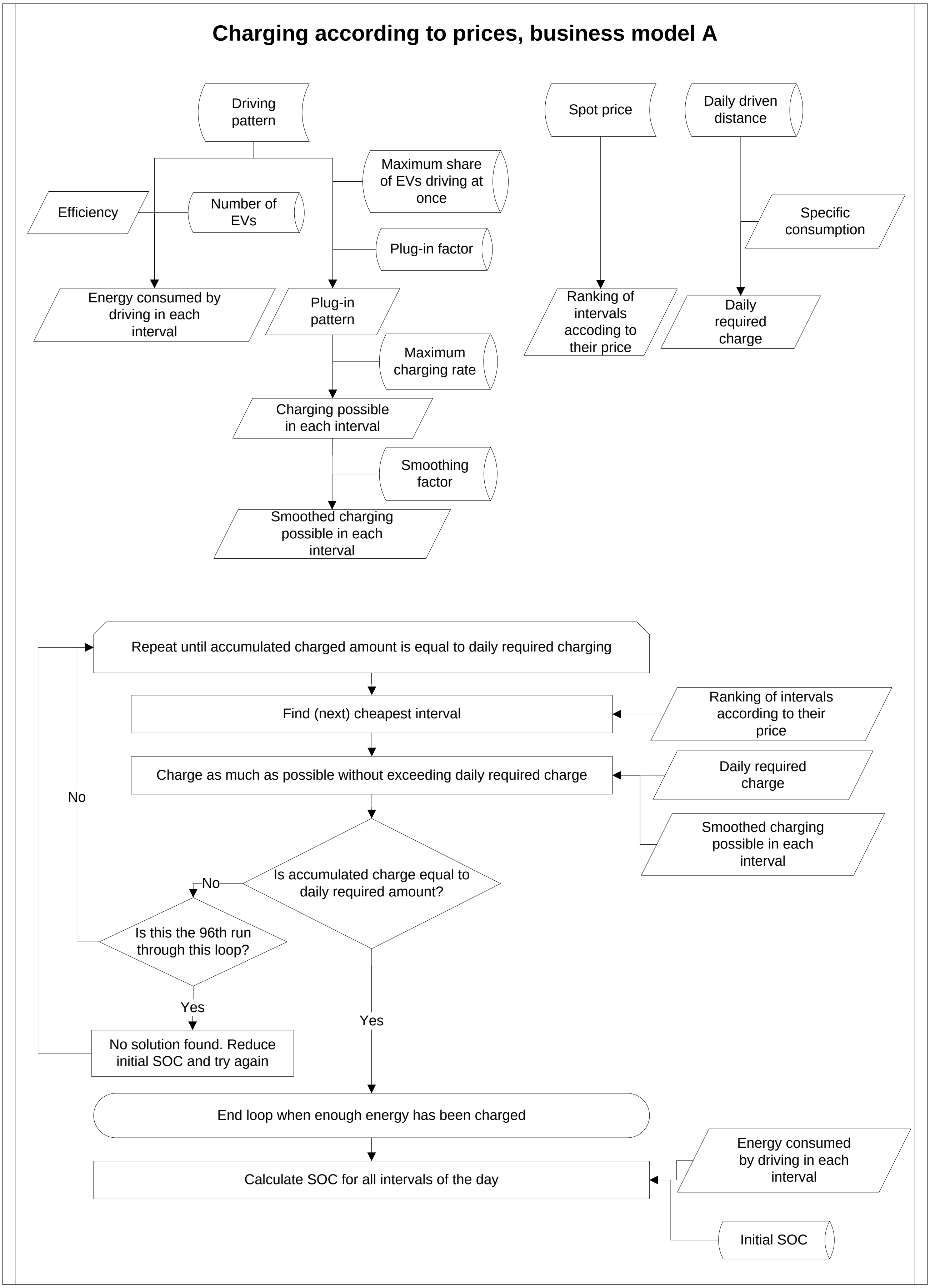

Figure 19: Charging of business model A, step 1/2

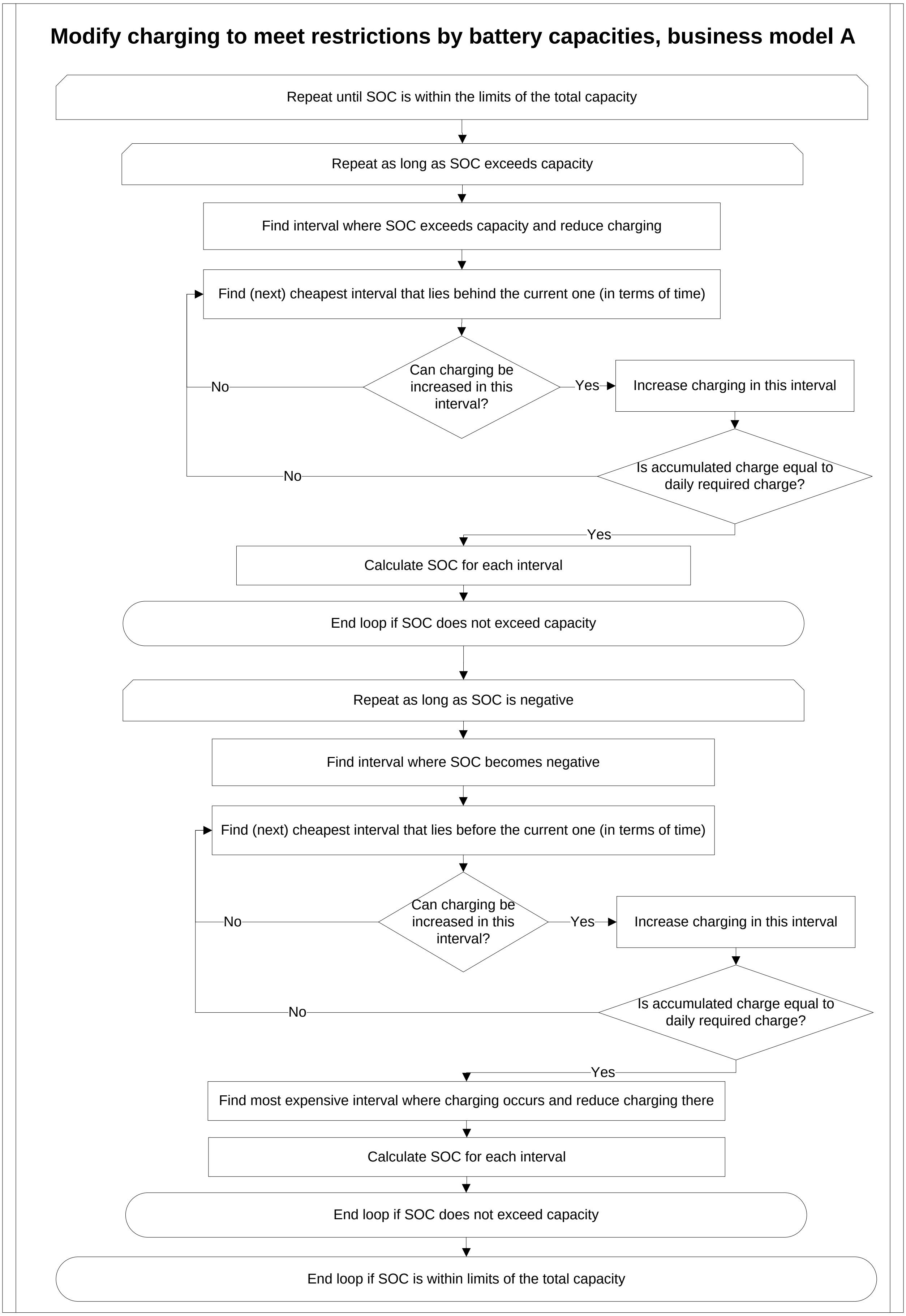

Figure 20: Charging of business model A, step 2/2

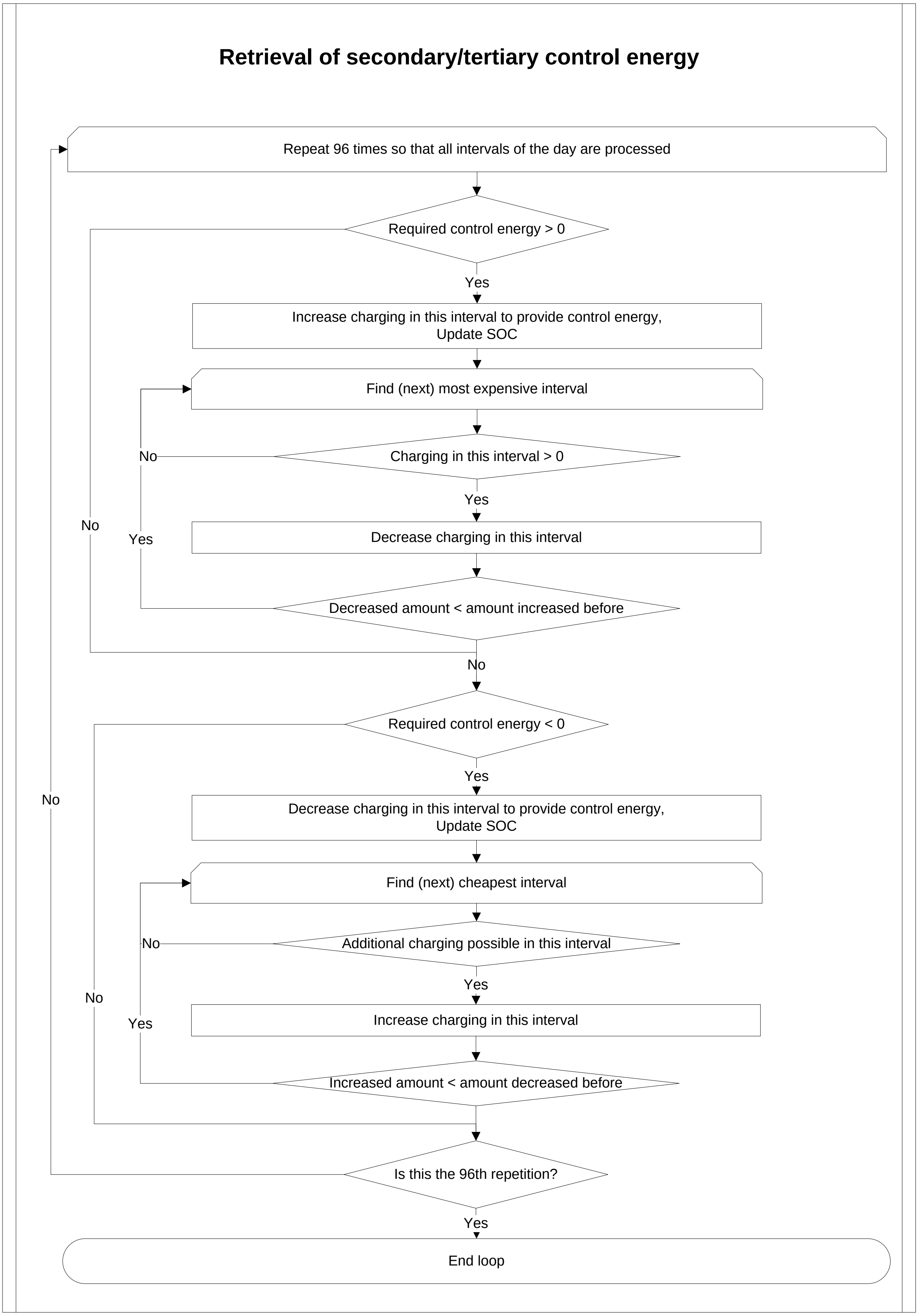

Figure 21: Charging including the retrieval of secondary/tertiary control energy

Calculate revenues/savings

In the first place, revenues or savings of the stakeholder groups of aggregators, producers and OEVs are calculated for the BAU (business-as-usual) scenario. The aggregator's revenue in a BAU scenario comprises only the winnings made by selling energy to OEVs. The savings achieved by OEVs are null since the BAU scenario is used as reference. The revenues of producers are determined by the provision of control services and the financial compensation going along with it.

Next, the revenues or earnings achieved in each business model are computed. The aggregator can generate profits by delivering energy or participating in the market for ancillary services. In the latter earnings are achieved by the procurement of control power and by the retrieval of control energy. Depending on the business model and the aggregator's preferences he can generate revenues in one or more of the fields shown in Figure 22.

The revenues of producers are generated by the provision of ancillary services. The fields in which a producer makes money are therefore similar to those of the aggregator. The amounts of required control power are determined by the database and therefore constant. This implies that the more control power is provided by the aggregator, the smaller is the share provided by the producer. The earnings of producers therefore shrink when the procurement share of the aggregator rises.

OEVs are likely to experience savings due to cost reductions attained by controlled charging.

The revenues generated in the BAU scenario are subtracted from the revenues achieved in the business models to obtain the financial effect a business model has on stakeholders. For each of the four business models the additional revenues/savings are calculated according to Formula (4.14).

$$revenues_{stakeholder\ X,\, delta} = revenues_{stakeholder\ X} - revenues_{stakeholder\ X,\, bau} \tag{4.14}$$

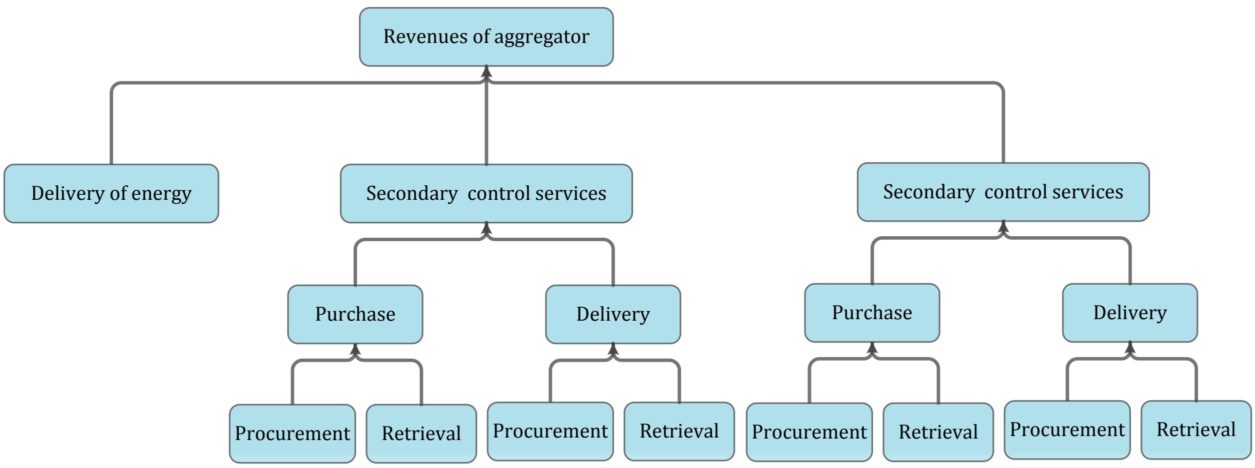

Figure 22: Fields in which an aggregator can generate revenues

4.2.4. Scenarios

In order to analyze the drafted business models A, B, C and D, scenarios are created. These vary in the number of EVs controlled by the aggregator (see Table 9). Three scenarios are used to simulate a growing penetration of EVs on the roads.

Table 9: Scenarios used to analyze business models

	Scenario I	Scenario II	Scenario III
Number of EVs:	100,000	500,000	1,000,000

For each of these three scenarios a reference scenario, the business-as-usual scenario exists. The BAU scenarios simulate uncontrolled charging. It is assumed that charging starts at 20:00 o'clock in the evening and lasts until the daily required energy is charged. Taking into account the driving pattern, plug-in factor and other relevant parameters, this takes 4.5 hours. Electricity prices vary not only with the time of day but also with the seasons. Nonetheless in all periods, one hour (20:00 – 21:00 o'clock) is subject to peak prices. The remaining 3.5 hours of charging fall into cheaper intervals but still not the cheapest intervals (see Figure 14). In the BAU scenario EVs do not contribute to the provision of ancillary services. The revenue of the aggregator is only generated by buying electricity at spot prices and selling it to OEVs. These revenues are determined by the aggregator's mark-up as described in section 3.3.2. The revenues of producers include all revenues generated by the provision and procurement of ancillary services for tertiary and secondary control. The costs (negative revenues) of OEVs are determined by the time of charging and the respective end-user prices (see section 3.3.3) for energy.

4.2.5. Assumptions

It is assumed that the aggregator buys electricity at spot prices. Hedging is not considered in the calculation of revenues.

All bids for tertiary control are made via the market maker. Consequently accepted bidders get paid not only for the retrieved control power but also for the procured control power.

The increase in supply in terms of providing ancillary services has no impact on the price of control services.

Producer and aggregator make bids only at the market price (see section 3.2.1 and section 3.2.2).

All bids of the aggregator are accepted, unless demand is exceeded. In other words the aggregator is privileged. The producer's bids are only accepted for the remaining required control power.

Aggregator and producer either provide a certain arbitrary amount of control power for the whole day (all 15 minute intervals) or not at all. They are not allowed to provide control power for only a few intervals of the day.

The charging rate is not limited by physical restrictions of the distribution grid.

4.2.6. Output

The output of the model comprises three elements that are relevant for the results. These are:

- Revenues/savings of affected stakeholders
- Procurement shares
- Charging patterns (forecasted and actual)

Furthermore, the input data is processed and can be displayed which helps to understand and explain certain changes in charging patterns.

Revenues/savings of affected stakeholders

The primary objective of the Matlab model is to calculate the financial effects that business models have on stakeholders. The market participants affected by the integration of EVs according to the business concept (see subchapter 5.1) are aggregators, OEVs and producers. Financial effects on these three groups of stakeholders are analyzed. The impact of a business model on the financial situation of one of these groups is determined by the change in revenues compared to the BAU scenario. This change in revenues defines the revenues/savings achievable by the application of the respective business model. It is now briefly explained why the business models have financial impacts on these three groups of stakeholders. The aggregator, who does not exist in the BAU scenario, generates revenues by selling energy to OEVs and by providing ancillary services, if applicable. By doing the latter, he absorbs revenues that previously went to the producer who provided the most part of ancillary services. The OEV experiences a cost reduction because controlled charging ensures that the vehicle's battery is charged when energy prices are low, unless the provision of ancillary services prevents it.

The financial benefit for OEVs and aggregators gained by controlled charging is determined by the sum of the revenues of aggregators and OEVs because, in the end, the aggregators have to create financial incentives to attract and contract OEVs. The distinction between the revenues generated by the aggregators and the savings experienced by OEVs is more or less arbitrary. The reason for the distinction practised in this work is that it reflects where additional costs arise or revenues are generated. What really matters are the revenues aggregator and OEV together can generate per EV. In order to evaluate these additional revenues, they have to be divided by the number of EVs present in the respective scenario.

Procurement shares

The Matlab model accepts desired procurement shares (see section 4.2.1) as input. Given the limited number of EVs available in a specified scenario, it is often not possible to procure as much control power as wanted. The model therefore calculates the actual procurement shares that can be achieved by the aggregator in each business model of a given scenario.

Charging patterns

In all four business models charging is controlled by the aggregator and happens according to prices and procured control power while taking into account restrictions caused by driving and the charging rate. The Matlab model calculates the forecasted and actual charging patterns which show how much energy is charged in each time interval. The actual charging pattern may differ from the forecasted one depending on the business model which determines how much control energy is provided. Adding the forecasted or actual charging pattern to the load forecast (of the control area APG) results in the total load curves including EVs. If all control power is provided by EVs, the actual load curve including EVs has to be the same as the forecasted load curve. Due to the algorithms used in the Matlab model, EVs that are not plugged-in for longer than 1 hour and 12 minutes between 01:00 and 05:00 o'clock are neglected. Their share on the total number of EVs controlled by the aggregator is considered insignificant. The algorithms used agglomerate the batteries of individual EVs to one big battery. The capacity is the sum of all individual battery capacities. The computation of the charging pattern does not consider that an individual EV may not be plugged-in and therefore cannot be charged. This is only relevant for EVs in the time between 01:00 and 05:00 o'clock since electricity prices are lowest in this period.

5. Results

5.1. Business concept

A business concept is essential for the integration of EVs in the electricity system since it creates a basis for business models. As shown in Figure 23, it describes which actors in the electricity market are involved with the integration of EVs and what their tasks in this matter are. It also defines an interface or mediator between the OEVs and the rest of the electricity market. The purpose of a business concept is the creation of an environment under which OEVs are enabled and tempted to participate in controlled charging. In order to be economically attractive and thus realizable, financial incentives for both sides, the OEVs and aggregators, must exist.

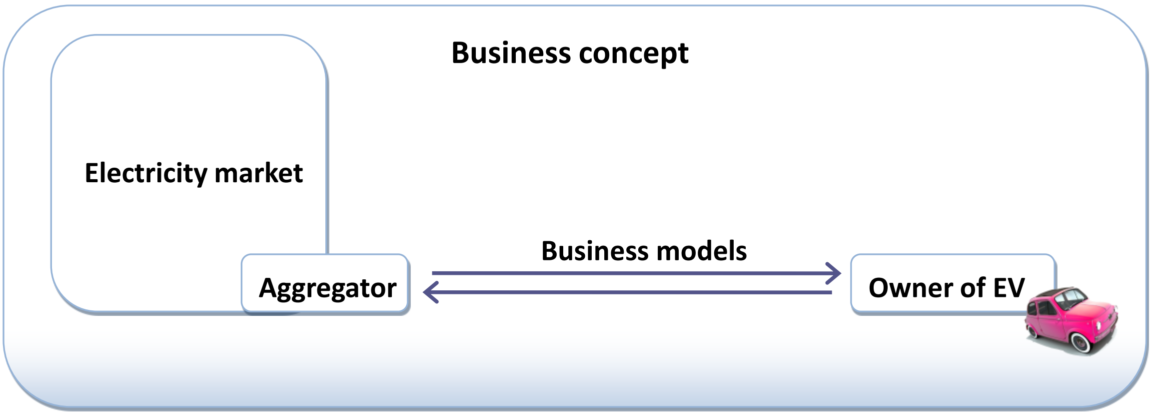

Figure 23: Business concept

5.1.1. Entity to realize business models

The entity introduced to realize business models shall be called an aggregator. The purpose of an aggregator is to reduce the complexity of the electricity market felt by OEVs. The efforts necessary by end-users to understand the functioning of these markets are not reasonable and would prevent the integration of EVs from moving to mainstream. Hence it makes sense to introduce an aggregator who functions as a mediator between OEVs and other market participants. The idea is illustrated in Figure 24. An aggregator has profound knowledge of the electricity market. He creates business models, which define the interaction between him and OEVs and determine his charging management. He contracts OEVs and assures them to manage the charging of their EVs' batteries in a cost-efficient manner. The longer EVs are plugged in, the fewer restrictions OEVs cause in terms of readiness and driving distance and the more EVs an aggregator is responsible for, the greater are his options and his possibilities to cut costs. As EVs are not plugged in all the time, availability of the resources is an issue. The aggregator should be seen as an entity separate to the supplier. In most cases, an OEV will be (household) consumer as well. He will have contracts with a supplier and a DSO in order to supply his home appliances with electricity. In addition to that, he will have a contract with an aggregator to economically manage the charging of his EV. An enterprise could be both a supplier and an aggregator.

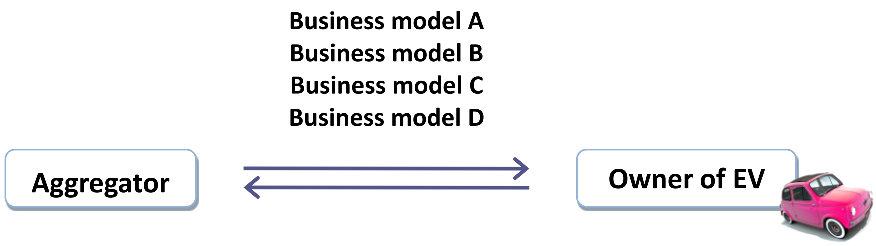

Figure 24: Business models

Theoretically any individual or enterprise can perform the functions of an aggregator. Considering the branch and the challenges it is likely that telecommunication enterprises, utilities or their spin-offs occupy this market segment. Telecommunication companies could profit from their technical knowledge of communication and network services. Utilities could use their experience and their knowledge of the electricity market. Joint-ventures are also an option. It seems likely that, similar to today's telecom market, a range of aggregators would exist and offer their services to OEVs.

5.1.2. Integration into the market platform

This section deals with the integrations of an aggregator in a market platform and his interaction with other market participants.

Market platform

The term "market platform" is used intentionally to allude to a future development of the electricity market. Today's electricity market is characterized by its complexity and there is a multitude of entry barriers for new participants. A market platform describes a rather open concept that eases the entry of new actors. Regulations should be intelligible to all. Ideally there would be one (online) platform where all necessary information could be obtained. The establishment of E-Control can be perceived as a step towards a market platform.

Interactions

An aggregator's duties are in some aspects similar to those of a supplier. The great difference is that an aggregator can participate in the market for secondary and tertiary control energy. The interactions of an aggregator with other actors are as follows:

- An aggregator designs business models and offers them to OEVs. The more end-users he can contract, the greater is the fleet of EVs he can manage and the revenue he can generate. The aggregator takes care of the charging of the EVs. In order to meet the needs of OEVs, they have to provide him with information concerning their driving pattern and any extra requirements. The aggregator may process this information together with other input data (e.g. daily plug-in times of EVs).

- Depending on the contracts with the aggregator, the OEVs might have to pay fees for the provided service, the energy used for charging and the transmission charges associated with it. Transmission fees are forwarded to the DSOs and TSOs.

- Like a supplier, the aggregator purchases electricity from a producer, an electricity wholesaler or on an energy exchange. This is done at least one day ahead of delivery. Unless the provision of ancillary services or other restrictions prevent it, most of the energy will be charged in periods of the day when electricity is cheap.

- DSOs have access to certain databases of aggregators. If an EV is connected to the distribution grid, its identification is checked and grid access is granted. Charging is managed by the corresponding aggregator. DSOs provide the interfaces, deliver the energy and measure the power flow.

- Similar to suppliers, the aggregator has to join a balancing group. He draws up schedules of the forecasted (day-ahead) electricity consumption and forwards them to the BGR (Balancing group representative). The CAM informs the CSA of the balancing energy provided by a certain aggregator. The CSA forwards this data to the BGR who takes it into account when allocating the charges for balancing energy to the members of the balancing group. This ensures that a provider of control services does not have to pay for a load deviation caused by his provision of balancing energy.

- The CAM pays aggregators for the provision of control energy. Aggregators provide this control energy by reducing or increasing the load represented by the fleet of EVs managed by them. In contrast to the situations discussed in section 2.2.2, the control energy is not provided by changing the output of generated electricity.

- If deviations between the projected schedules and actual consumption or production (e.g. of renewables) occur, which is usually the case, the CAM has to retrieve balancing energy. In today's electricity system this is mostly provided by producers.

  In a future market platform, the CAM could publish real-time requests for control power on his website. Aggregators could make bids online. If they do so within a certain time period (e.g. one minute), the CAM inserts these bits in the merit order list and retrieves them according to their prices. Most of this process would be automated to meet time requirements. If a bid is accepted, the aggregator is informed. He reacts by adjusting the charging of the EV fleet (via the smart grid). The CAM informs the CSA of the provision of balancing energy thus the aggregator is not charged for his deviation from the projected schedule.
  The Matlab model used to calculate changes in revenues of stakeholders implements today's situation and therefore does not consider this possible option.

Figure 25 shows the interactions of an aggregator with other stakeholders in the market platform. For reasons of readability interactions among other actors are hidden.

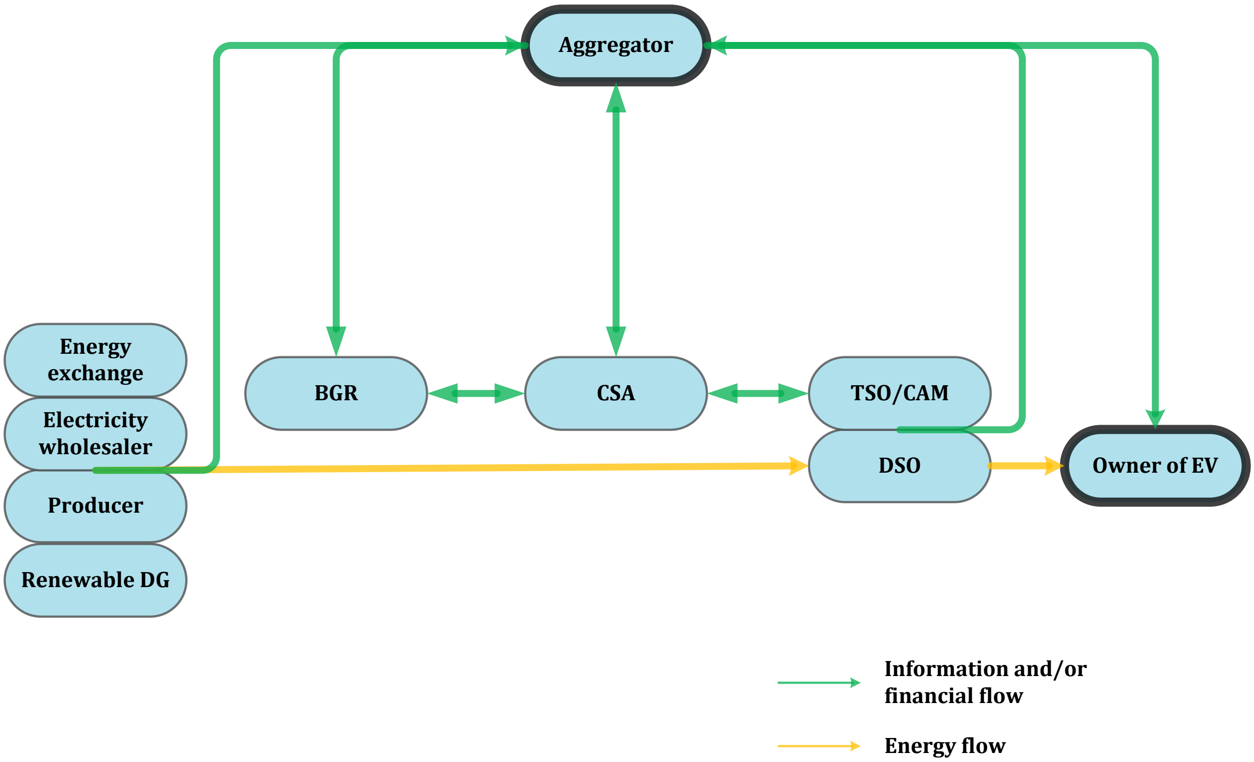

Figure 25: Interactions of the aggregator with other market participants

Roaming

Roaming would allow OEVs to charge their EVs not only within their home country but also abroad. This is vital to enable cross-border traffic. It therefore is essential to have standardized communication interfaces and services on an international (ideally global) level. In this case, the procedure could be as follows:

- The OEV connects his EV to a charging station.
- The DSO responsible for the region, which the charging station belongs to, requests identification.
- The EV discloses its associated aggregator and vehicle ID (similar to a computer's MAC[12]-address).
- The DSO connects to the data base of the respective aggregator and checks the information for validity. If the ID is correct, the DSO grants grid access.
- The associated aggregator manages the charging of the EV and compensates the DSO for his services.

[12] Media Access Control

Tasks of an aggregator

Here is an exemplary list of the tasks an aggregator accomplishes in order to manage the charging of his fleet of EVs:

- Check how many EVs are plugged-in and what their battery states are. Calculate the possible bandwidth of load that could be charged considering the driving pattern of the OEVs and their extra requirements.
- Check the homepage of the CAM for published real-time requests for balancing energy.
- Check which physical limitations could apply. The DSO might restrict the load or the charging rate in specified areas.
- Use the projected schedule, which has been forwarded to the BGR, together with the data obtained from the previous steps as input for a model which calculates how the load should be managed.
- Control charging according to the output of the model.

It is likely that all of these tasks will be computerized and fully automated.

5.1.3. Prerequisites

In order to achieve a large-scale integration of EVs in the electricity system according to the business concept described above, certain requirements need to be met. These are the following:

- Bidirectional communication services in order to allow time-based pricing.
- Secrecy of communication to address privacy concerns.
- Security of communication services to prevent attacks and ensure reliability of the system.
- In order to provide a reasonable share of the total required control power, the number of EVs has to be sufficiently high. (With a market penetration of 100,000 EVs, the aggregator can cover only up to 36 % of tertiary power for purchase or up to 25 % of secondary control power for purchase.)
- In order to provide control services to the CAM, batteries of EVs have to support intermittent charging.
- A legal framework has to be established. In the interest of OEVs, E-Control could be charged with the supervision of this market segment. It could provide price comparisons like it does for electricity prices.
- Standardized communication interfaces and services are necessary to increase competition and allow OEVs the switching of aggregators.

Some of these requirements are not restricted to the integration of EVs. They are general requests for smart grids.

5.2. Business models

Four business models are constructed. They differ in the way of participation in the electricity system and markets for control power. The business models can be seen as agreements or contracts between an aggregator and OEVs. They define and restrict the aggregator's options. Whether a business model can be applied or not depends on the communication infrastructure and capacity of the power grid. If more than one business model is feasible, OEVs could be given a choice. There are a few possibilities for an aggregator to generate revenues and thereby potential profits. Besides the delivery of energy to clients (OEVs) in order to charge their vehicles' batteries, an aggregator could:

- Control the charging in order to charge when prices are the lowest
- Participate in the market for tertiary control power
- Participate in the market for secondary control power

All three options require a bidirectional communication. As shown in Figure 7, the provision of ancillary services is very time critical. The participation in tertiary control services requires communication intervals of a few minutes, e.g. 7 minutes. The provision of secondary control services calls for communication intervals in the range of 20 seconds. This is necessary so that charging can be controlled according to retrieval requests of control power by the TSO.

Considering the different communication requirements, four business models are created. Their features are listed in Table 10. None of the business models envisions the discharging of batteries to feed electricity back into the power grid. Although possible and useful for the provision of control services for delivery, it is not practised in any of the business models examined in this work. The reason is that discharging would result in increased battery wear. The number of charging cycles would rise and reduce battery life. The controlled charging investigated in this work does not cause additional battery wear because all energy charged here needs to be charged anyway in order to travel the desired distances. The aggregator charges only as much energy as is consumed by driving. The application of business models affects the battery only in so far that it is charged intermittently (in many small steps). Providing the use of lithium-based batteries, partial discharge does not cause additional battery wear since this kind of batteries do not show a memory effect.(Buchmann 2010)

Table 10: Business models and provided services

Business model:	A	B	C	D
Controlled charging:	x	x	x	x
Tertiary control services:		x		x
Secondary control services:			x	x

5.3. Economic analysis

The revenues generated by the application of business models created in subchapter 5.2 are analyzed using the three scenarios described in subchapter 5.2. After the impacts of the different business models in each scenario have been examined, the development of revenues over the number of EVs (which is the distinctive feature of scenarios) is discussed. The desired procurement shares and the parameters "smoothing factor" and "initial state of charge" can be chosen by the aggregator. It is assumed that an aggregator adjusts the parameters so that the sum of his and the OEV's revenues is maximized. The resulting optimal values or ranges are used in each scenario. The optimal parameter constellation for the aggregator and OEV is shown in Table 11.

Table 11: Optimal parameter values

Parameter	Value
Desired procurement share secondary delivery:	0 %
Desired procurement share secondary purchase:	100 %
Desired procurement share tertiary delivery:	0 %
Desired procurement share tertiary purchase:	100 %
Initial state of charge:	10 – 40 %
Smoothing factor:	4 – 8 h

5.3.1. Scenario I

In scenario I the aggregator controls the charging of 100,000 EVs. The results obtained by the use of the parameter values of Table 11 are shown in Figure 26. It illustrates the absolute annual changes in revenues compared to the BAU scenario (same number of EVs but uncontrolled charging) for the four business models. Figure 27 shows the additional revenues generated per EV. These values are more meaningful.

If not stated otherwise, all figures in this subchapter which hold power or energy values in their y-axis show the situation on a working day in winter. This is done exemplarily to keep the number of figures on a reasonable level. Due to the structure of the model (see Figure 16) six such diagrams - for working days and weekend days in each period - are calculated.

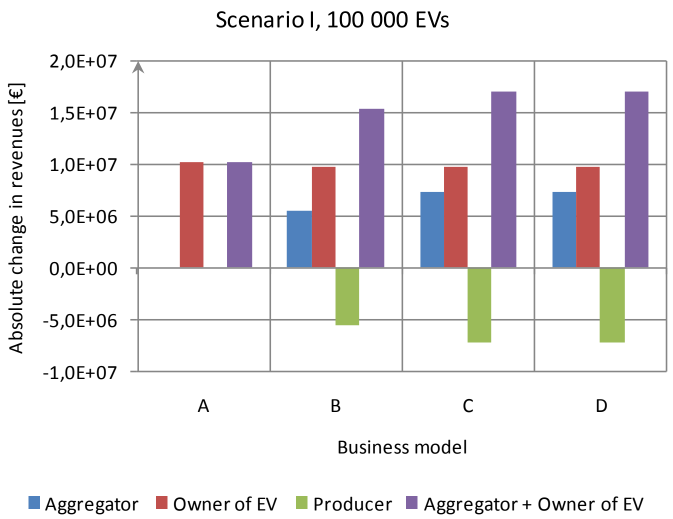

Figure 26: Scenario I, revenues (absolute)

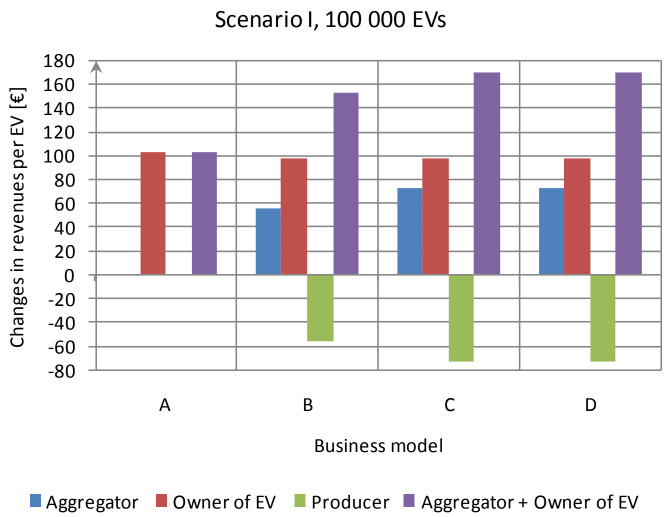

Figure 27: Scenario I, revenues (per EV)

Business model A

Since business model A does not allow the provision of ancillary services, the desired procurement shares shown in Table 11 have no effect and the financial situations of the aggregator and producer remain unchanged. The OEV experiences annual savings of about 103 €. These are the result of controlled charging. Energy is charged when electricity prices are low, which is primarily at night time. The corresponding charging pattern is shown in Figure 28. Fluctuations in the withdrawn power are caused by the availability of plugged-in vehicles. The evolution of the SOC over the day can be seen in Figure 29. It is determined by the amount of energy charged in each interval and the amount of energy consumed for driving in each interval. The SOC at 00:00 and 24:00 o'clock are defined by the input parameter "initial state of charge".

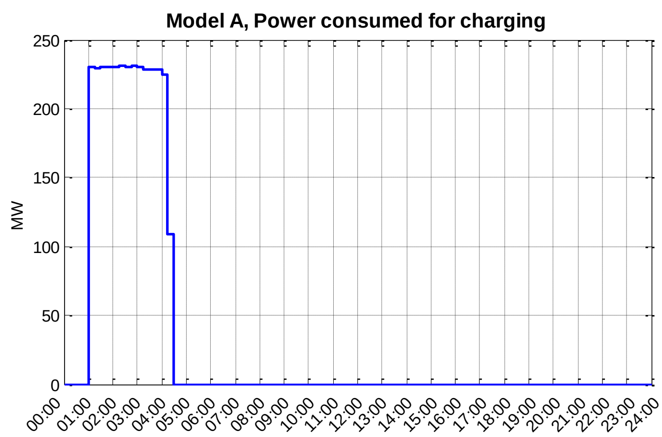

Figure 28: Scenario I, A, charging pattern

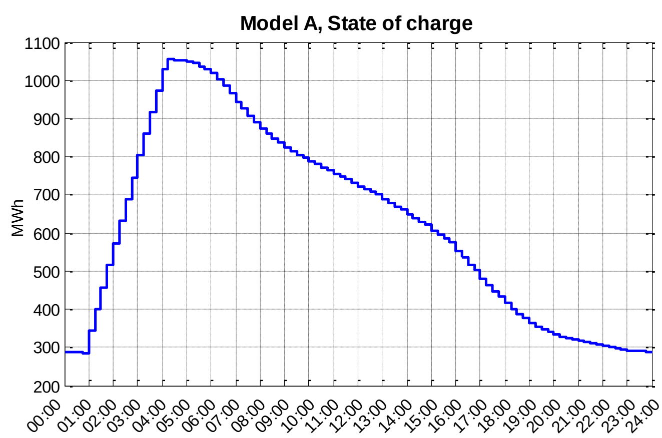

Figure 29: Scenario I, A, SOC

The sensitivity analysis in Figure 30 shows that the financial effects remain the same if the initial SOC lies between 10 % and 40 % of the total battery capacity. The initial SOC can be interpreted as an offset which has no effects if it remains within a certain range. If the parameter is chosen to be greater than 40 %, the savings experienced by the OEV shrink.

The aggregator tries to charge when prices are cheapest. This is between 01:00 and 05:00 o'clock. The initial SOC poses a restriction because this SOC has to be achieved at midnight. If the initial SOC is high, the aggregator is forced to charge in the hours before midnight which results in higher costs. A SOC close to 0 % causes an error in the model since it would not allow any driving in the first 15 minute interval of the day. The driving pattern, however, is defined by the database and driving occurs also in the first interval. This explains why the sensitivity analysis starts at 10 %.

The smoothing factor is described in section 4.2.1 and poses an upper limit for the chargeable amount of energy in each interval. Figure 31 illustrates that a value of up to 8 h has no effect on revenues. The energy consumed daily for driving is 7.7 kWh. If the smoothing factor is 8 h, the maximum charging rate for each interval is 2.25 kW per EV according to Formula (4.10). Given the number of 100,000 EVs, the maximum charging rate of the entire fleet amounts to 225 MW.

$$charging\ rate_{max,\ fleet} = charging\ rate_{max,\ individual\ EV} \cdot number\ of\ EVs = 225\ MW \qquad (5.1)$$

This is only slightly lower than the power charged between 01:00 and 04:00 o'clock, 231 MW. (see Figure 28). The aggregator thus reduces charging in this time period and increases charging in the intervals between 04:15 and 05:00 o'clock, which feature the same low energy prices. If the smoothing factor is further increased, charging has to occur during more expensive periods and the cost savings of the OEV decrease.

The plug-in factor can have a huge impact on the savings of OEVs (see Figure 32). The more and the longer EVs are plugged-in the greater are the aggregator's options and possibilities to save costs by charging when prices are low. The sensitivity is high when the parameter value is lower than 50 %. For higher values of the plug-in factor, sensitivity decreases because the relative increases of an aggregator's options become smaller. The plug-in factor in this work is assumed to be 70 % (see section 4.2.1). The sensitivity around this value is relatively low.

The impact of the parameter "maximum share driving at once", which has a default value of 80 %, in business model A is insignificant because the majority of EVs can be charged in cheap intervals regardless of its value (see Figure 33).

Business model B

The changes in annual revenues for the three stakeholders are visible in Figure 26 in absolute values and in Figure 27 in relation to the number of EVs. The revenues of aggregator and OEV add up to 153 € per year. This is more than in business model A. The savings of the OEV are slightly lower than the ones in business model A. Due to the retrieval of tertiary control power, energy is not entirely charged in cheap periods, which causes the reduction in savings. In contrast to business model A, now the aggregator and producer are affected as well. The aggregator can generate additional revenues by providing ancillary services to the CAM. The increase in revenues of the aggregator is equal to the decrease in revenues of the producer. In the BAU scenario all control power was provided by the producer. The additional revenues generated by the aggregator depend on the achieved procurement share (for tertiary control power) and the corresponding prices taken from the database (see section 3.2.2). The achieved procurement share for tertiary control power (purchase) is computed by the Matlab model and amounts to 35.85 %. All other control power is provided by the producer.

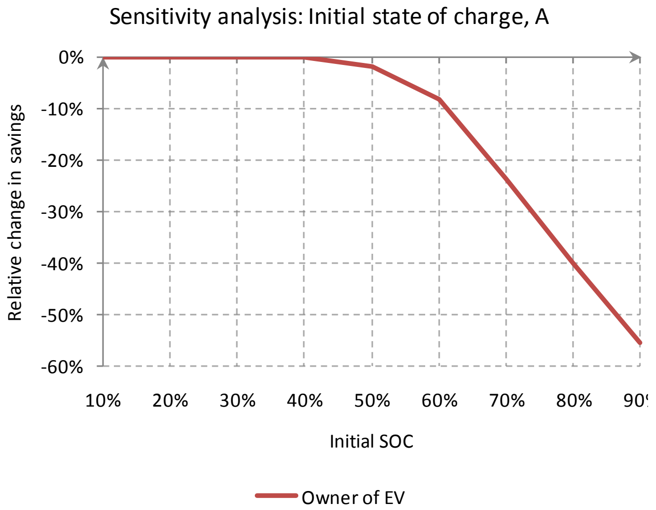

Figure 30: Scenario I, A, initial SOC

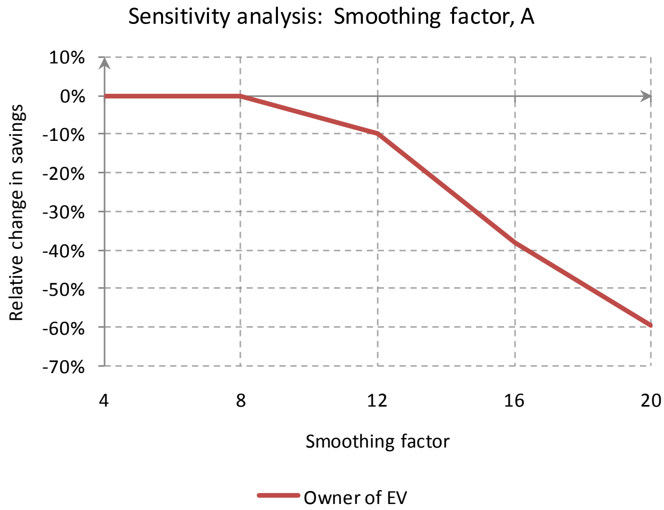

Figure 31: Scenario I, A, smoothing factor

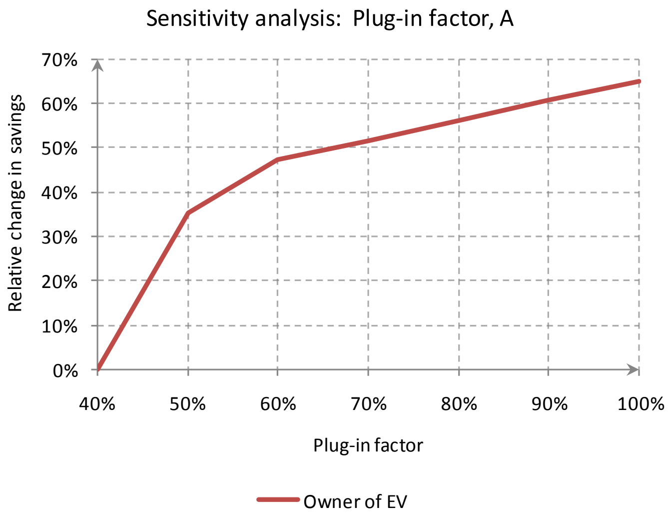

Figure 32: Scenario I, A, plug-in factor

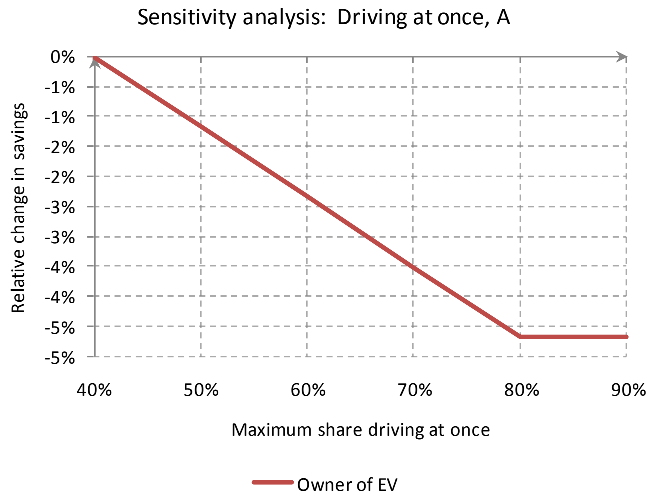

Figure 33: Scenario I, A, driving at once

The forecasted charging pattern differs to the one of business model A (see Figure 28) since control power for purchase is procured. The maximum charged power is now 186 MW (see Figure 34). Adding the procured control power of 47 MW yields the maximum charged power in business model A of 231 MW. The procured control power is calculated according to Formula (5.2). The auctioned amount is the amount of control power requested by the CAM (see section 4.2.1).

$$procured\ control\ power = procurement\ share_{tertiary,\,purchase} \cdot auctioned\ amount \qquad (5.2)$$

The aggregator provides ancillary services by altering forecasted charging when the CAM requests control power. Actual charging therefore deviates from the forecasted pattern (see Figure 35). The deviations are small since the required tertiary control power itself is small.

The deviations are equal to the control power released by the aggregator. The control power provided by the aggregator (see Figure 36) is proportional to the required tertiary control power shown in Figure 77. The proportionality factor is the procurement share.

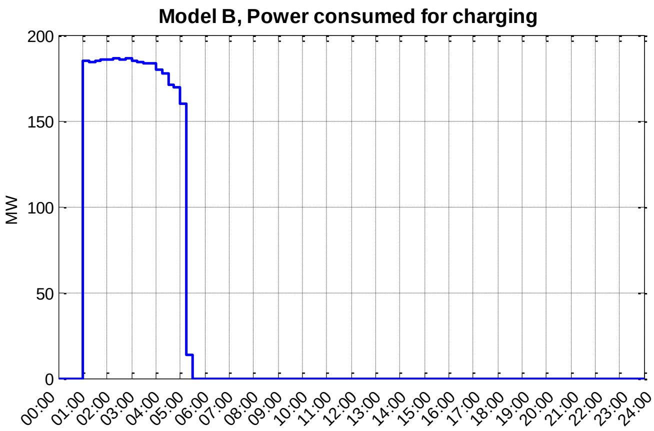

Figure 34: Scenario I, B, forecasted charging

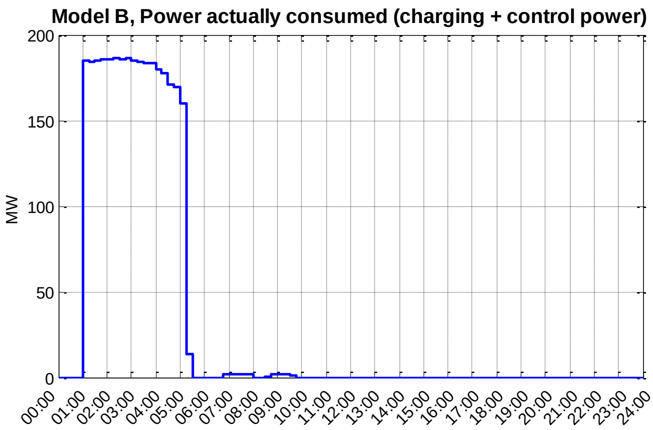

Figure 35: Scenario I, B, actual charging

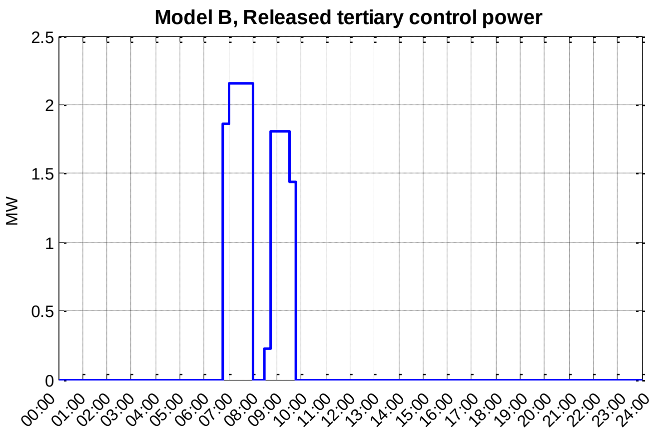

Figure 36: Scenario I, B, released tertiary control power

Analogous to business model A, the changes in revenues are insensitive to the initial SOC as long as it remains between 10 % and 40 %. Figure 37 illustrates that a higher initial SOC forces the aggregator to charge in intervals of higher prices. Capacity limits along with the driving pattern reduce the control power the aggregator is able to procure. This reduces his revenues. The producer's revenues show an inverse behaviour and increase.

A smoothing factor greater than 8 h reduces the savings of the OEV as more energy is charged in rather expensive intervals. This can be seen in Figure 38. The relative reduction in savings is greater because the savings in absolute terms achieved in business model B are smaller than those in business model A. Hence, changes that are equal in absolute terms have a greater effect in business model B. The revenues of aggregator and producer are not influenced by the smoothing share, unless values far above 20 h are chosen. However, there is no point in choosing such high values.

Same as for other business models, a rising plug-in factor increases the savings of the OEV and the revenue of the aggregator since his scope of action grows. As illustrated in Figure 39, the effect on the revenue of the producer is inverse that of the aggregator.

The sensitivity analysis of the input parameter "maximum share driving at once" is shown in Figure 40. In contrast to business model A, the savings of the OEV increase when the parameter value rises. The more EVs drive at the same time, the less control power can be procured which leads to more energy being charged in intervals with low prices. This explains not only the increase in savings of the OEV but also the decrease in revenues of the aggregator. Decreasing revenues of the aggregator go in hand with rising revenues of the producer.

In compliance with Table 11, only control power for purchase is provided. The more such control power is provided the higher are the revenues for the aggregator. The sensitivity of the parameter "procurement share for tertiary delivery" is illustrated in Figure 41. (The reference y-value in this diagram is the one obtained at a desired procurement share of 50 %. Changes in revenues are calculated by varying the procurement share in steps of 10 %.) For desired values higher than 40 % there are no further improvements of the aggregator's financial situations. This saturation can be explained by the limited resources. The maximum achievable procurement share for tertiary control power for purchase is 35.85 %.

In addition to the provision of control power for purchase, control power for delivery can be provided as well. Figure 42 shows the results when the desired procurement share for purchase is 100 % and the desired procurement share for delivery is varied in steps of 10 %. The procurement of control power for delivery increases the aggregator's revenues but reduces the OEV's savings disproportionately high. The revenues of aggregator and OEV together in absolute terms decrease. The producer's revenues also shrink. The procurement of control power for delivery is therefore not desirable. Analogous to the desired procurement share for purchase, saturation due to the limited number of EVs occurs here as well.

Business model C

The annual revenues generated by aggregator and OEV together increase to 171 € per EV. The achieved procurement share for secondary control is 25 % (and for tertiary control 0 %).The revenues generated by the provision of secondary control services are larger than the ones made by the provision of tertiary control services. The reason is that more secondary control energy than tertiary control energy is needed. This is shown in Figure 77 and in Figure 78 the appendix.

The savings of the OEV are the same as in business model B. This time secondary and not tertiary control power is procured. The loss in revenues of the producer is greater than in business model B because part of the revenues of the producer now go to the aggregator as he participates in the provision of secondary control power.

The sensitivities of revenues to the examined parameters "initial state of charge", "plug-in factor" and "maximum share driving at once" are exactly the same as in business model B. The sensitivity to the smoothing factor is very similar to its counterpart in business model B.

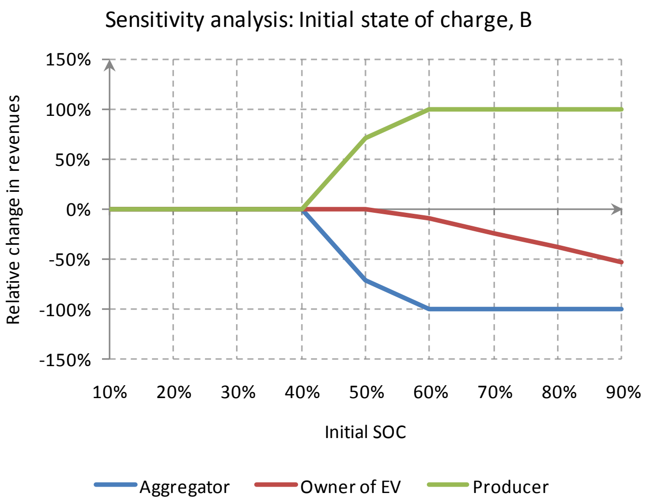

Figure 37: Scenario I, B, initial SOC

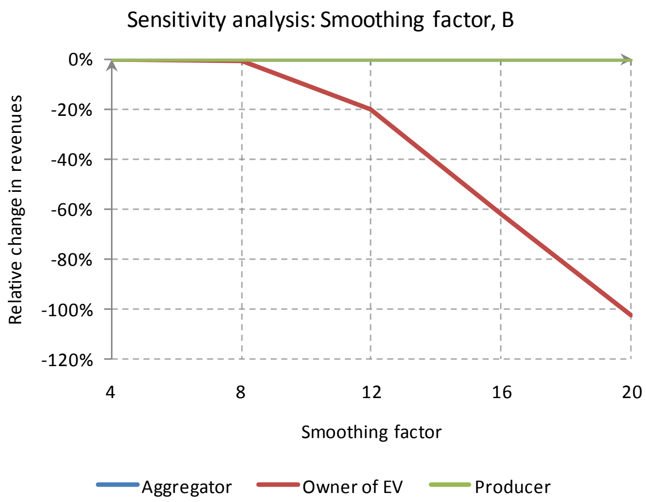

Figure 38: Scenario I, B, smoothing factor

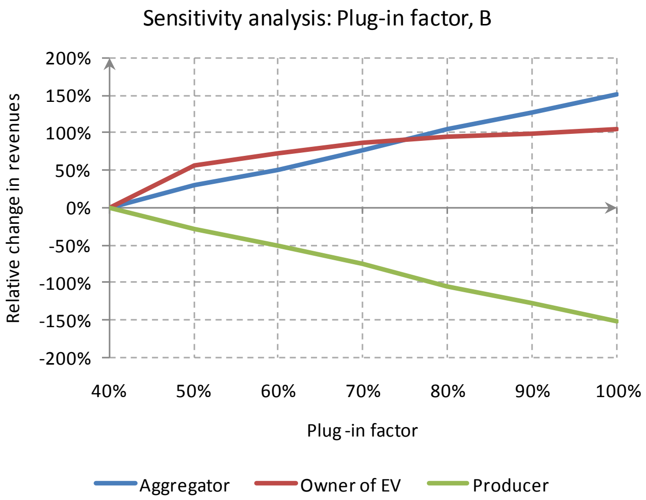

Figure 39: Scenario I, B, plug-in factor

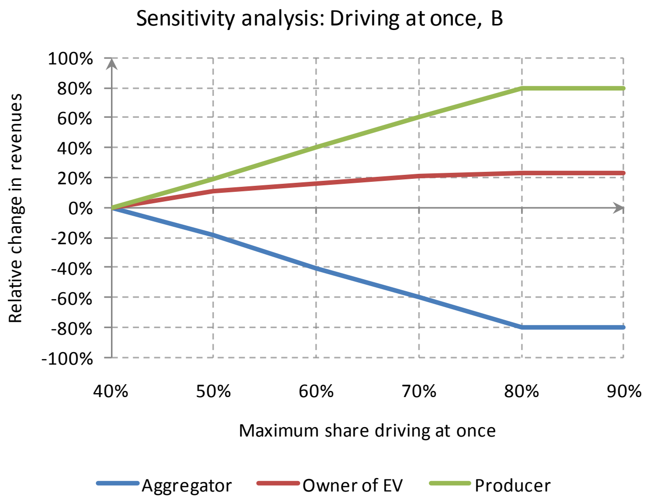

Figure 40: Scenario I, B, driving at once

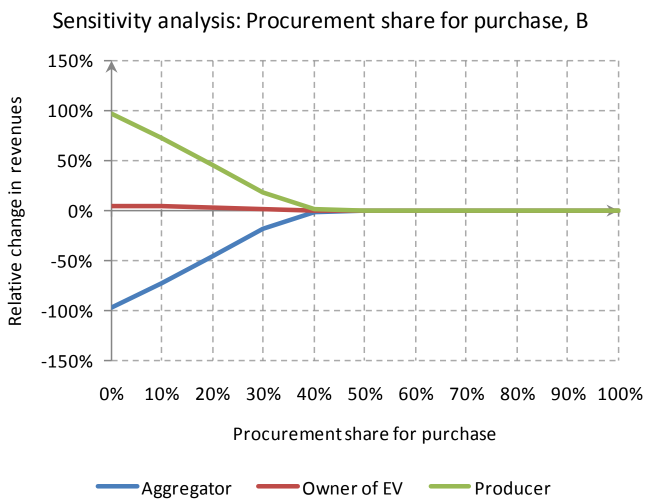

Figure 41: Scenario I, B, power for purchase

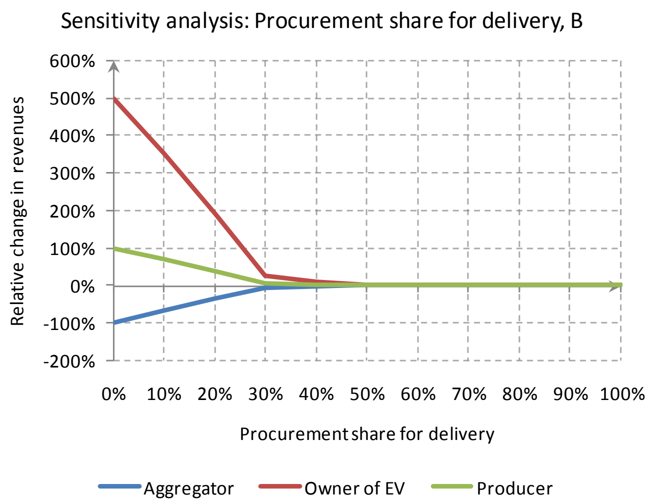

Figure 42: Scenario I, B, power for delivery

The sensitivity of revenues to the desired procurement share for control power for purchase is the same as in business model B (see Figure 43). The one regarding the procurement share for control power for delivery varies slightly from the one in business model B because the reference y-value is not the same. The reference y-value in Figure 44 is the one obtained at a desired procurement share for delivery of 50 %. For business model C, where secondary control is provided, this value is different to the one of business model B, where tertiary control is provided. Changes in revenues are calculated by varying the procurement share in steps of 10 %.

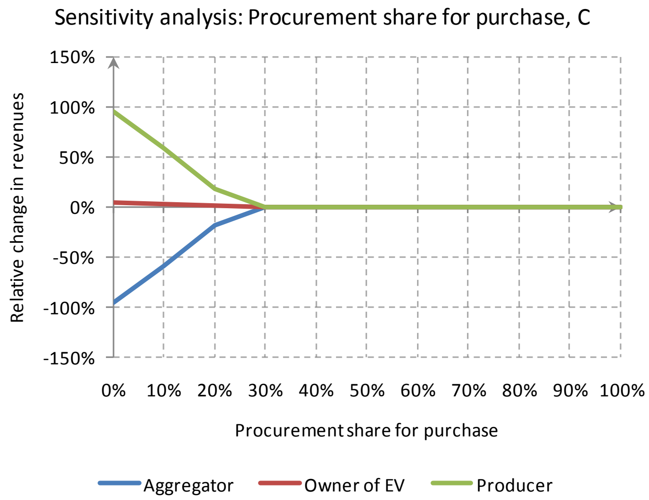

Figure 43: Scenario I, C, power for purchase

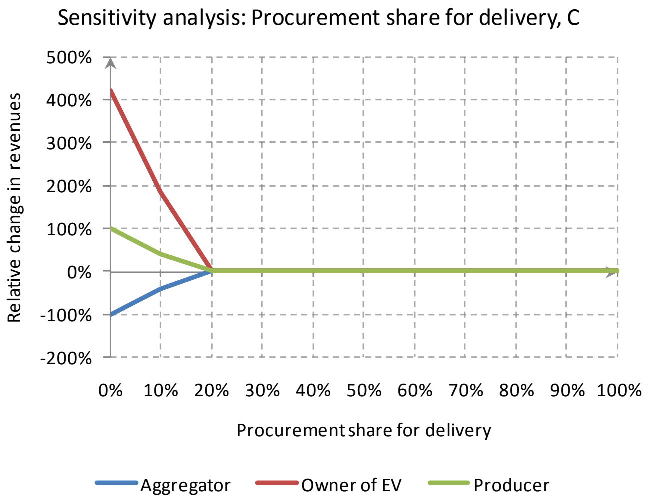

Figure 44: Scenario I, C, power for delivery

Business model D

Both secondary and tertiary control services are provided if possible. The priority lies on secondary control services as revenues generated there are greater. A glance at Figure 27 reveals that the financial situation in business model D is the same as in business model C. The reason is that the resources (number of EVs) are not sufficient to cover all secondary control power requested by the CAM. The aggregator therefore has no further resources to participate in the market for tertiary control power. The situation is therefore the same as in business model B. This changes when the number of EVs is increased which is the case in scenario II and scenario III.

5.3.2. Scenario II

In scenario II the number of EVs controlled by the aggregator is 500,000. The annual changes in revenues for all four business models are shown in Figure 45 and Figure 46. The development of revenues over the various business models is similar to that in scenario I. The greatest revenues of aggregator and OEV together are achieved by the application of business model D.

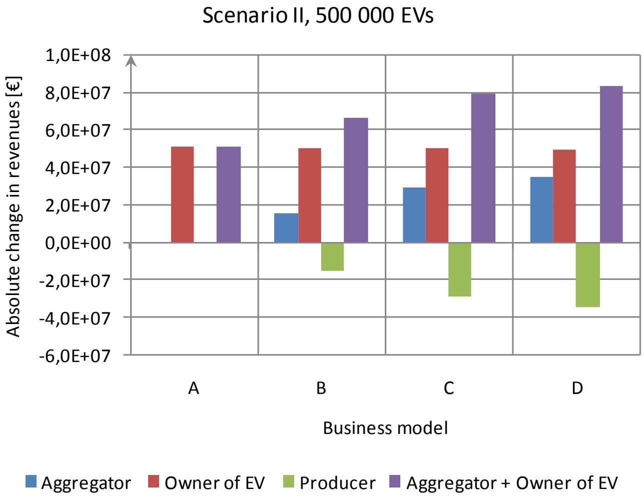

Figure 45: Scenario II, revenues (absolute)

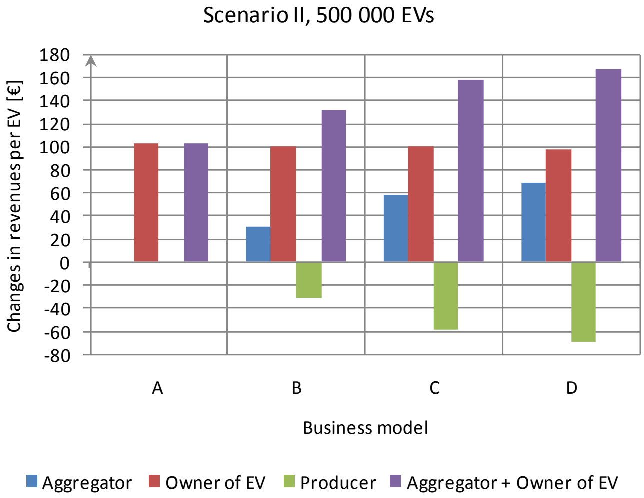

Figure 46: Scenario II, revenues (per EV)

Business model A

The situation is basically the same as in scenario I. The only difference is that the number of EVs is 5 times as high. The savings of the OEV in absolute terms achieved by controlled charging increase linear and are therefore 5 times as high as in scenario I. Aggregator and OEV together can increase their annual revenues by 103 € per EV.

Sensitivity analyses produce the same results as in scenario I for business model A. The only exception is the sensitivity of changes in revenues to the input parameter "maximum share of EVs driving at once". As shown in Figure 47 the sensitivity for values below 80 % is very low. Values greater than 80 % force the aggregator to postpone part of the charging into intervals where prices are higher.

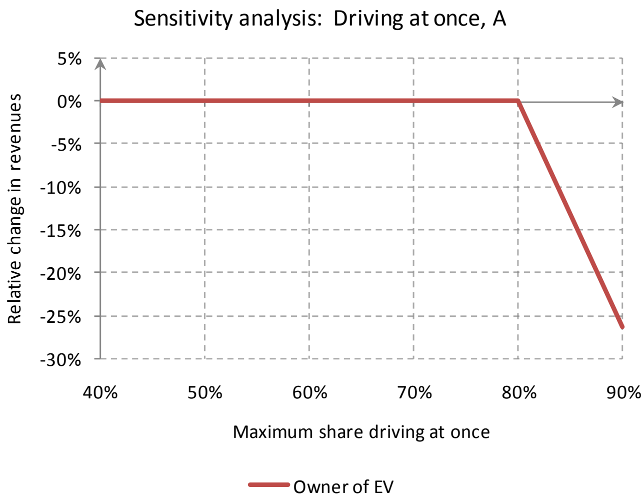

Figure 47: Scenario II, A, driving at once

Business model B

In business model B aggregator and OEV together can generate 131 € of additional annual revenues per EV. This is 28 € more than in business model A of this scenario. The procurement share (for tertiary control power for purchase) amounts to 100 %. The share desired by the aggregator (see Table 11) could be reached. However, this implies that the resources are not fully used. The annual change in revenues per EV is therefore smaller than in scenario I.

The initial SOC has a similar effect on the change in revenues as is the case in scenario I (see Figure 48). A higher initial SOC forces the aggregator to charge more energy in pricy intervals which has a negative impact on the savings of OEVs. It also limits the aggregator's options as concerns the provision of control services.

The impact of the smoothing factor on revenues is mostly limited to the OEV. Values higher than 20 h would also affect the aggregator and indirectly the producer. However, there is no point in choosing such high values. For smoothing factors lower than 8 h, the charging rate is restricted by the maximum charging rate allowed by the EV which explains why there is no impact in this range (see Figure 49).

As shown in Figure 50 the only stakeholder whose revenue is sensitive to the plug-in factor is the OEV, unless the plug-in factor is extremely low. A very low plug-in factor would also affect the aggregator's possibilities regarding the provision of ancillary services. Thus, there would be an impact on the aggregator and indirectly on the producer as well. However, such low values seem unrealistic and shall not be examined in this work. Sensitivity in the area of the default value 70 % is fairly small. A low plug-in factor prevents the aggregator from charging the majority of EVs in night time when prices are low.

The share of EVs maximally driving simulataneously has a much smaller effect than in scenario I (see Figure 51). The reason lies in the high number of EVs. At the default value of 80 % not all EVs are used. These over capacities do not generate revenues. If the maximum share of EVs driving at the same time increases, more and more of the EVs are used. This is fine until the parameter value reaches 70 %. Then all EVs are used and a further increase restricts the aggregator and lowers the achievable procurement share. The aggregator's revenues decrease and those of the producer increase.

The interpretation of the sensitivities to the procurement share of control power for purchase and delivery is the same as in scenario I except for one significant distinction. Now, with a number of EVs of 500,000, the resources are available to achieve the desired procurement shares. This explains why there are no saturation effects in Figure 52 and Figure 53.

Business model C

In business model C the annual revenues of aggregator and OEV together amount to 158 € per EV. This is 27 € more than in business model B. The reason is the same as in scenario I: more secondary control energy than tertiary control energy is released. The procurement share is 100 %, all required secondary control power can be covered by the aggregator.

The sensitivity analyses of the parameters "initial SOC", "maximum share of EVs driving at once" and "desired procurement share for purchase" produce the same results as in business model B of this scenario.

The sensitivity to the smoothing factor is little higher than in business model B. It is shown in Figure 54.

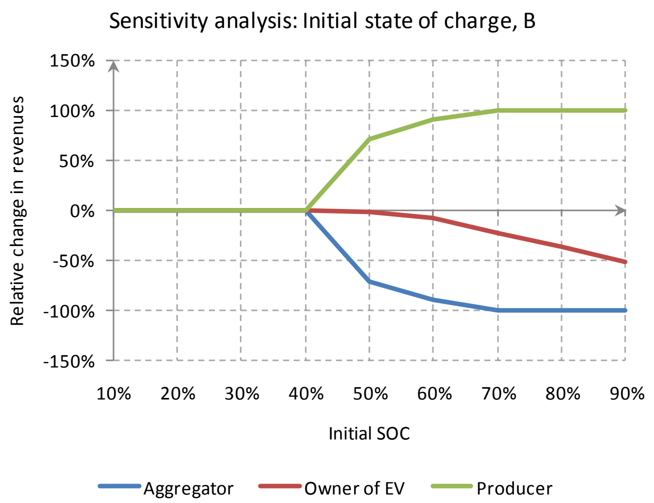

Figure 48: Scenario II, B, initial SOC

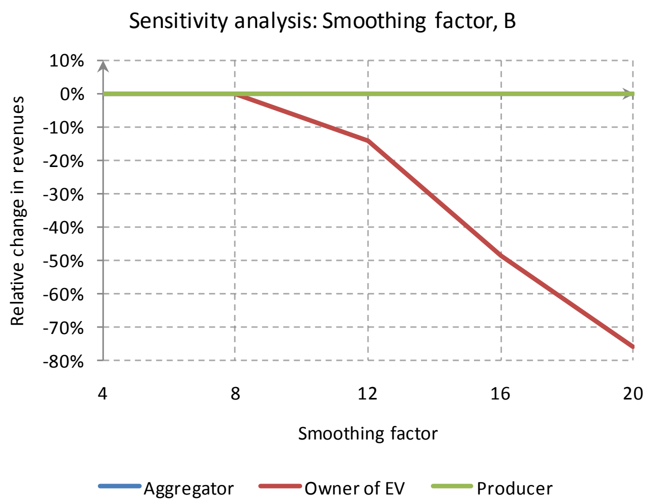

Figure 49: Scenario II, B, smoothing factor

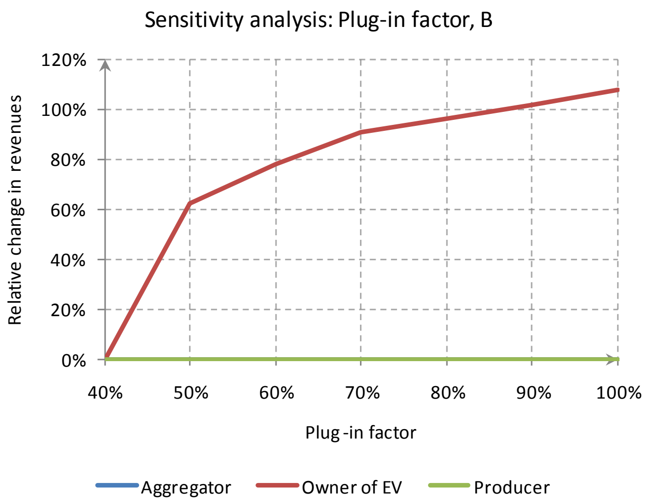

Figure 50: Scenario II, B, plug-in factor

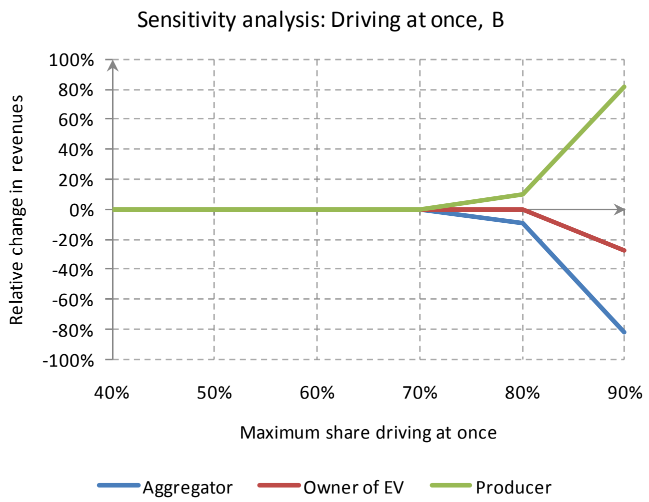

Figure 51: Scenario II, B, driving at once

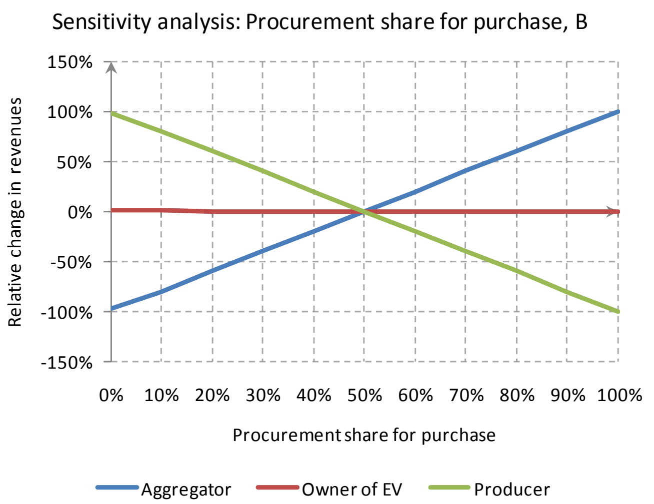

Figure 52: Scenario II, B, power for purchase

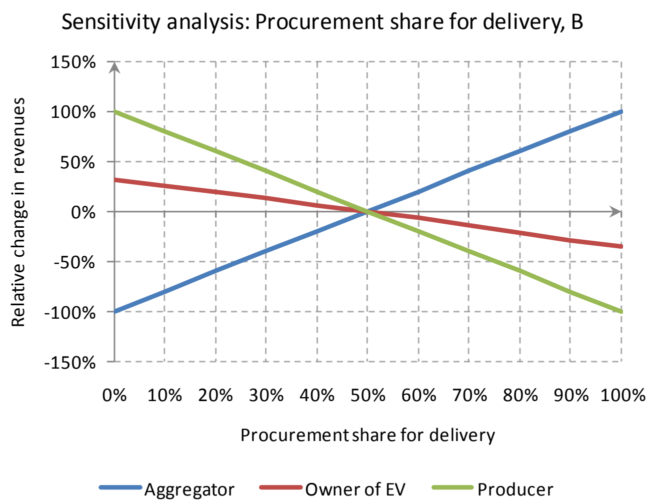

Figure 53: Scenario II, B, power for delivery

In contrast to business model B, the revenues of all three stakeholders are sensitive to the plug-in factor. This was also the case in scenario I. Figure 55 shows that revenues of the aggregator and OEV increase when EVs are plugged in longer. A high plug-in factor allows the aggregator to charge in cheap intervals which has a positive effect on the savings of the OEV. It also allows the aggregator to increase his provision of secondary control services. The auctioned amount of secondary control power is greater than the one of tertiary control power which explains why there was no effect on the revenues of the aggregator and the producer in business model B. Again, the sensitivity around the default value of 70 % is relatively low.

The sensitivity to the maximum share of EVs driving at once is significant in both directions around the default value of 80 % (see Figure 56). This parameter has a critical impact on the results.

The sensitivity analysis of the procurement share for delivery (see Figure 57) features the same interpretation as in scenario I. The only distinction is that the development of revenues does not saturate with increased procurement shares. This is a result of the high number of EVs.

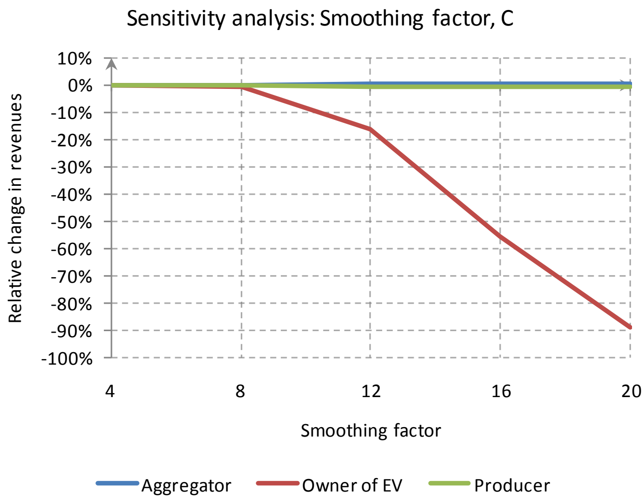

Figure 54: Scenario II, C, smoothing factor

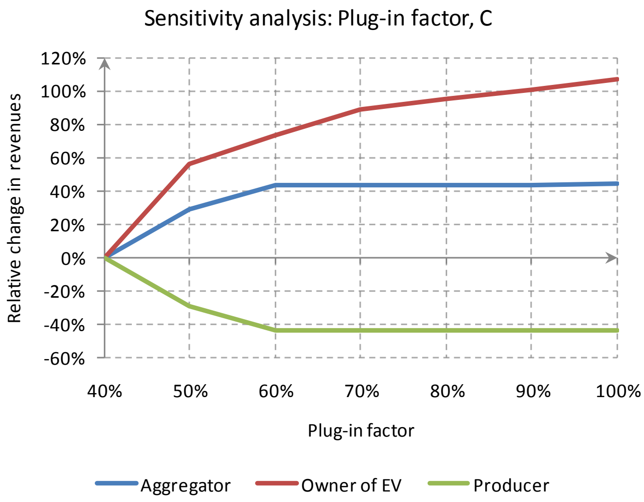

Figure 55: Scenario II, C, plug-in factor

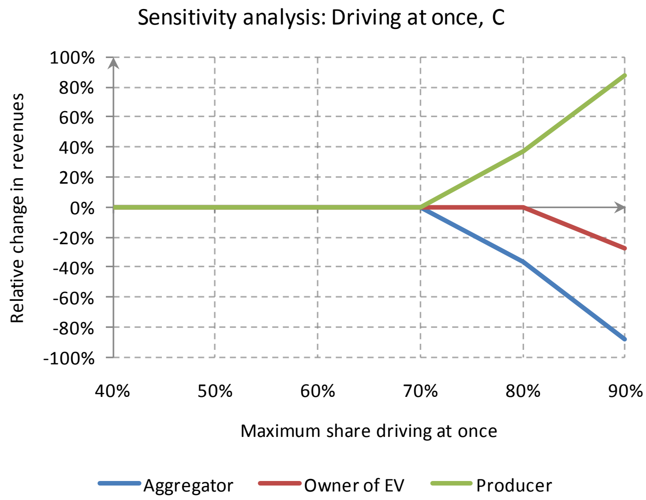

Figure 56: Scenario II, C, driving at once

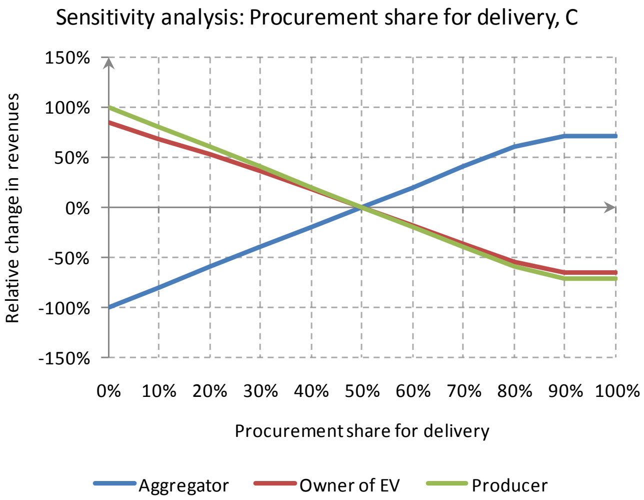

Figure 57: Scenario II, C, power for delivery

Business model D

The annual revenues of aggregator and OEV together amount to 167 € which is 9 € more than in business model C. The increased revenues are generated by the provision of tertiary control power in addition to the provision of secondary control power. The procurement shares are 100 % for secondary control power and 35.36 % for tertiary control power. The aggregator's revenues generated by the provision of secondary control are the same as in business model C (58 €). The additional provision of tertiary control power allows him to increase his revenues by 11 € to 69 €.

The sensitivity to the initial SOC is the same as in business model C.

The impact of the smoothing factor on revenues is shown in Figure 58. It is slightly stronger than in business model C, because the resources (number of EVs) are now fully exploited.

The sensitivity of the aggregator's and producer's revenues to the plug-in factor is much greater than in business model B because the required amount of control power is much greater than the amount the aggregator is capable of providing. Therefore, the restrictions caused by the plug-in factor are relevant (see Figure 59).

For the same reason the sensitivity to the maximum share of EVs driving at the same time is also slightly greater than in business model B (see Figure 60).

The sensitivities to procurement shares are illustrated in Figure 61 and Figure 62. They show saturation effects when the procurement shares reach values of about 80 %. These result from the limited amount of EVs which is not sufficient to provide all control power that is auctioned. The priority lies on the provision of secondary control power. Revenues generated thereby are greater than those generated by the provision of tertiary control power. This explains why the sensitivity decreases when the procurement share rises.

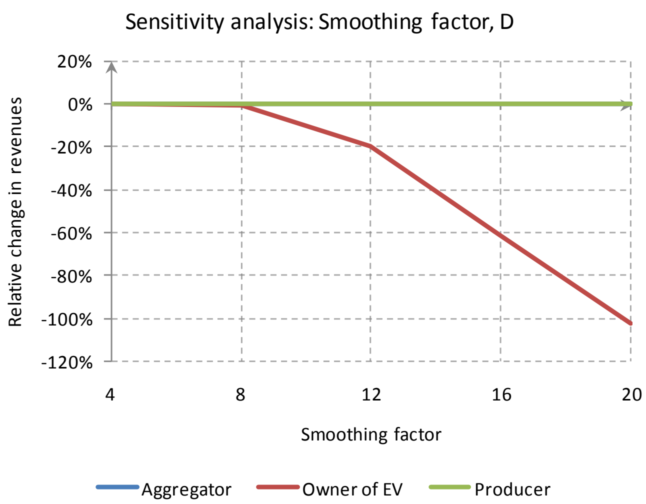

Figure 58: Scenario II, D, smoothing factor

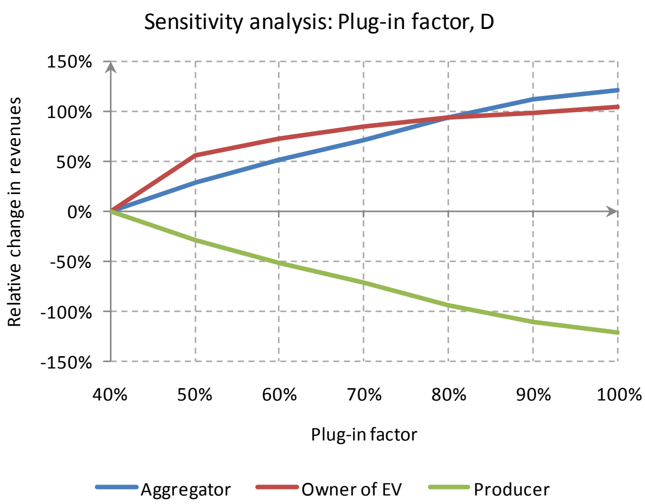

Figure 59: Scenario II, D, plug-in factor

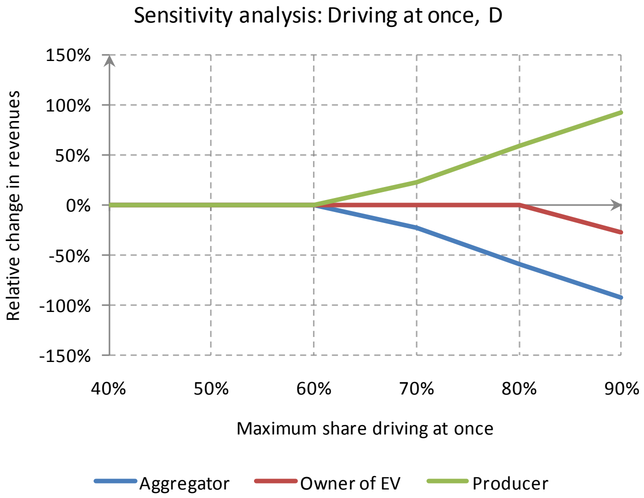

Figure 60: Scenario II, D, driving at once

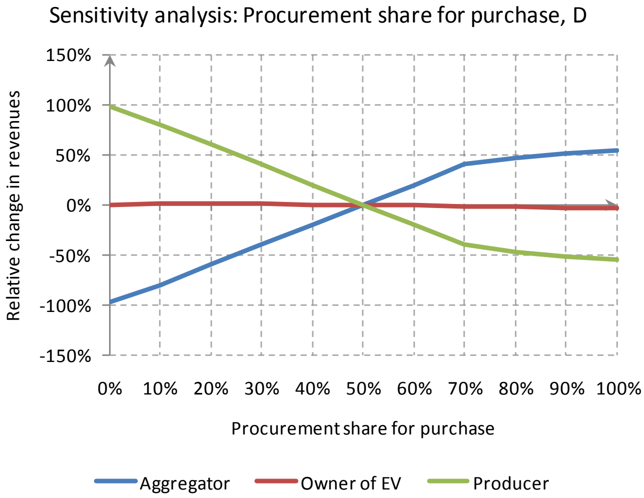

Figure 61: Scenario II, D; power for purchase

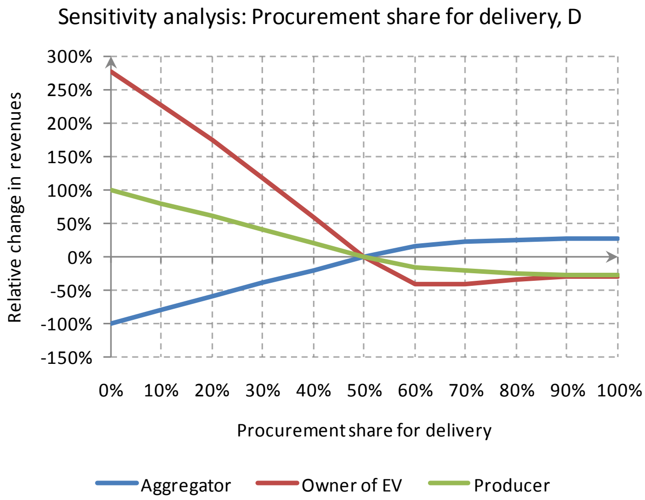

Figure 62: Scenario II, D, power for delivery

5.3.3. Scenario III

In scenario III the number of EVs controlled by the aggregator is 1,000,000. The annual changes in revenues for all four business models are shown in Figure 63 and Figure 64. The development of revenues over the various business models is similar to that in scenario I. The greatest revenues of aggregator and OEV together are achieved in business model D.

Business model A

The annual savings experienced by the OEV amount to 103 € per EV. This is the same value as in scenario I and scenario II because electricity prices did not change.

All sensitivities are identical to the ones in scenario II.

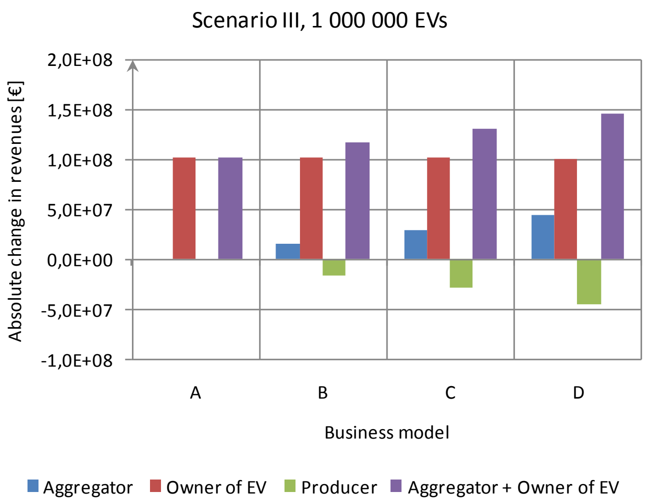

Figure 63: Scenario III, revenues (absolute)

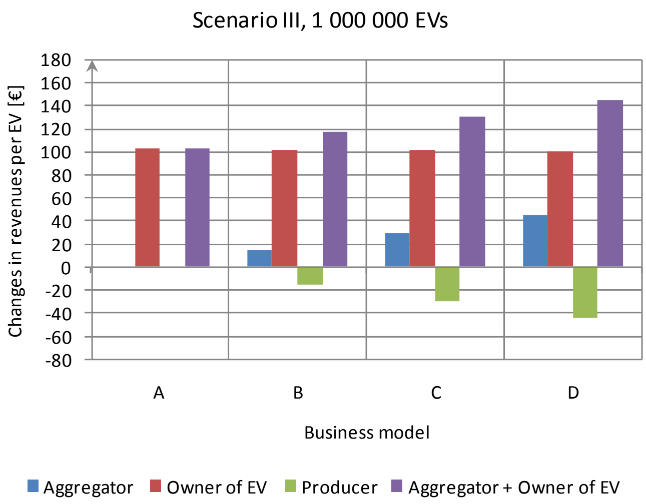

Figure 64: Scenario III, revenues (per EV)

Business model B

The annual revenues the aggregator generates by providing tertiary control power amount to 15 € per EV. Aggregator and OEV together achieve additional annual revenues of 117 € per EV.

The sensitivities to various input parameters are mostly the same as in scenario II. Two exceptions exist. These are the plug-in factor and the maximum share of EVs driving at once.

As shown in Figure 65, the sensitivity to the plug-in factor is slightly lower than in scenario II. Again, the impact a variation of the parameter around its default value produces is small. Aggregator and producer are not affected at all since the number of EVs is sufficient to achieve the desired procurement share even at low values of the plug-in factor.

Since more EVs are available, the impact of the maximum share of EVs driving at once occurs at higher values than in the other two scenarios (see Figure 66).

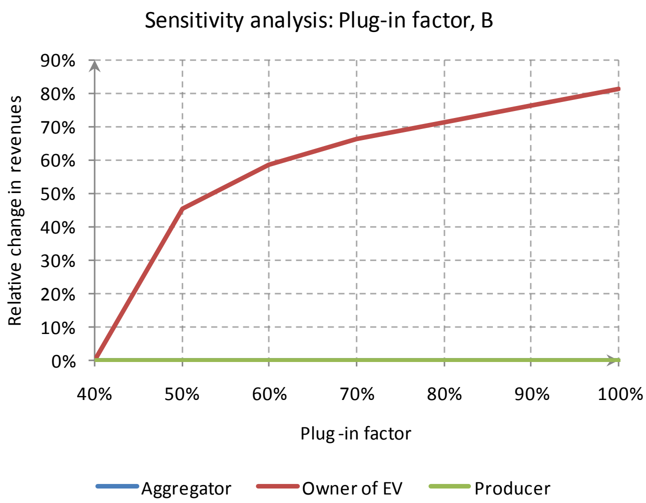

Figure 65: Scenario III, B, plug-in factor

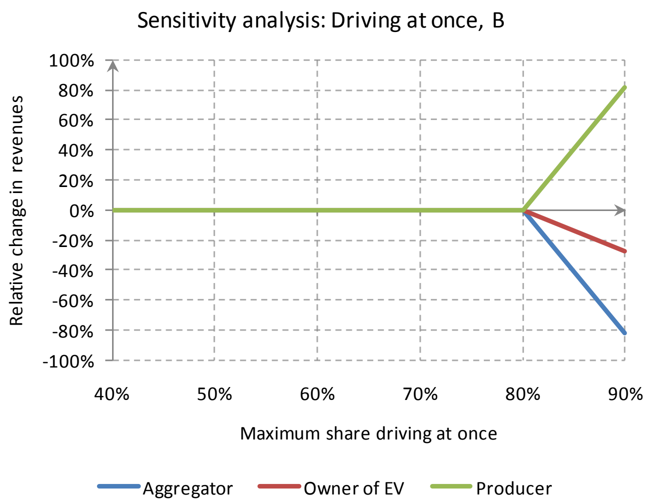

Figure 66: Scenario III, B, driving at once

Business model C

The annual revenues of aggregator and OEV together are 13 € higher than in business model B and amount to 130 €. Like in the other two scenarios, revenues generated by providing secondary control power are greater than those achievable by providing tertiary control power. The achieved procurement share is 100 %.

Apart from the plug-in factor, all sensitivities of changes in revenues to parameters are equal to those in business model B. The effects caused by a change in the smoothing factor are not identical but very similar to those in business model B.

The sensitivity to the plug-in factor is somewhat higher than in business model B. Figure 67 shows that the OEV is the only affected stakeholder. The explanation given in business model B applies here as well.

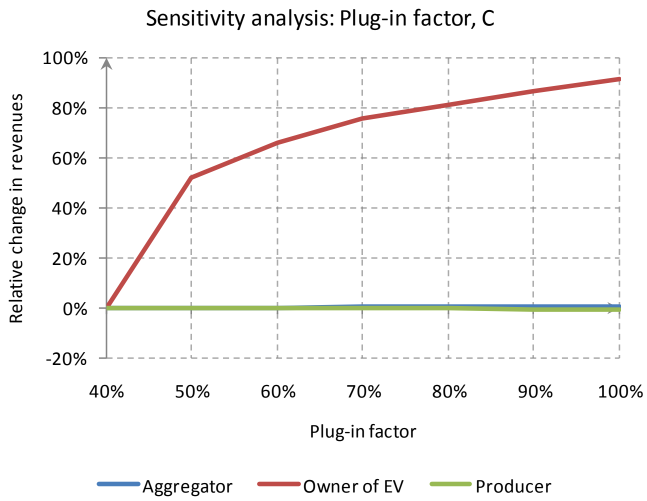

Figure 67: Scenario III, C, plug-in factor

Business model D

The annual revenues of aggregator and OEV together are 15 € higher than in business model C and amount to 145 €. The achieved procurement shares of both secondary and tertiary control power are 100 %. The additional annual revenues per EV (compared to the BAU scenario) created by the aggregator are the sum of the revenues generated by the provision of secondary control and the revenues generated by the provision of tertiary control. The values can be read in Figure 64 and amount to 29 € and 15 € respectively. This is only the case because enough EVs are available to provide all control power that is required.

The sensitivities to most parameters are identical to those in business model C. The ones that are not are discussed now.

The impacts on revenues caused by a change in the smoothing factor are not identical to those in business model C. They are insignificantly higher.

Changes in the plug-in factor mainly affect the OEV. If the plug-in factor is lower than about 50 %, the revenues of aggregator and producer are affected because the desired procurement shares cannot be reached any more (see Figure 68).

A high share of EVs driving at the same time restricts the aggregator in the provision of control power. At a parameter value of around 70 %, the aggregator fails to reach the desired procurement share which results in a decrease in revenues. The corresponding sensitivity analysis is shown in Figure 69.

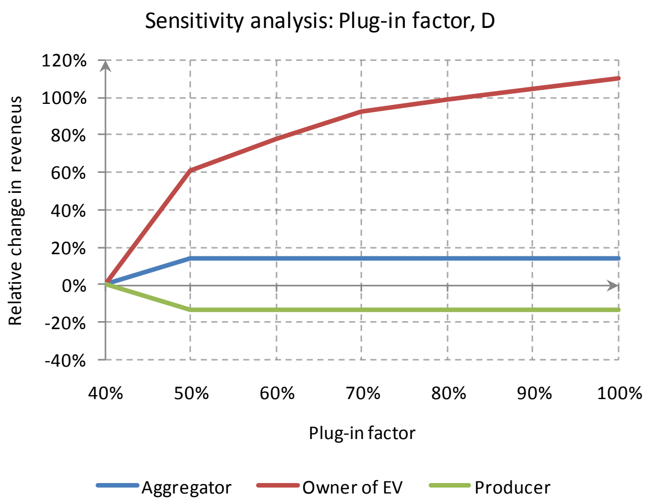

Figure 68: Scenario III, D, plug-in factor

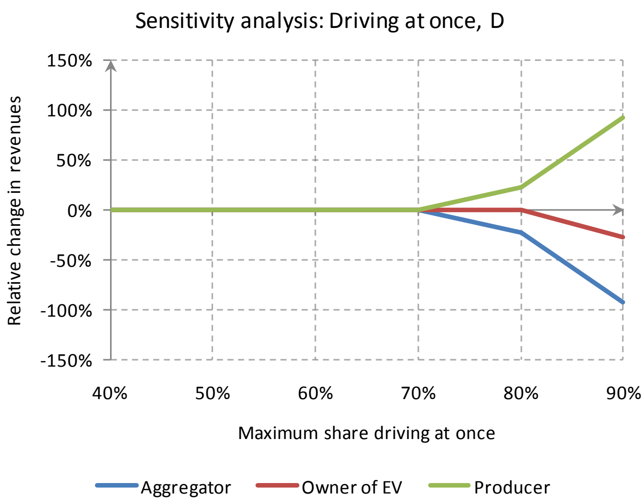

Figure 69: Scenario III, D, driving at once

5.3.4. Comparison of revenues across scenarios

The relevant figure for the creation of financial incentives for OEVs is the sum of the additional annual revenues generated by the aggregator and the OEV divided by the number of EVs. This figure determines the potential profit of aggregator and OEV. The evaluation of actual profits and the way this money is shared among the two stakeholders is not part of this thesis.

Figure 70 shows the annual additional revenues per EV that aggregator and OEV together can generate in each business model in the three scenarios. These are the values when all parameters that can be controlled by the aggregator are adjusted so that the sum of the aggregator's and OEV's revenues is maximized (see Table 11). The greatest revenues per EV occur in scenario I in business model C and D. Compared to the BAU scenario, additional annual revenues of 171 € are achievable. The reason why business model C and D produce the same results lies in the limited number of EVs which prevents the aggregator from providing tertiary control power in business model D.

The additional annual revenues/savings generated simply by controlled charging (business model A) amount to 103 €. It has to be mentioned that these revenues depend on the BAU scenario (see section 4.2.4). If OEVs are very price sensitive and charge their EV only in cheap intervals of the day, the introduction of an aggregator would result in lower savings.

When comparing the revenues across the scenarios, it is easy to see that revenues per EV decrease as the number of EVs grows. This is due to saturation effects in the provision of control services. If the procurement share is 100 %, which means that all required control power is provided by the aggregator, an increase in the number of EVs does not result in higher revenues of the aggregator. The redundant number of EVs can be interpreted as over capacities which reduce the revenues per EV. This affects all business models except for business model A, which does not allow the provision of control services.

The revenues discussed so far occur if the aggregator provisions only control power for purchase. "Purchase" means that the aggregator has to increase the load if requested by the CAM. Increasing the load is done by increasing charging in the specified interval. The procurement of control power for purchase causes only small restrictions for the aggregator. He has to make sure that the amount of energy charged in each interval is lower than the maximum chargeable amount in this interval. Otherwise he would not be able to increase the charging if required. This results only in minor cost increases. In the Matlab model, these cost increases, if applicable, are allocated to the OEV as he has to charge in more expensive periods.

Sensitivity analyses show that an increase in the procurement share of control power for delivery has a negative effect on the revenues of aggregator and OEV together. "Delivery" means that the aggregator has to decrease load if requested by the CAM. When the aggregator provides control power for delivery, he has to be able to decrease the charging in the specified interval if required. In order to do so, he has to charge a certain amount of energy in each interval. This implies that he has to charge EVs also during pricy periods of the day which results in dramatic cost increases for the OEV. Figure 71 shows the results when instead of control power for purchase, control power for delivery is provided. The revenues in business model A are unaffected since no control services are provided in this business model.

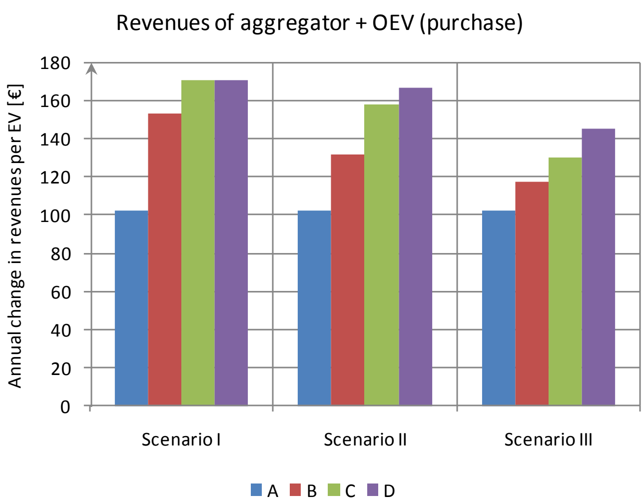

Figure 70: Revenues in the case of purchase

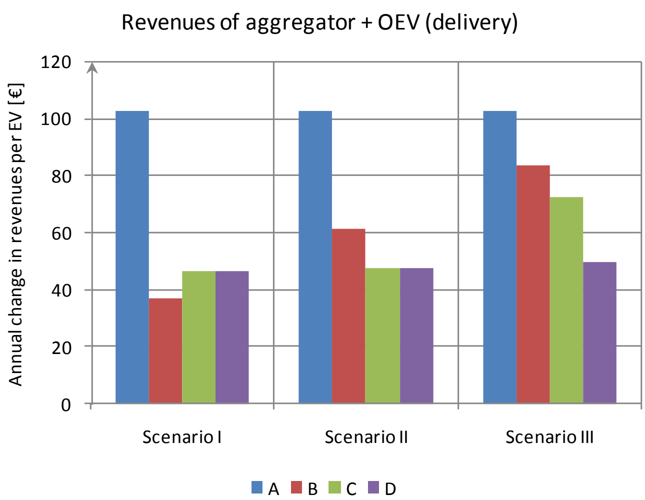

Figure 71: Revenues in the case of delivery

Across all scenarios, the revenues are insensitive to the battery capacity within a wide range. Since discharging back into the power grid is not executed in any of the business models (in order to prevent additional battery wear), the energy that can be used for the provision of control services is limited by the energy consumed for daily driving. This is determined by the daily driven distance and the efficiency of the vehicle. Provided that battery capacities are sufficient to allow drivers at least to cover the average daily driven distance (37.68 km), the daily consumed energy and not the battery capacity pose the relevant limit for the provision of control power.

6. Conclusion

This work examines application possibilities of the connection of EVs to the power grid in terms of controlled charging and the provision of ancillary services to grid operators. The growing share of renewable technologies, such as wind power, in the electricity system increases the amount of required control power, which is necessary to keep generation and consumption in balance at all times.

Research on the electricity market and markets for control services was conducted in order to identify stakeholders. A business concept that introduces a new actor, the aggregator, was constructed. Business models were developed and implemented in Matlab using a bottom-up approach. Most data was acquired from online databases and is of the year 2010 since this is the most recent year for which complete data is available. Scenarios were used to examine the economic impacts the application of these business models have on market participants. Sensitivity analyses were applied to study the significance of parameters.

The stakeholders financially affected by the integration of EVs are the aggregator, the OEV and the electricity producer. The aggregator functions as a mediator between the OEV and the electricity market. He controls the charging of his EV fleet and thereby achieves cost savings for the OEV by charging in cheap periods of the day. He can generate additional revenues by providing ancillary services to the CAM in order to support the electricity system.

The use of EVs for the provision of control power allows aggregators and OEVs to increase their revenues. This increase in revenues goes in hand with declining revenues of producers as their share on the provision of control power declines. This latter effect should not be seen too critical since the increase in renewable technologies may lead to a significant rise in the amount of required control power.

The aggregator should only provide control power for purchase, not for delivery. The procurement for control power for delivery results in cost increases for the OEV (due to charging in more expensive periods) that cannot be compensated by revenue increases of the aggregator. From a financial point of view, EVs should therefore not be used to provide control power for delivery.

The amount of control power that can be provided by the aggregator is very sensitive to the plug-in behaviour of OEVs. The aggregator should therefore create financial incentives in order to increase the time EVs are plugged in.

The amount of control power that can be provided by the aggregator is limited by the energy consumed daily for driving, since discharging into the power grid is not intended in this work.

The amount of control power that can be provided by the aggregator is insensitive to the battery capacity. The battery capacity poses an upper limit but this limit is not relevant, since the restrictions caused by the daily consumed energy are stricter.

There is a trade-off between the provision of control power for delivery and the flattening of the total load curve of a control area. The procurement of control power for delivery (regulate down) forces the aggregator to charge EVs in all those periods where he provides ancillary services. The provision of control power for delivery is, hence, not only financially unattractive but also counteracts the flattening of the total load curve of a control area.

The revenues of aggregator and OEV are higher the more control power is provided. The highest revenues can be generated in business model D (controlled charging including the provision of secondary and tertiary control services). Disregarding costs of the required communication infrastructure, this business model is the most desirable one for the aggregator and the OEV. Business model A (controlled charging without the provision of ancillary services) is the most preferable one for the producer as he does not face competition by the aggregator. It is thinkable that the functions of the aggregator and the producer are in the hands of one enterprise (a supplier). The use of EVs for the provision of control power for purchase could come at lower costs than the utilization of power plants for this purpose.

The application of the business models examined in this work does not increase battery wear since no additional discharging occurs and only the amount of energy that has to be charged anyway in order to meet driving requirements is charged. The choice of a business model is therefore rather a question of the available communication infrastructure. Business model B (controlled charging including the provision of tertiary control services) requires bidirectional communication in intervals of minutes (e.g. 7 minutes). Business model C (controlled charging including the provision of secondary control services) and D require bidirectional communication in intervals of seconds (e.g. 20 seconds).

Revenues generated per EV decrease when the number of EVs increases. The reason are saturation effects that occur when more EVs are available than needed to provide the required amount of control power.

The additional annual revenues per EV that can be generated by aggregator and OEV together are shown in Figure 72. These are additional revenues compared to the BAU scenario, in which charging is not controlled by an aggregator. The highest specific revenues are achievable in scenario I where the aggregator controls the charging of 100,000 EVs. Aggregator and OEV together can generate additional annual revenues of up to 171 € when business model C or D is applied. The revenues per EV decrease as the number of EVs grows. This is due to saturation effects in the provision of control services. If all required control power is already provided by the aggregator, an increase in the number of EVs does not result in higher revenues of the aggregator. The redundant number of EVs reduces the revenues per EV. This affects all business models except for business model A, which does not allow the provision of control services.

The findings of this work suggest that aggregators should be introduced in order to realize the integration of EVs in the electricity market. Aggregators should manage the charging so that energy is consumed when prices are low. This results in a flattening of the load curve in the control area of APG. Once the market penetration of EVs has risen to about 100,000 EVs (which is equivalent to 2.3 % of passenger cars in Austria), the aggregator should participate in the markets for control energy. If the available communication infrastructure meets the time requirements, he should provide secondary and tertiary control power for purchase. The priority should lie on the provision of secondary control power since this is economically more attractive.

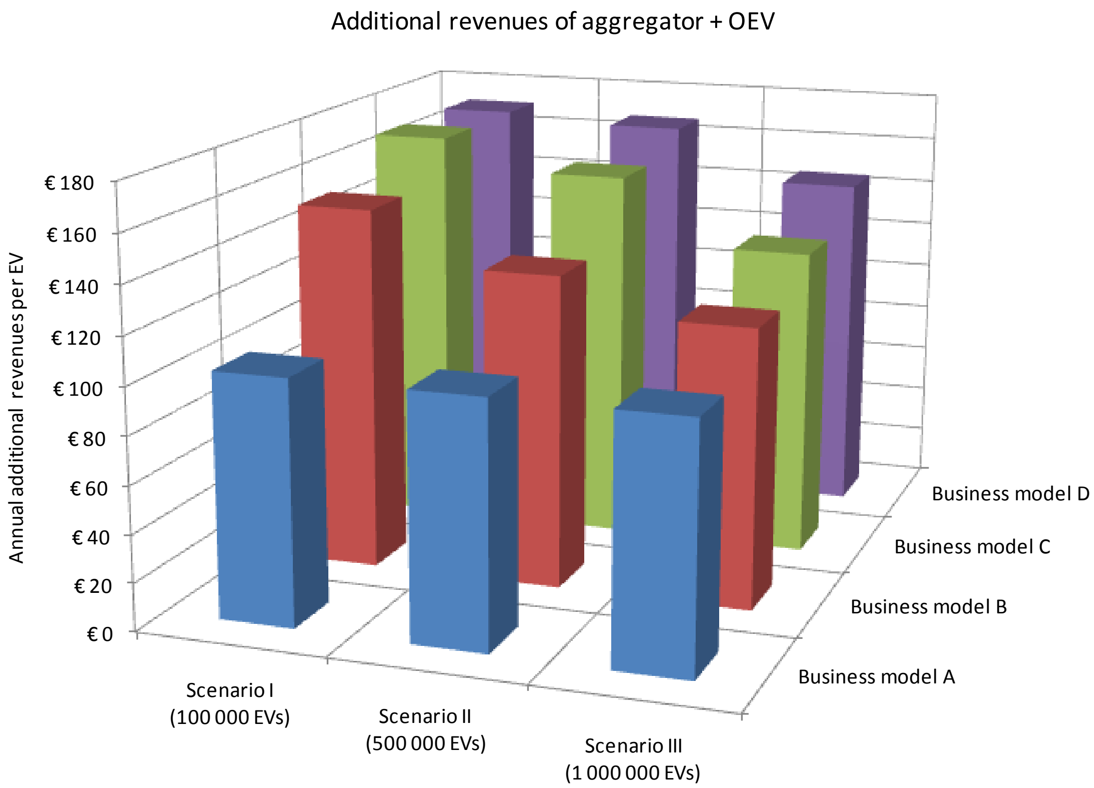

Figure 72: Annual additional revenues achievable by the application of business models

If a suitable infrastructure is available (smart grid) it would make sense to use it for the provision of control services by the use of EVs.

In this work, the additional revenues that can be generated by the provision of control services were examined. In order to find out whether they justify the construction of the required communication infrastructure, the costs of such an infrastructure need to be studied.

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Appendix

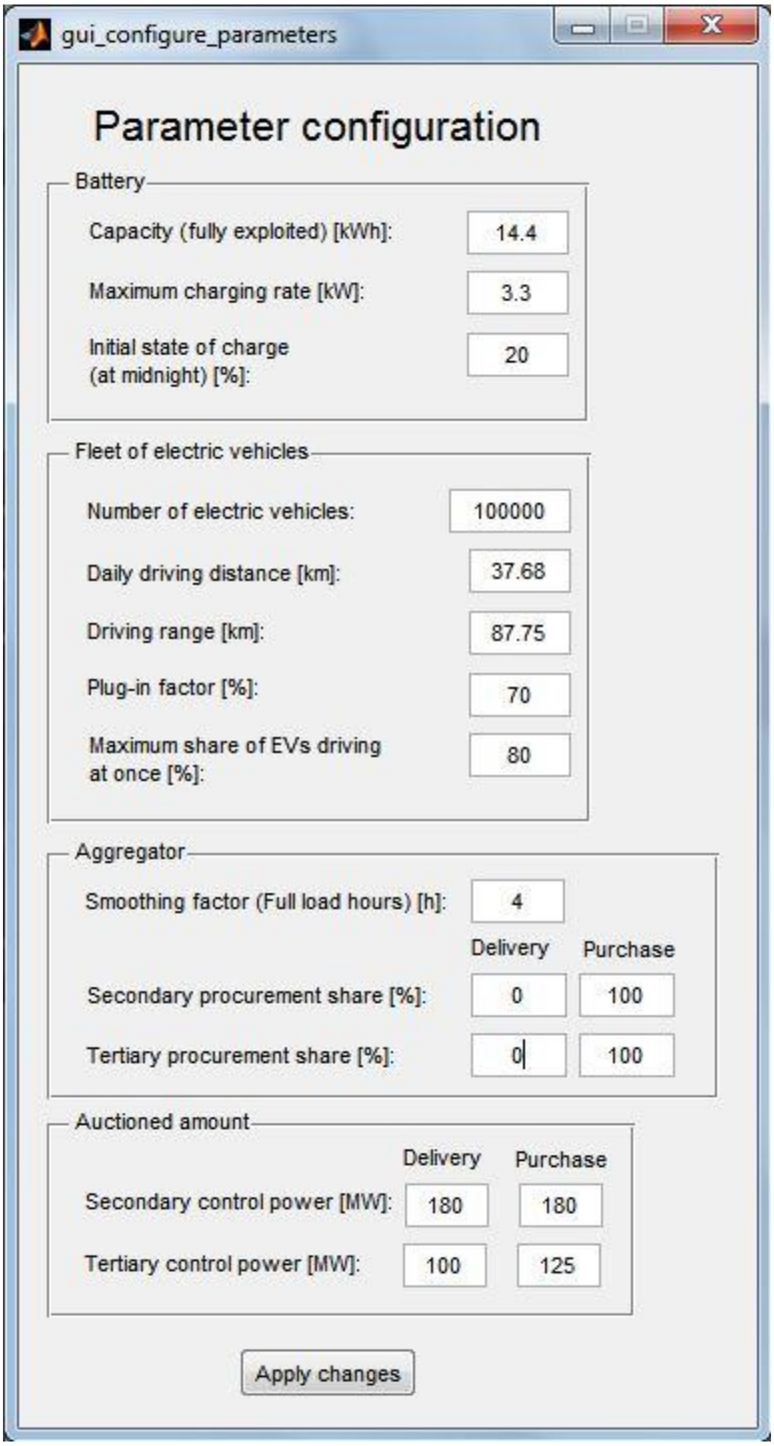

Figure 73: GUI that allows to configure parameter and show default values

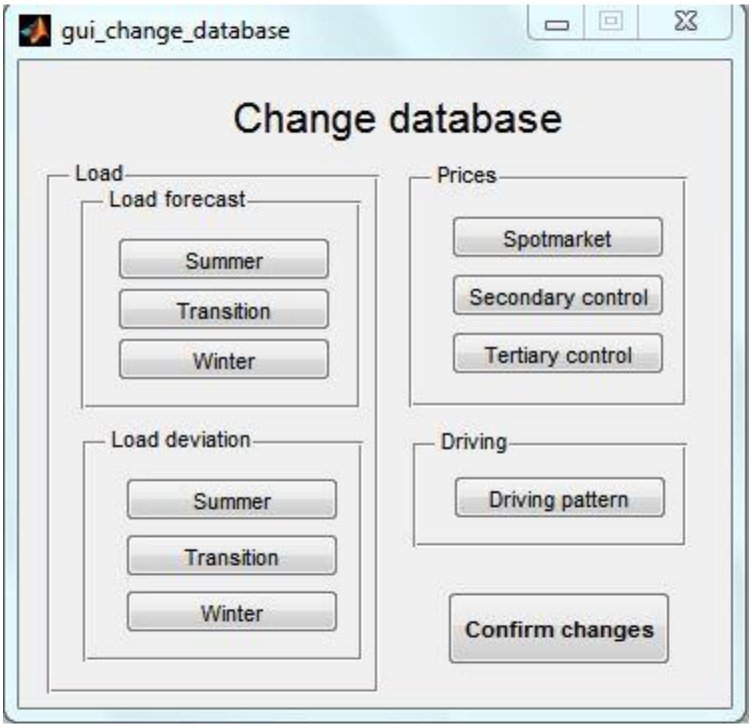

Figure 74: GUI that allows to select Excel-Files which contain input data

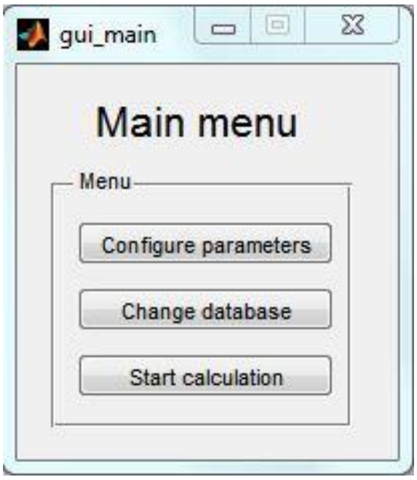

Figure 75: Main GUI that opens when the Matlab model is started

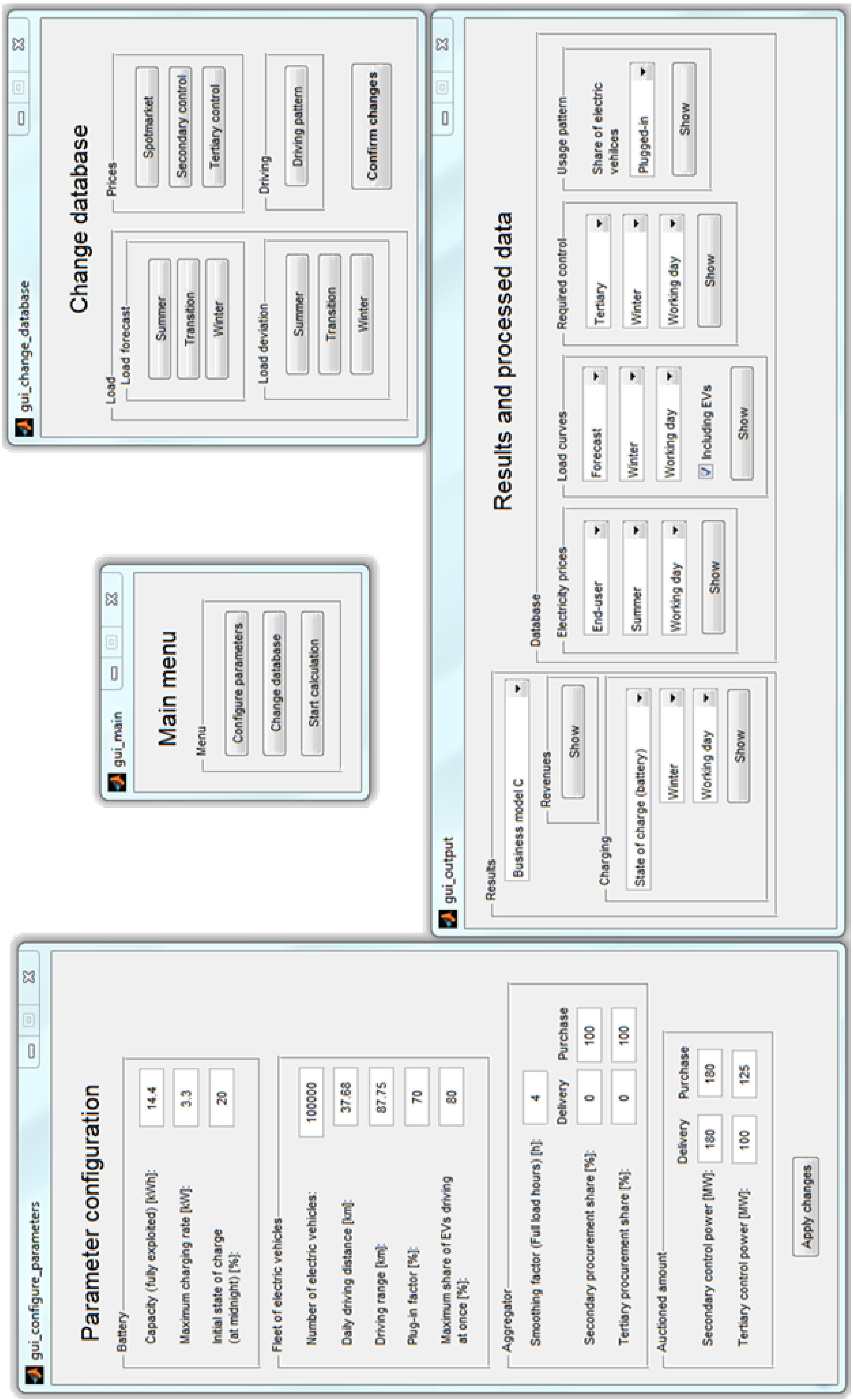

Figure 76: GUIs of the Matlab model

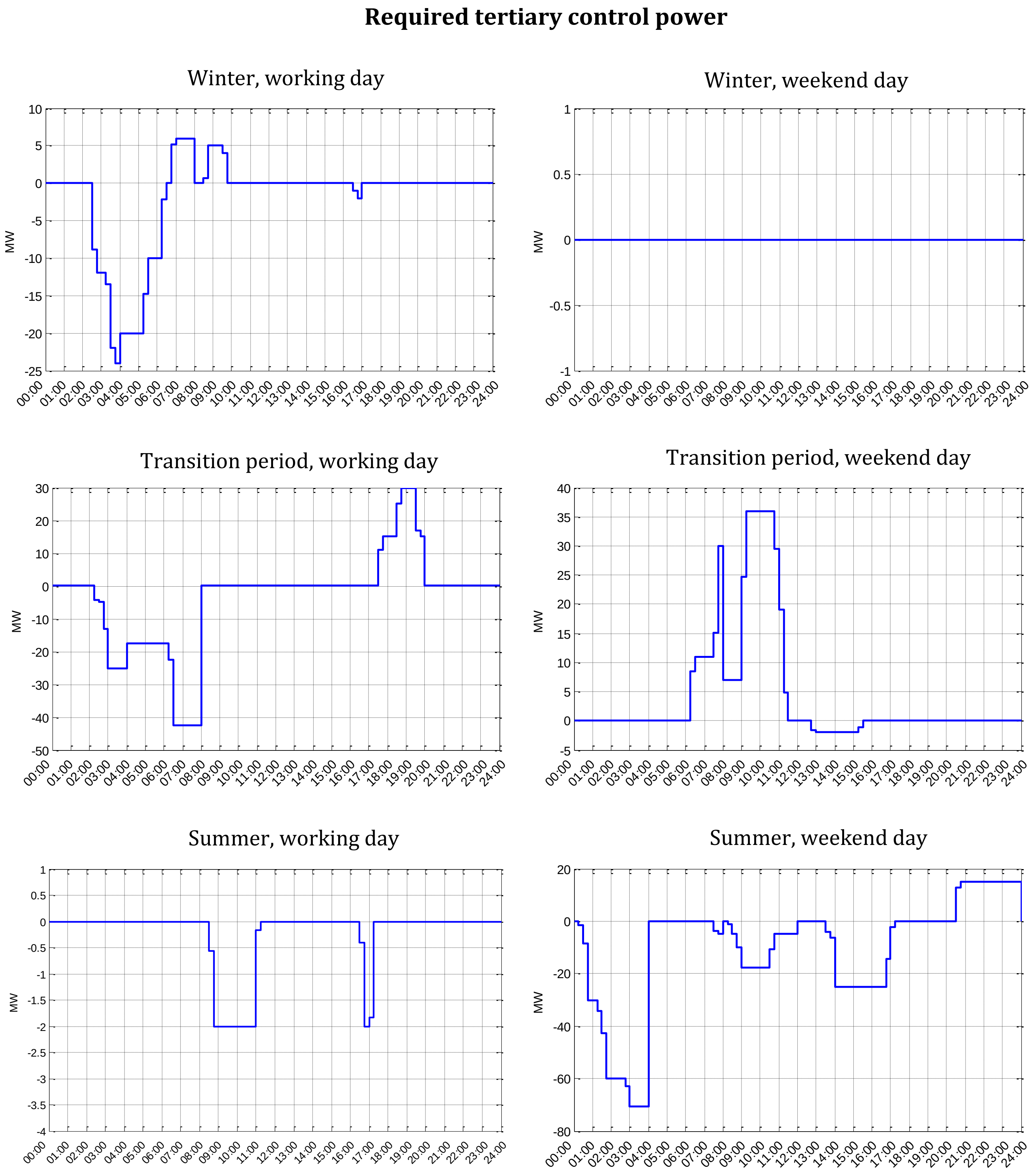

Figure 77: Required tertiary control power (APG 2011d)

Required secondary control power

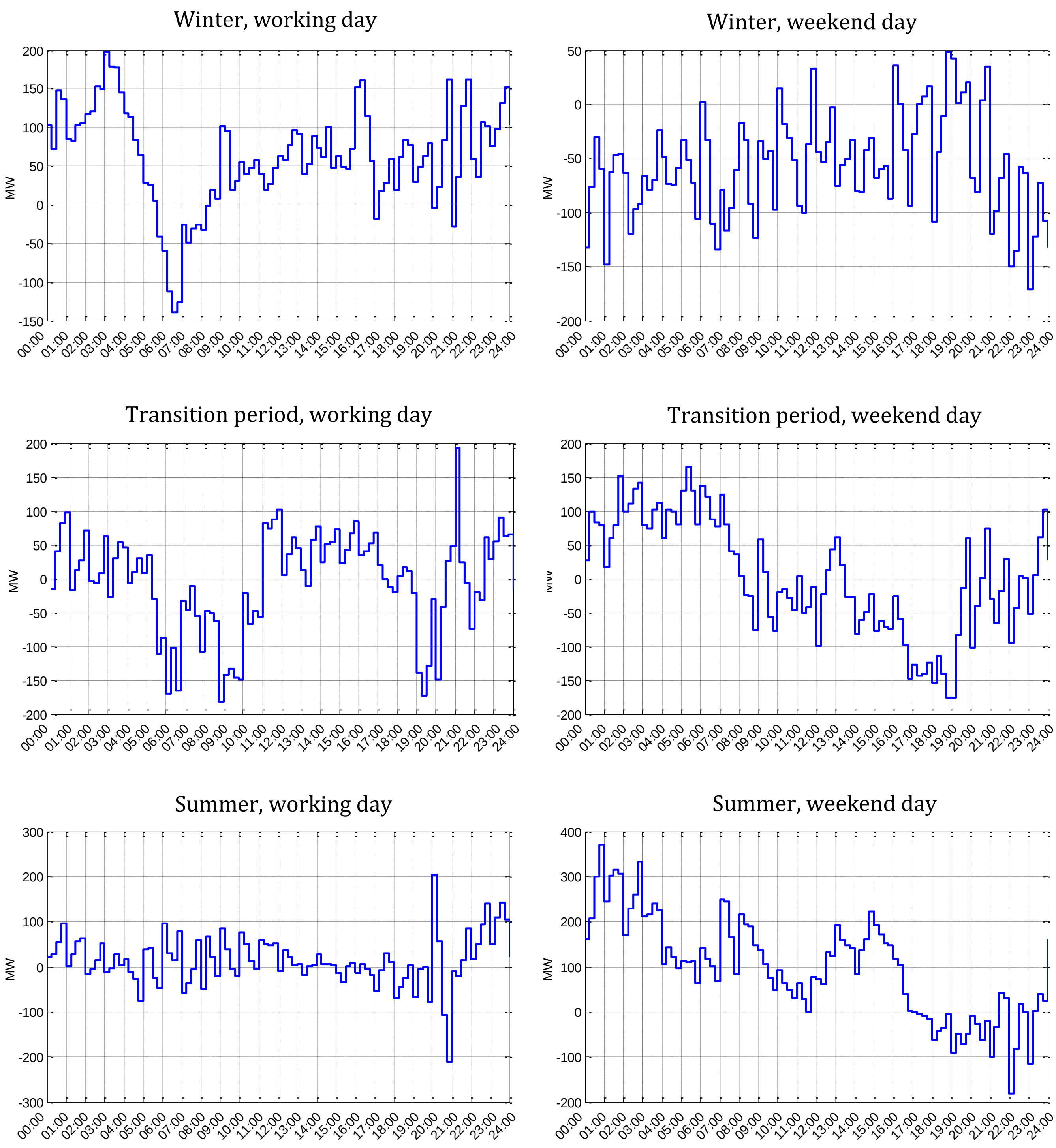

Figure 78: Required secondary control power (APG 2011d)

Additional outputs of the Matlab model

The Matlab model calculates not only the financial effects business models have on stakeholders but also the charging patterns, the development of the SOC over time and the released control power. The following figures show these outputs for scenario III when business model D is applied. Figure 79 to Figure 85 show the results when control power for purchase is provided and the parameters are chosen according to Table 12. Figure 86 to Figure 92 show the results when control power for delivery is provided and the parameters are chosen according to Table 13. Parameters not listed in these tables are set to their default values (see Figure 73). The following figures show the situation for a working day in winter. The letters “d” and “p” stand for the kind of provided control power, “delivery” and “purchase” respectively. The Matlab model executes the calculations for working days and weekend days in all three seasons.

Table 12: Optimal parameter values (for the provision of control power for purchase)

Parameter	Value
Desired procurement share secondary delivery:	0 %
Desired procurement share secondary purchase:	100 %
Desired procurement share tertiary delivery:	0 %
Desired procurement share tertiary purchase:	100 %
Initial state of charge:	10 – 40 %
Smoothing factor:	4 – 8 h

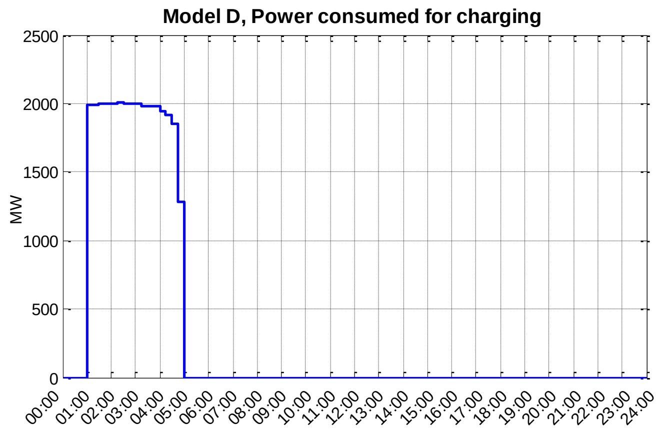

Figure 79: III, D, forecasted charging, p

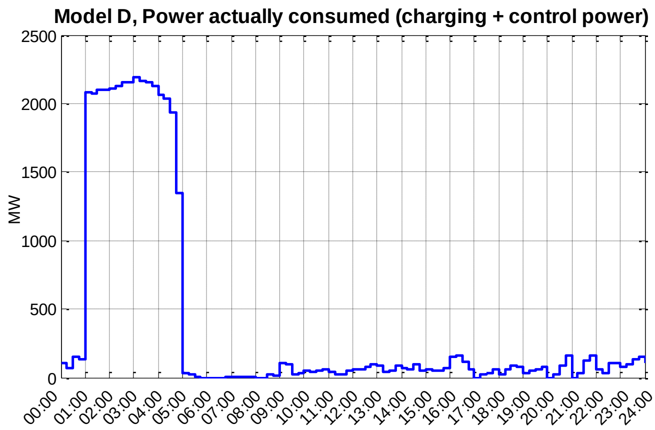

Figure 80: III, D, actual charging, p

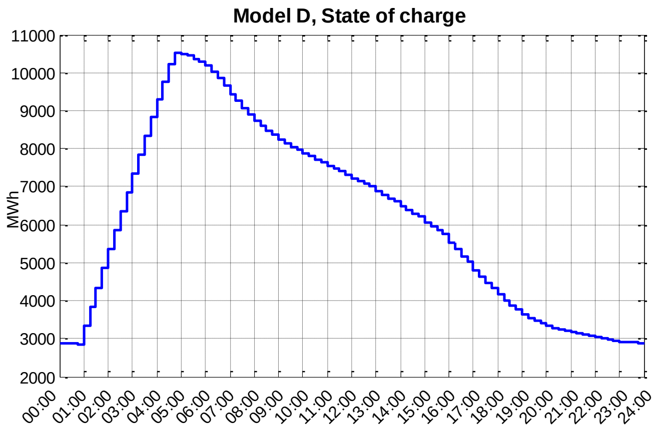

Figure 81: III, D, SOC, p

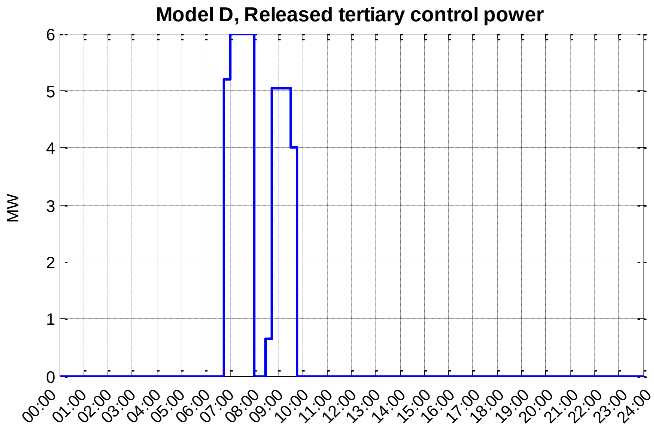

Figure 82: III, D, released tertiary power, p

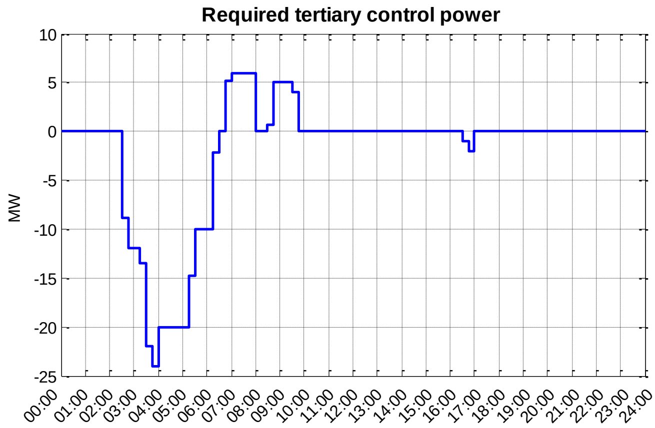

Figure 83: III, required tertiary power

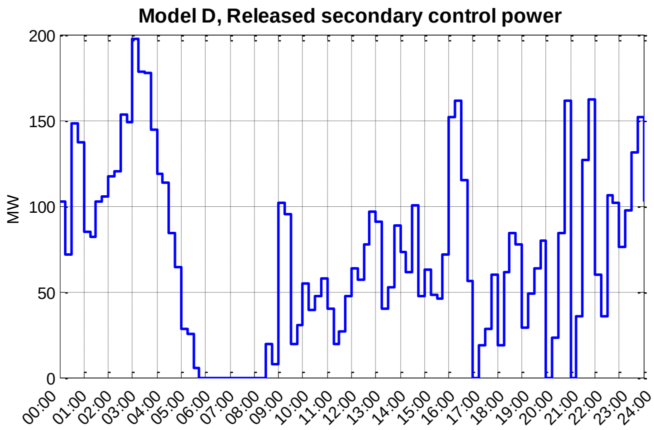

Figure 84: III, D, released secondary power, p

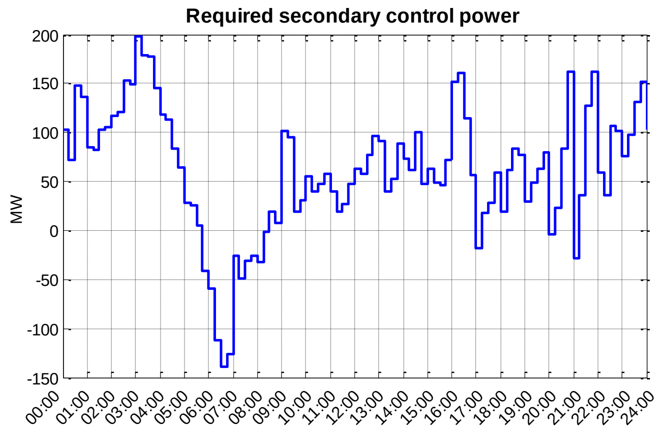

Figure 85: III, required secondary power

Table 13: Parameter values (for the provision of control power for delivery)

Parameter	Value
Desired procurement share secondary delivery:	100 %
Desired procurement share secondary purchase:	0 %
Desired procurement share tertiary delivery:	100 %
Desired procurement share tertiary purchase:	0 %
Initial state of charge:	10 – 40 %
Smoothing factor:	4 – 8 h

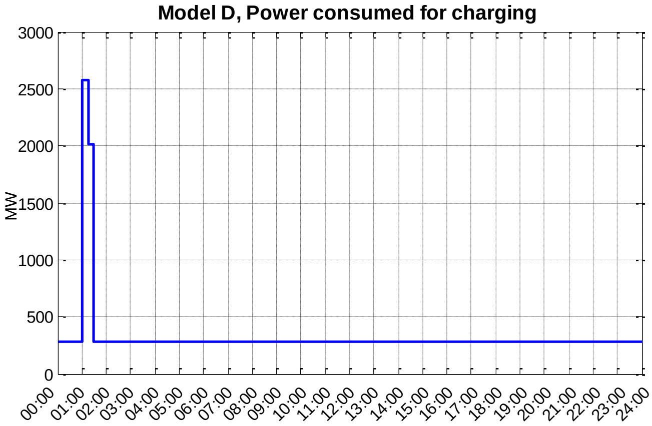

Figure 86: III, D, forecasted charging, d

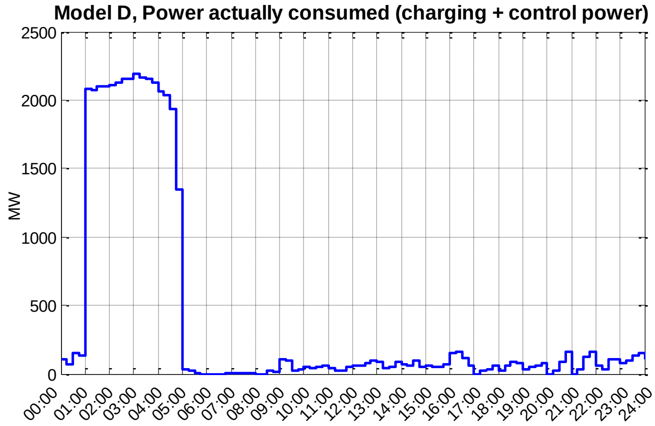

Figure 87: III, D, actual charging, d

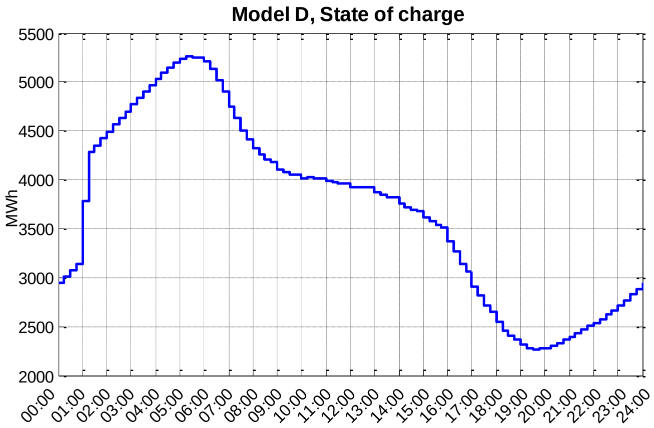

Figure 88: III, D, SOC, d

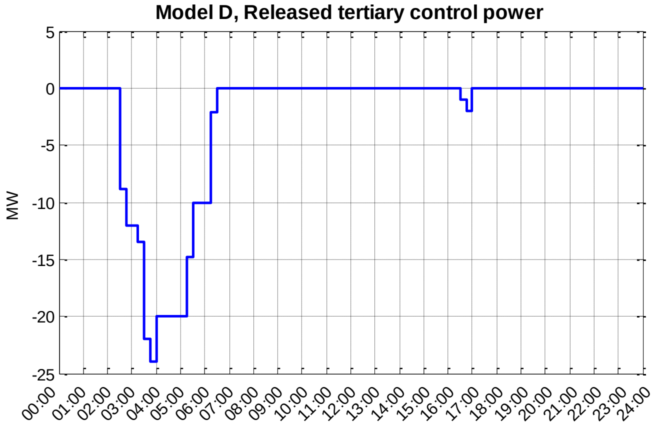

Figure 89: III, D, released tertiary power, d

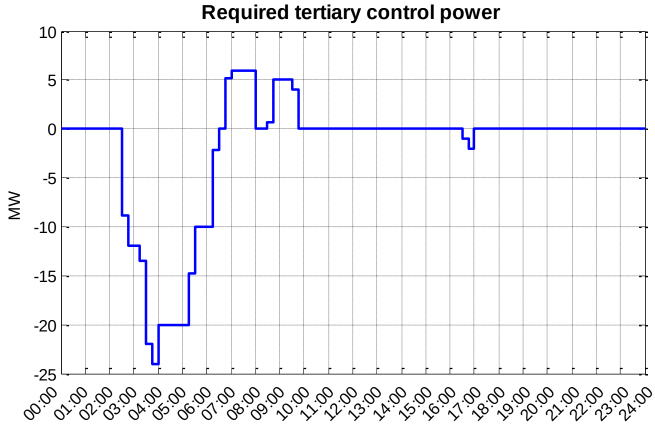

Figure 90: III, required tertiary power

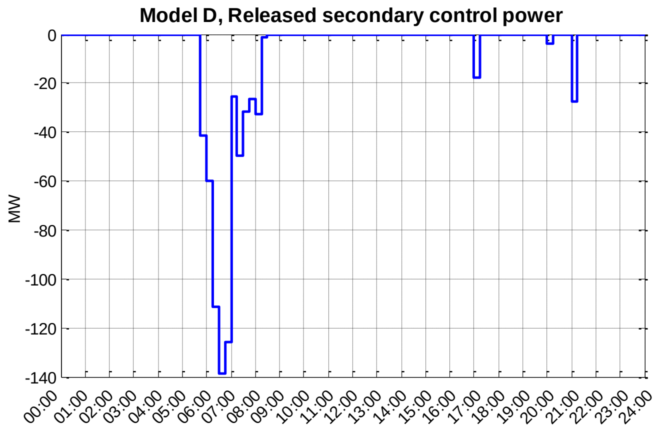

Figure 91: III, D, released secondary power, d

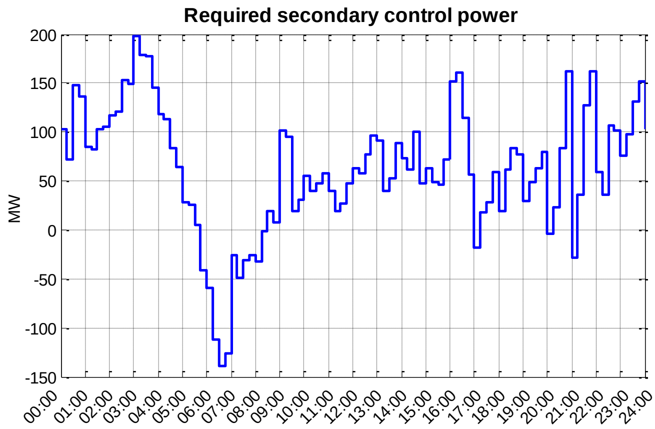

Figure 92: III, required secondary power