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Master Thesis

Maximizing Profits for an Aggregator Providing Vehicle-to-Grid and Smart Charging Services in the Dutch Market

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Abstract

In this thesis the profits for an aggregator providing regulating services for the electricity markets in the Netherlands is ought to be maximized. An aggregator is required in order to combine the battery capacities of several Electricial Vehicles (EVs). The aggregated battery capacity can be used to store energy via Smart Charging (SC), and to provide electricity back to the grid via Vehicle-to-Grid (V2G). This thesis considers several important practical considerations, including the real bidding horizon, realistic degradation costs, and an incitement compensation for EV owners. For the latter, a survey is conducted to obtain a realistic estimate of the height of the incitement compensation required to motivate EV owners to participate in V2G and SC. The public acceptance of V2G and SC is fundamental for the socio-technical system that is V2G and SC. This work simulates a profit optimization algorithm using Model Predictive Control (MPC) to estimate the potential profits of an aggregator in the Netherlands. For V2G, potential benefits are between -€14,60 and €773,80, and for SC between -€120,45 and €244,55. The large range of potential benefits is due to the different types of EV, and other practical considerations.

Acknowledgement

In this thesis the socio-technical problems of V2G are addressed, which could not have been possible without the collaboration between the Faculty of Science and Engineering and the Faculty of Behavioral and Social Sciences of the University of Groningen. I would like to thank several supervisors in particular that helped me with the research, and writing of my thesis. First of all, I would like to thank Sebastian Trip PhD who gave me the opportunity to do research in this topic, helped me with the problem scope and definition, and who provided daily supervision at the beginning. Second, I would like to thank Michele Cucuzzella PhD, who was involved with my thesis from the beginning. He provided daily supervision to the end, and allowed me to write my own work, but steered me in the right direction whenever I needed it. Third, I would like to thank Thijs Bouman PhD from the Faculty of Behavioral and Social Sciences, who helped me address the social aspects of V2G, using a survey. Thijs Bouman PhD assisted me in designing and analyzing the survey. Lastly, I would like to thank my first and second supervisors, prof. dr. ir. Jacquelien M.A. Scherpen and prof. dr. ir. Ming Cao respectively for providing me with interesting feedback and giving me the opportunity to address the problems of my interests.

Contents

Nomenclature

B_i^{cap}	Battery capacity of vehicle i
B_i^{cp}	Connection power of vehicle i
$B_i^{deg}(t)$	Variable to model battery degradation
B_i^{DOD}	Depth of charge of the battery of vehicle i
$B_i^{POP}(t)$	Preferred operating point of vehicle i at time t
$Benefits$	The total benefits with respect to the baseline of an aggregator
C	Costs of the aggregator
$C_i^{battery}$	Battery pack replacement costs of vehicle i
C_i^{deg}	Degradation costs of the battery
$C^{El,normal}$	Normal electricity costs for regular charging
C^{incite}	Motivation compensation for vehicle i
$Cvar(t)$	Variable costs at time t
$E_i^{AP\downarrow}(t)$	Maximum additional power draw of vehicle i at time t
$E_i^{AP\uparrow}(t)$	Minimum additional power draw of vehicle i at time t
$E_i^{IMD\downarrow,bid}(t)$	Energy sourcing capacity bid in the IDM for vehicle i at time t
$E_i^{IMD\downarrow,provide}(t)$	Energy sourcing capacity provided in the IDM by vehicle i at time t
$E_i^{IMD\uparrow,bid}(t)$	Energy supplying capacity bid in the IDM for vehicle i at time t
$E_i^{IMD\uparrow,provide}(t)$	Energy supplying capacity provided in the IDM by vehicle i at time t
$E^{R\downarrow}(t)$	Regulation down capacity of an aggregator at time t
$E^{R\uparrow}(t)$	Regulation up capacity of an aggregator at time t
$E_i^{REG}(t)$	Energy required for regular charging by vehicle i at time t
$E^{RR}(t)$	Responsive reserve capacity of an aggregator at time t
$E_i^{RRP\downarrow,bid}(t)$	Energy sourcing capacity bid in the RRP market for vehicle i at time t
$E_i^{RRP\downarrow,provide}(t)$	Energy sourcing capacity provided in the RRP market by vehicle i at time t
$E_i^{RRP\uparrow,bid}(t)$	Energy supplying capacity bid in the RRP market for vehicle i at time t
$E_i^{RRP\uparrow,provide}(t)$	Energy supplying capacity provided in the RRP market by vehicle i at time t
$E_i^{SR}(t)$	Reduction in power draw available for spinning reserves of vehicle i at time t
E^{system}	System net load at time t
$E_i^{V2G}(t)$	Total power for V2G combining regulation and responsive reserves
$E^{\epsilon,max}$	Maximum day-ahead forecasted load
$E^{\epsilon,min}$	Minimum day-ahead forecasted load
$E^{\downarrow,\uparrow}$	Energy for regulating services up and down
In	Income of the aggregator
$P^{El,charged}$	The price of energy charged to the customer
$P^{El,normal}$	normal regular electricity price
$P^{IDM\downarrow,bid}(t)$	Bid price energy sourcing for the IDM at time t
$P^{IDM\uparrow,bid}(t)$	Bid price energy supplying for the IDM at time t
$P^{R\downarrow}(t)$	Forecasted price of regulation down for time t
$P^{R\uparrow}(t)$	Forecasted price of regulation up for time t
$P^{RR}(t)$	Forecasted price of responsive reserves for time t
$P^{RRP\downarrow,bid}(t)$	Bid price energy sourcing for the RRP market at time t
$P^{RRP\uparrow,bid}(t)$	Bid price energy supplying for the RRP market at time t
$P^{RRP\downarrow,settle}(t)$	Settlement price energy sourcing for the RRP market at time t

$P^{RRP\uparrow,settle}(t)$	Settlement price energy supplying for the RRP market at time t
$P^{\downarrow,\uparrow}$	Price for regulating services up and down
$Profit^{RRP,t}$	Profits of providing RRP services at time t
$Profit^{baseline,t}$	Profits of the baseline scenario at time t
$SOC_i(t)$	State of charge of vehicle i at time t
SOC_i^{GDR}	Minimal guaranteed driving range SOC of vehicle i
$SOC_i^{initial}$	Initial SOC of vehicle i when it plugs-in
$SOC_i^{req}(t)$	The required SOC to charge vehicle i to SOC^{trip} at time t
$SOC_i^{trip}(t^{trip})$	The required SOC of vehicle i at time of departure
T_i^{charge}	The time vehicle i enables V2G or SC
$\alpha_i(t)$	Compensation variable to account for unplanned departure of vehicle i at time t
$\epsilon[...]$	Expected value function
η_i	Charging efficiency of vehicle i
η_{tr}	Transmission efficiency of the net
$\rho_i(t)$	Term to account for discharge efficiency
ϕ_i	Binary variable to indicate V2G or SC
$_i$	Binary variable to indicate priority or normal charging

List of Abbreviations

B	B value of linear regression
C	Commuter
DAM	Day-Ahead Market
DOD	Depth Of Discharge
DSO	Distribution System Operator
EMPC	Economic Model Predictive Control
ESR	Equivalent Series Resistance
EV	Electrical Vehicles
GDR	Guaranteed Driving Range
G2V	Grid-to-Vehicle
H	Hypothesis
LB	Lower Bound
M	Mean
MPC	Model Predictive Control
OTC	Over-The-Counter
PHEV	Plug-in Hybrid Electrical Vehicle
PRP	Program Responsible Party
PTU	Program Time Unit
R	Resident
RC	Resident Commuter
RRP	Regulation and Reserve Power
RQ	Research Question
SC	Smart Charging
SD	Standard Deviation
Sig	Significance two-tailed value
SOC	State Of Charge
SQ	Subquestion
TSO	Transmission System Operator
UB	Upper Bound
USEF	Universal Smart Energy Framework
V2G	Vehicle-to-Grid

1 Introduction

The electricity generation throughout the world is shifting from the depletion of natural resources towards a sustainable generation of electricity using solar energy and wind farms. The concerns about global warming and energy independence push these technological changes [13]. This also resulted in the trend of Electrical Vehicles (EVs) becoming more popular [21]. The market of producing EVs has gained priority as well, several European countries even plan to prohibit the sale of combustion engine type cars by 2040 in e.g. France and Germany [26].

The early concerns that coincided with the use of EVs, such as short driving range and long loading time, have been mitigated over the years. Nowadays, the EVs gain increasing popularity over the years. However, alongside the growing share of sustainable electricity generation, the gradual increase of EVs poses serious challenges for the electricity grid. The increase of the number of EVs that require charging, will push the boundaries of the electricity grid's capacity. Besides, the generation of sustainable electricity cannot be controlled.

As a result of the challenges, efficient storage of electricity has become of major importance. However, large storage facilities are expensive. As a consequence, the need for a change in the energy network arises. The Universal Smart Energy Framework (USEF) was founded to drive the fastest, most cost-effective route to an integrated smart energy future [44]. The key attribute of USEF is the trading of energy and flexibility in energy. Flexibility is considered as a product in by USEF and can be contribute in electricity markets where short-term changes to demand and supply are traded. This study is inspired by this framework. Therefore, the USEF framework is briefly explained in the next Section.

1.1 USEF

A visualization of the USEF interaction model is presented in Figure 1. Note that not all relations and parties will be explained. Not all relations and parties are relevant for now or for this study. In the USEF model it is described how energy and flexibility can be traded. One of the important stakeholders in this model are the prosumers. The prosumer is a consumer of electricity who is also producing electricity and creating flexibility. Electricity can be produced using e.g. solar panels. Flexibility can be created by e.g. doing laundry during the night instead of at peak hour.

An aggregator is required to combine the produced energy and flexibility of multiple prosumers in order to create a large capacity of energy and flexibility. Without an aggregator, a prosumer has little to no impact to the stabilization of the electricity grid. The combined capacity of all prosumers can be traded in the electricity markets by the aggregator.

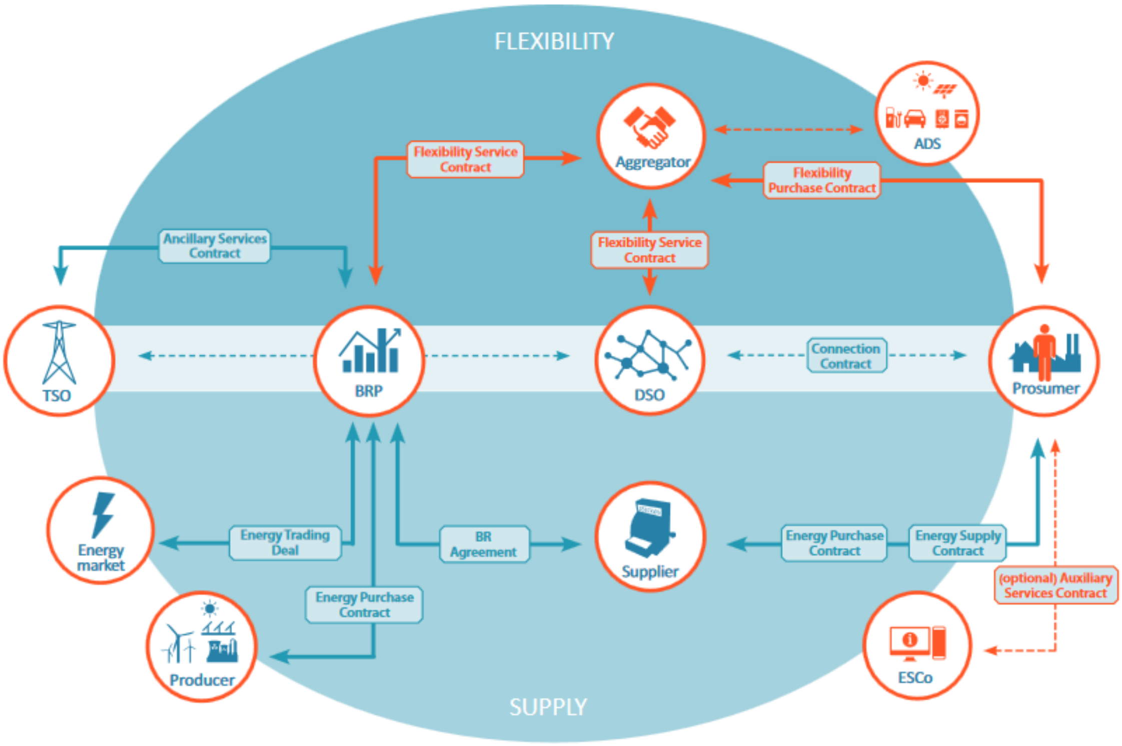

Figure 1: USEF interaction model [44]

Inspired by the USEF model, this study focusses particularly on the prosumers than own an EV. More specifically, only the EVs are used to produce energy and create flexibility, i.e. households are not considered. EVs are in possession of batteries for their primary function of transportation. These batteries can however, also be used to store electricity, create flexibility, and to provide energy back to the grid. This is called Vehicle-to-Grid. In this thesis, it is studied how an aggregator could make a profit using EVs to create flexibility and to produce energy. In previous several practical considerations including a bidding horizon and incitement compensation were not considered. Moreover, this thesis studies the Dutch electricity market that could differ from other countries. The contributions and challenges addressed in this thesis are:

Contributions:

- In this thesis a survey is conducted to obtain a realistic estimation of an incitement compensation
- This study formulates a profit optimization problem considering several novel practical consideration including the bidding horizon and the incitement compensation

Challenges addressed in this work:

- The specific case of the Netherlands which has not received much attention besides [17]
- The use Model Predictive Control in the profit optimization algorithm for an aggregator

2 Problem Analysis

The problem analysis encompasses the first Chapter of this research. In the problem analysis a clear overview of the problems undertaken in the research is provided. The problem analysis is performed to obtain a better understanding of the situations and interests of the different stakeholders involved, and to postulate structure for the rest of the research.

- In Section 2.1 the problem context is described
- In Section 2.2 the problem owner analysis is performed, the problem owner of this study is a hypothetical aggregator
- In Section 2.3 the system is described, including a model overview of the system, and the boundaries of the research
- In Section 2.4 the interests and objectives of the other stakeholders involved in the system are examined
- In Section 2.5 the problem definition and the goal of this research are provided
- In Section 2.6 the research question for this study is formulated
- In Section 2.7 the conceptual causal model is presented, the conceptual causal model evaluates the potential problems and challenges that are associated to the research goal
- In Section 2.8 the subquestions are formulated, the subquestions are required to answer the research question
- In Section 2.9 the outline for the rest of this thesis is provided

2.1 Problem Context

Environmental considerations have become a concern many people are aware of nowadays. Besides the numerous changes this required for industries, individuals have also become more conscious of the problems associated to global warming. This supported a shift towards the use of electrical vehicles (EVs). EVs are promising for relieving global warming stresses as they are able to drive using sustainable energy instead of fossil fuels.

Regardless of the environmental advantages the growing electrical vehicle fleet has, for electrical platforms such as electricity producers and the grid transmission operators the growing EV fleet provides both challenges and possibilities. Charging all EVs is one of the major challenge electrical platforms faces. The electricity grid, controlled by the Transmission System Operator (TSO), has a maximum capacity for electricity flow. Charging numerous EVs at the same time could exceed this capacity limit. In addition, charging numerous EVs simultaneously is a challenge for electricity producers as well. This could potentially lead to an increase of electricity generation capacity as the number of EVs keeps growing.

The growing fleet of EVs could however, also be used to stabilize electricity generation and demand. One of the possibilities of the growing electrical fleet is to use the batteries EV inherent as either an electricity source or as storage. Using the batteries as an electricity source is called Vehicle-to-Grid (V2G), and using the batteries of the EV fleet as storage is called Grid-to-Vehicle (G2V). V2G can be used to reduce the necessity to increase electricity generation capacity for the producers. G2V can be used to store electricity generation excesses. By storing excess generated electricity it is prevented that large generators have to be turned-down. Turning-down or decreasing capacity of large generators could lead to high costs.

The possibilities of EVs to stabilize the grid however, do constrain the flexibility of the EV owners. The charging time of an EV could increase, and the owner of the EV might be subject to more additional efforts to make stabilizing the market possible. Because of the necessity of longer charging times to reduce several problems relating to the charging of EVs, EV owners should be incited to lend their EVs to the grid. Lending in this case, implies that EV owners should connect their EV to the grid, and that the grid is then able to use the EV either as a source or storage if needed.

From here on, the term V2G encompasses the bi-directional use of an EV, i.e. using an EV both as a source (V2G) and as storage (G2V). The term Smart Charging (SC) is used to describe the uni-directional use of an EV where the EV is only used as storage (G2V).

V2G and SC possibilities have the potential to assist in the stabilization of the electricity grid by serving as a source or storage. The issue with V2G and SC is that one single EV does not have sufficient capacity to make the difference in stabilizing the grid. In fact ,thousands of EVs are required [35]. In order to facilitate V2G and SC a third party is required, and should combine the capacity of numerous EVs. Such a party is a so-called aggregator [20]. An aggregator is able to stabilize the grid by providing regulating services to the TSO. Providing regulating services can be highly profitable, giving rise to a business model for aggregators.

2.2 Problem Owner Analysis

The problem owner in this research is a hypothetical aggregator. An aggregator is the third party required to combine the capacities of many EVs to generate 'one large battery'. This capacity can be used to make bids in the electricity market. By making these bids, the aggregator is both stabilizing the electricity grid as it is providing regulating services, as well as it is seeking to make some benefits by doing so. The latter objective is actually the main objective of the aggregator, trying to make a profit by providing regulating services. In fact, both objectives are somewhat contradictory. If the objective is to stabilize the grid, the profit margin for the provision of regulating services is low. The prices for regulating services determined by the TSO depend somewhat on the stability of the grid, see Chapter 4for more details. The more stabilized the grid becomes, the lower the settlement prices become, and the less regulating services are required. If the grid becomes unstable on the other hand, prices could become highly profitable, and more regulating services are required.

2.2.1 Functional Problem

The objective of the problem owner is to make a profit by providing regulating services. The output of this research is an algorithm which maximizes the profit for an aggregator. A functional problem is related to the output of the system. An instrumental problem on the other hand is related to the system itself. As this research aims to maximize the profits using an algorithm, which is directly related to the output of the system, the problem of this research is a functional problem.

2.3 System Description

Previously it was discussed that the objective of the aggregator is to maximize profits by providing regulating services. There are two markets where SC and V2G can provide regulating services. The first is the is called the Regulating- and Reserve Power (RRP) market in the Netherlands, and the second is called the Intraday Market (IDM) in the Netherlands, see Chapter 4 for more details about the markets. Bidding or providing RRP implies that a regulating service is bid or provided respectively. This system of bidding and providing RRP, and stabilizing the grid contain some of the most important elements of this research. The system is visualized in Figure 2. In this figure the EVs and EV owners are also incorporated.

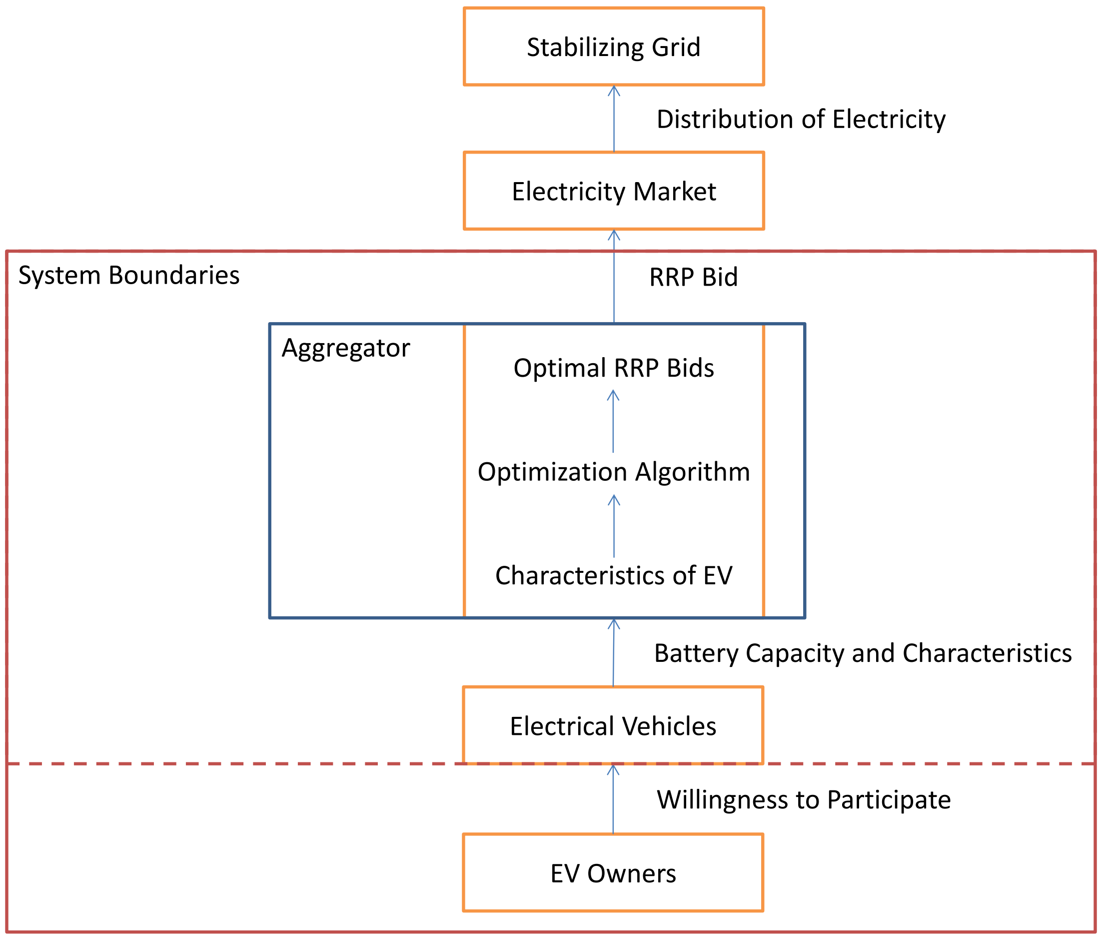

Figure 2: Model overview of system description

In the blue box, the role of aggregator is represented. The input of the system is a number of vehicles, each of which have their own characteristics, e.g. the EV's battery capacity and charging power. This input is used in order to make bids that optimize profit for the aggregator. The bids for the electricity market are the outcome of the system. For the calculation of the optimal bids a profit optimization algorithm is used. The profit optimization algorithm is one of the major contributions of this research.

The system boundaries are described by the red solid line around the aggregator, EVs and EV owners. This research takes into account the different characteristics different EVs possess. Moreover, the willingness to participate of the EV owners is considered. The dotted line represents the system boundaries of several other V2G profit optimization algorithms in the literature [17, 29, 35]. Many of the current researches do not take the willingness of EV owners to participate in V2G into consideration. The uniqueness of this research is that it strives to consider as much practical limitations as possible, in order to get a realistic estimate of the potential profits for an aggregator. Due to these considerations, it is expected that the potential profits obtained in this research are lower than other scholars have found.

What should also be noted, is that the electricity market itself and stabilizing the grid is outside the system boundaries of this research and therefore not taken into account. This also differs from several existing literature, but is due to the perspective applied. This research takes the perspective of the aggregator, seeking to maximize profit. There also exists a line of research taking the perspective of the TSO, seeking to stabilize the electricity grid [42].

Other important assumptions in this research include the assumption that an aggregator has access to a sufficient amount of EVs in order to make a valid bid. A sufficient amount of EVs is around 10.000 EVs [35]. Moreover, the costs of the hardware and software to make V2G possible are considered as a fixed costs, however the exact hardware and software necessary is not investigated. If one is interested in the software required for V2G we refer to [13], where the authors discuss the potential of the ZigBee receiver in V2G. The exact costs of the hardware and software required for V2G are yet unknown. As discussed in [43] three elements are essential for an EV in order to provide V2G services: a connection to the grid for electrical energy flow; a logical connection for communication with the grid operator; and controls and metering on-board the vehicle. These elements are required to make V2G possible, and to get the input of the EVs, the battery characteristics. From now on it is assumed that knowledge about EV owner preferences and battery characteristics are known when the EV plugs in, and that the aggregator can thus use that information to make bids.

2.4 Stakeholder Analysis

EV owners are one of the most important stakeholders of the V2G concept. The concept is based around EVs, which are owned by the EV owners. EV owners do not inherently have an interest in stabilizing the electricity grid, and are mostly interested in using their EV for transportation. EV owners on the other, could be incited to participate in SC or V2G. For this instance, they would desire an incitement compensation which would be at least higher than the perceived inconvenience costs associated to SC and V2G [28]. Inconveniences associated to SC and V2G could be lower flexibility, longer charging times and extra efforts.

The second stakeholder inseparable of the SC and V2G concept, is the TSO in the Netherlands, TenneT. TenneT is responsible for stabilizing the electricity grid and controlling supply and demand. In order to continuously match this supply and demand, TenneT has institutionalized different electricity markets. These markets have the sole purpose of buying and selling electricity in order to equalize supply and demand. Excess electricity has to be sold, as the grid possesses negligible storage, and a shortage of electricity should be bought in order to be able to meet demand. Moreover, if SC or V2G results in better distribution of peak loads, TenneT and local grid operators can delay investments in additional capacity.

The government is interested in providing electricity for all electricity consumers. TenneT was instituted as a government owned company, therefore TenneT has to oblige by electricity prices dictated by the government. These price regulations are important as TenneT maintains a monopoly. The government thus is responsible to establish fair prices.

Electricity consumers in the Netherlands are interested in receiving electricity whenever desired. They find black-outs undesirable, and therefore value a stable electricity provision. Generally, consumers do not exactly know how the market is regulated and frankly do not mind. They have a contract with an energy supplier, who in turn should guarantee the electricity.

Electricity suppliers are frequently also electricity generators, e.g. Nuon and Essent. These parties have an interest in providing the guaranteed electricity to the consumers in order to make profits. Even though, these parties are also the generators of electricity and in turn want to produce electricity at minimal costs.

2.5 Problem Definition

The objective of this research is to maximize the potential profits for an aggregator. In literature there are many studies which seek to optimize the profit for an aggregator, e.g.[17, 29, 35]. However, practical limitations are not always considered. In Sortomme et al. (2012) the authors consider the American electricity market and only consider one type of vehicle, whereas at the moment there are several different EVs on the market. Pelzer et al. (2014) formulated a price responsive algorithm focused on the market in Singapore, however the potential profits of an aggregator depends on the greatly on the country and its electricity market. Hoogvliet et al. (2017) are one of the few to consider the Dutch electricity market, however, they do not take into account the bidding horizon of the electricity market (see Chapter 4).

In literature most of the models did not take into consideration the willingness of car owners to participate. The willingness to participate could be increased by providing an incitement compensation. One article which evaluated the willingness was Parsons et al (2014). However, they did not incorporate this incitement compensation in a profit optimization problem.

The problem addressed in this research is that there is no profit optimization algorithm for aggregators focused on the Dutch electricity market taking into account the practical limitations discussed above and in the coming literature study.

The goal of this research is to maximize profits for an aggregator providing regulating services to the TSO via V2G and SC in the Dutch electricity market considering several practical limitations and the willingness of EV owners to participate.

2.6 Research question

To address the research goal, a research question is formulated. In order to find out how aggregators can maximize profits, the following research question is ought to be resolved:

- RQ: *How can profits for an aggregator in the Netherlands, using the V2G and SC concepts, be maximized considering practical limitations?*

In this question there are several aspects that first need to be defined properly. First, the V2G and SC concepts require a concise description. Second, it is important to know what exactly an aggregator is, and what it does with respect to V2G. Third, the ways an aggregator is able to make profits through V2G should be explained. Lastly, practical limitations should be defined. When these aspects have been described, it is possible to evaluate how profits can be maximized.

2.7 Conceptual Model

In the conceptual causal model depicted in Figure 3 the factors that could have an influence on maximizing the profits for an aggregator are depicted. There are two main categories: Income and Costs.

For the income of the aggregator the following should be taken into account:

- Income for the aggregator could be obtained from two sources: RRP and IDM
- EV characteristics could limit profits due to the physical limitations of the battery
- EV owner preferences could limit profits as they have different desires than an aggregator
- The fleet size in turn determines the total capacity of a bid, a higher fleet could result in higher profits

For the costs of the aggregator the following should be taken into account:

- Regular charging costs are required to charge an EV without providing SC or V2G
- Fixed costs are required to make V2G possible with regard to the physical capabilities of the EV and charging station
- Degradation costs are required for EV owners as V2G could decrease battery lifetime and performance
- A compensation for EV owners is required to obtain a large group of EV owners participating in SC and V2G

Figure 3: Conceptual Causal Model for maximizing the profits of an aggregator in the Netherlands

2.8 Subquestions

In order to answer the research question stated above, descriptions for the aspects discussed above are required. Subquestions (SQ) 1, 2 and 3 will provide the necessary descriptions. SQ 4 discusses the details of the Dutch power market, as this research seeks to maximize profits for an aggregator in the Netherlands. In SQ 5 several practical considerations are discussed, as these should be taken into account when designing the optimization model. The practical considerations are an important aspect of this research, as it is what makes this research unique. The first 5 SQs are used to explain the different aspects present in the research question. SQ 6 strives to get an answer on how EV owners can be incited. SQ 7 seeks for an optimization model to maximize profits, and the last SQ, 8, evaluates the robustness of the model by changing the variables of the practical considerations as these are not always exactly known in advance.

- SQ 1: *What are the V2G and SC concepts?*
- SQ 2: *What is an aggregator, and what is its role in the V2G and SC concepts?*

- SQ 3: *How can profits be made in the V2G and SC concepts?*
- SQ 4: *How is the Dutch power market regulated?*
- SQ 5: *What are the practical considerations of profit maximization?*
- SQ 6: *How can EV owners be incited to participate in the V2G and SC concepts?*
- SQ 7: *How can the practical considerations be incorporated in a profit maximization algorithm?*
- SQ 8: *What is the impact of the practical considerations on the profits of an aggregator?*

2.9 Outline

The remainder of the report is divided in 7 chapters.

- In Chapter 3 the theoretical background is provided. The theoretical background is used to answer SQs 1, 2 and 3. In this chapter the V2G and SC concepts are described, the role of the aggregator is explained, the different electricity markets and vehicles are discussed, and it is explained how an aggregator is able to make a profit using V2G and SC. A literature study was used to provide the theoretical background.
- In Chapter 4 the specifics of the Netherlands regarding the electricity market and EV characteristics are examined. First, the electricity market is explained focusing on the IDM and RRP market as these are suitable for V2G and SC. Afterwards, the commuting and EV statistics are provided. This chapter provides an answer to SQ 4, and uses a literature study for this purpose.
- In Chapter 5 the practical limitations are discussed. Three main practical limitations can be distinguished: Battery degradation, investment costs, and social barriers. These are the practical limitations of SQ 5 that should be taken into account in SQ 7. Moreover, in Section 5.3, a survey is constructed in Qualtrics. This survey is used to give an answer to SQ 6 as to how EV owners could be incited to participate in the V2G and SC concepts. This chapter provides an answer to SQ 5, and again requires a literature study.
- In Chapter 6 the profit optimization problem is formulated to give an answer to SQ 7. First, a literature study is performed to obtain insights from existing models. Then, these insights are used to formulate the optimization problem of this study. Three optimization models can be separated, a model for the RRP market, a model for the IDM, and a dispatching algorithm.
- In Chapter 7 the analysis of the survey and the optimization problem is performed. The survey is analyzed using SPSS, and provides an answer to SQ 6. The optimization problem is analyzed in CVX in Matlab. The problem formulization is simulated for 6 different EVs, and gives an indication of the potential profits. A sensitivity analysis is performed to test several scenarios that could impact the potential profits of an aggregator, providing an answer to SQ 8.
- In Chapter 8 it is discussed what the impact of several assumptions is on the profit of an aggregator. This is done using a literature study. Several of the discussion points are: the use of a centralized controller in this work, and the assumed EV owner preferences.
- In Chapter 9 the conclusion and future work is described.

3 Theoretical Background

In this Chapter the theoretical background is described. This Chapter is used to establish a good understanding of the V2G and SC concepts and of the different components that are important for these concepts. After reading this Chapter the reader should understand the basic premises of the V2G and SC concepts, what the role of an aggregator is and how profits could be made.

- In Section 3.1 the V2G and SC concepts are explained
- In Section 3.2 the role of the aggregator is described
- In Sections 3.3 and 3.4 the different vehicles and electricity markets are explained
- In Section 3.5 it is illustrated how profits can be made
- In Section 3.6 the role of a TSO is described
- In Section 3.7 a summary of the findings in the theoretical background is provided including short descriptions of the answers to SQs 1,2 and 3

3.1 Vehicle-to-Grid and Smart Charging Concept

In the coming decades, the number of EVs is expected to increase continuously [21], resulting in, at some point in time, a deep penetration of EVs [13]. This accumulated number of EVs, form a new load to be supplied. Smart grids have been instituted for leveling peak loads, e.g. by providing incentives to consumers to do their laundry at night. However, the EV fleet requires different incentives to level peak loads, as vehicles are required all day. Moreover, the amount of electricity needed to charge all EVs simultaneously forms a huge challenge to the current system [15].

The EV fleet could potentially be more than merely another system that requires to be charged. An EV could be used as a storage system as well since EVs naturally possess storage required for transportation. An EV has the potential to store electricity generation excess and to supply electricity if there is shortage. Excess and shortage of electricity depends on the supply of the electricity suppliers, and on the demand of electricity consumers. Such a storage system is possible if bi-directional power transfers are possible when a connection between an EV and the electricity grid is secured [13]. The possibility of using EVs as a storage and source of electricity is the basic premise of the V2G concept [20]. The SC concept slightly differs from the V2G concept as in the SC concept the EVs are only used as storage and not as a source of electricity.

The integration of the EV fleet in the electric power grid form a system with great potential to manage energy and power [20], and to improve reliability, economics, and environmental attributes of this system [13]. The power grid has typically no storage besides the 2.2% capacity in pumped storage. This requires a constant matching between supply and the volatile demand. Nowadays, large generators are used to match demand on a minute-by-minute basis. These large generators run at about 57% of its total capacity, resulting in high capital costs. The EV fleet has low capital costs and is available 96% of the time for other tasks than transportation [20]. From a TSO perspective, using the EV fleet to manage the discrepancies between supply and demand could be economically interesting. On the other hand, EVs have low durability and high costs per kWh of electricity with respect to large generators. Therefore, V2G and SC should only be used in high-value, short-duration power markets [20].

3.1.1 Elements of V2G and SC

In the previous Section the general idea of the V2G and SC concepts was described. Three main elements of V2G and SC could be distinguished that are essential for the concepts. These are:

- Aggregators
- EVs
- Electricity markets

Other elements include among others: parking facilities and loading points. These other elements, however are merely required for the physical implementation of V2G and SC. Aggregators enable V2G and SC because a single EV does not have enough capacity to make an impact for the electricity grid [13]. EVs are required as the EVs are the storage of the electricity. V2G and SC cannot exist without EVs. Electricity markets are an important element as several different electricity markets exist, and only the high-value, short-duration electricity markets are of interest for V2G and SC. In Figure 4 the relation between the different elements of V2G and SC is visualized. The aggregator bids into electricity markets using the aggregated capacity of multiple EVs. This bid can then be used to stabilize the electricity grid.

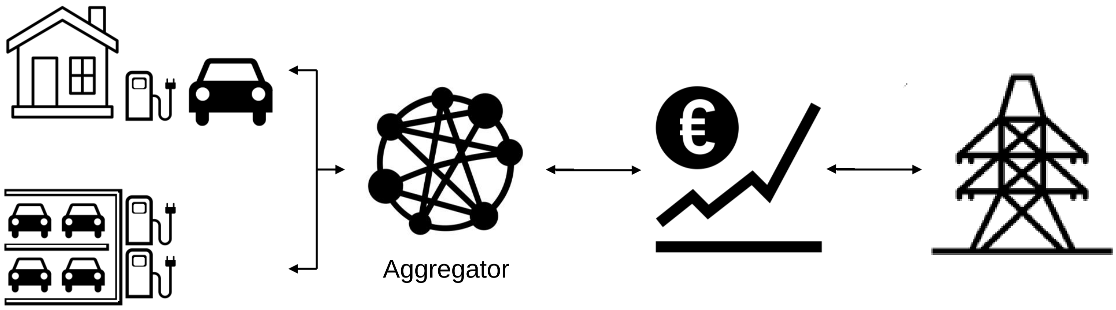

Figure 4: The different components of V2G and SC, and their relations

3.2 Aggregator

In order to use the flexibility of an EV for the electricity an aggregator plays an important role [15]. An aggregator is an entity that couples multiple different EVs, which each have unique battery characteristics and EV owner preferences, so that together they form a storage or source of electricity that is large enough to make an impact for the grid. An aggregator is required for V2G and SC as a single EV does not have the capacity to make an impact for the grid in any meaningful manner. When thousands of EVs are combined by an aggregator however, the capacity of the aggregated storage or source is large enough to make an impact. This enables an aggregator to exploit the economic possibilities of the electricity markets [13].

Moreover, aggregation of large numbers of EVs is important as a single EV is unpredictable in terms of its departure time, charging time and needs. The behavior of large group of EVs can be predicted with high accuracy though, which enables an aggregator to reliably bid a certain capacity into the electricity to seize the economic opportunities. An aggregator therefore, has to continually monitor the status of each EV with respect to its State Of Charge (SOC), flexibility considerations and requirements. This data is required to make the next bid, as the capacity of the bid is dependent on the availability of an EV as well as the available capacity in the battery. The data which is transmitted between an EV and an aggregator can be seen in table 2 [13].

Data	Nature	Comment
ID	Unique alphanumeric information characterizing the BV	The key to retrieve the specific characteristics of the EV
EV connection status	Binary information	Connected/disconnected value
Preferences/constraints of each EV owner	Minimum level of energy desired in the battery and desired time to disconnect the EV	Specific data other than stored information
EV battery SOC	Percentage	Key criterion for EV deployment
Power flow from the EV battery to the grid	Signed power quantity	Required for payments

Table 2: Data transmitted between EV and Aggregator [13]

3.3 Cars Suitable for V2G and SC

An important characteristic of the cars suitable for V2G and SC is that the vehicles are electric vehicles. EVs however exist in three variants, each with its own characteristics. First the different types of EVs are discussed as for practice it is important to distinguish between the three types due to their characteristics. Thereafter several important general notions will be elaborated which are true for all types of vehicles.

EVs are defined to have an electric-drive motor powered by batteries. The three types of electrical vehicles exist due to differences in chemistry and capacity of the batteries. The three types of electrical vehicles are: battery vehicles, fuel cell vehicles, and hybrid vehicles [20].

Battery vehicles store electricity in an electrochemical cell [21], such as lithium-ion. Battery vehicles charge when plugged in, i.e. when it has a connection with the grid. Hybrid vehicles combine a combustion engine with a battery. The normal hybrid models have a relatively larger mechanical than electric drive, and do not have an electrical connection to the grid. Therefore, the normal hybrids are not suitable for V2G. On the other hand, Plug-in Hybrid Electrical Vehicles (PHEVs) have larger batteries and by definition have a connection the grid, hence 'plug-in' hybrid. PHEVs are suitable for V2G and SC. The last type of electric vehicle is the fuel cell vehicle. A fuel cell vehicles type typically stores energy in molecular hydrogen. For V2G and SC this implies that the fuel cell vehicle would produce electricity from the hydrogen, convert it to 60 Hz AC, and then supply this electricity to the grid. Normally a fuel cell vehicle does not come with a grid connection, therefore additional costs are required to enable V2G with fuel cell vehicles. Whether this is economically sound depends on costs and returns from V2G and SC profits [20].

For all types of vehicles it holds that transportation is its primary function. A research about commuting in the US resulted in an average commuting period of 2 hours. The potential range of electrical vehicles is larger than the average of 100 km, typically for 2 hours of commuting. This implies not all the energy in the batteries is consumed by transportation [13]. The amount of electricity not consumed could be expressed as a ratio with respect to its maximum capacity, this ratio is called the SOC of the battery. The SOC is 100% when fully charged and 0% when fully discharged. To obtain better understanding of the SOC, the SOC for a normal weekday is visualized in figure 5. The SOC is one of the most important parameters that determines the capacity an EV can use for V2G and SC services.

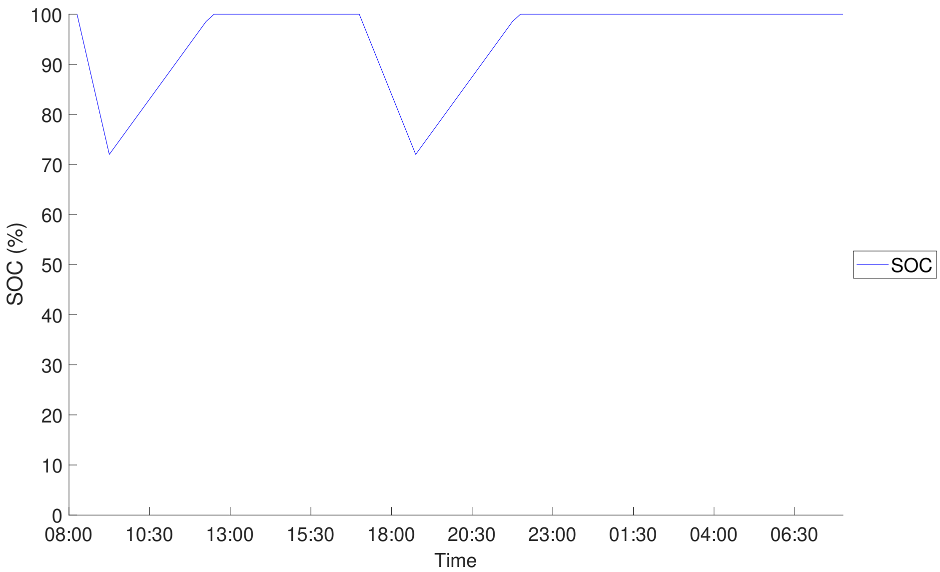

Figure 5: The SOC of an electrical vehicle during a normal day [13]

3.4 Power Markets Suitable for V2G and SC

The electricity market is divided in multiple categories, each with their own specifications and control. Below, five of these markets are discussed. The spinning reserves and regulation market belong to the ancillary services, which are the high-value, short-duration services [35]. The storage of renewable resources market is a near future market combining several aspects of the other markets [20]. The framework, details and requirements of the markets could vary per country. The different power markets described next are the general descriptions of the power markets. In Chapter 4 the framework, details and requirements of the Dutch electricity market are provided.

3.4.1 Baseload Power

Baseload power is the energy which is continuously generated to provide the lowest amount of load required throughout the day. Baseload power generation typically has low costs per kWh, and is generated mainly by nuclear or coal-fired plants. Even though baseload power generation is not competitive for V2G [20], EVs that are charging at night could resolve issues with low utilization of baseload power generators at night. Charging EVs at night could potentially result in a higher utilization of baseload power generators. Using the concept of valley filling, visualized in Figure 8, the low utilization rate at night could be increased when thousands of EVs are charging during the night, see Figure 7. This concept is already promoted with nighttime electricity prices that are lower than during the day to incite electricity consumers to e.g. do their laundry at night. When baseload power generators can attain higher continuous steady output, lower costs per kWh could be achieved due to efficiencies of scale and higher capacity usage [13].

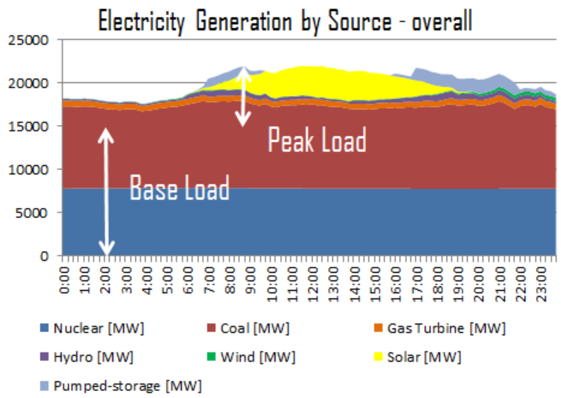

Figure 6: Visualization of baseload power [37]

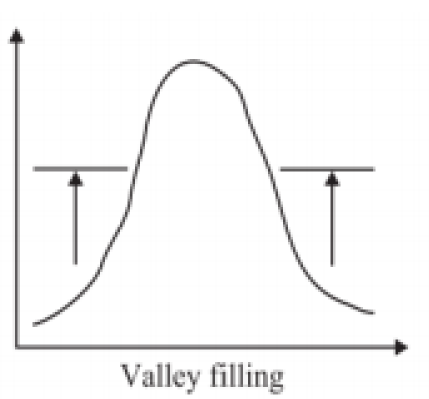

Figure 7: Concept of valley filling

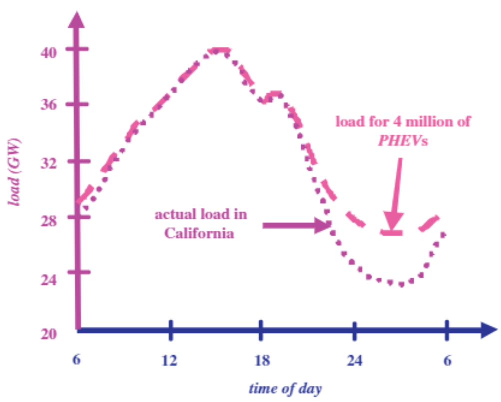

Figure 8: How V2G and SC could improve baseload utilization rate by valley filling [13]

3.4.2 Peak Power

Peak power constitutes the remainder of day-to-day power generation. The shape of the demand curve is influenced by many factors, such as seasonal effects, holidays, and weekends. However, it can be estimated with relatively high accuracy to actual demand. Provided that the estimation of the demand is good, supply can be generated with minimal discrepancies. Peak load power is generated by power plants that can be turned on and off for shorter periods than baseload power plants. Gas power plants are an example, and these types of power plants have in comparison to baseload power plants low capital costs. Since peak load power is required only a limited amount of hours per year, it is economically better to use low capital cost power plants with higher kWh prices than baseload power plants [20].

Despite evidence that V2G peak power may be economically interesting for an aggregator under special circumstances, it does not utilize the potential of V2G to its maximum [20]. Both the generation of baseload and peak power will not be further considered.

3.4.3 Spinning Reserves

Baseload and peak power encompass the electricity supply for the lower bound of electricity demand. Despite accurate estimations, discrepancies remain inevitable. Spinning reserves comprise the additional generation capacity that can provide these discrepancies in a short period of time. Generally this period would be 10 min after request from the grid operator. Because spinning reserves require quick notice responses, the generators should always be on standby. The amount of time the generators are ready and available is paid for, on a capacity by time basis. When the spinning reserve is required, an additional price is paid for the actual provided energy [20].

3.4.4 Regulation

Regulation is also known as frequency control. It is used to calibrate the frequency and voltage of the grid to the demand. Continuous monitoring is required to respond within a minute to the request of the operator [20]. There are two types of regulation possible, depending on what is required by the grid operator. Regulation down is the absorption of power, and regulation up is the provision of power. A battery can provide regulation up or down depending on its SOC [13]. Regulation is requested more frequently than spinning reserves, about 400 times a day instead of 20 times a year for spinning reserves. Regulation also requires faster response times than spinning reserves, and is typically of a shorter duration. Both spinning reserves and regulation belong to the ancillary services. These services account for 5-10% of electricity costs [20]. These markets are promising for V2G as they call for the strengths of the electrical vehicle fleet, i.e. fast response times.

3.4.5 Storage of Renewable Resources

The most important role for V2G and SC may ultimately be in emerging power markets to support renewable energy [21]. Photovoltaic and wind turbines are both intermittent. At low levels of penetration of the renewable energy sources, the intermittency of can be handled using the existing mechanisms for managing supply and demand discrepancies. However, as renewable energy exceeds 10-30% of the total power supply, additional resources are needed to match the fluctuating supply to the already fluctuating demand. The intermittency can be managed by backup or storage. V2G can provide both [21].

3.5 How profits can be made

Aggregators are able to make profits by providing regulating services to the electricity market. The regulating services are required for the electricity market to balance demand and supply. By aggregating numerous EVs an aggregator has a large capacity of storage and supply under its disposal.

Profits for an aggregator can be obtained in various ways, either by providing regulation, providing spinning reserves or supplying peak power. The potential profit of an aggregator is calculated by comparing it to the situation where not V2G or SC is provided. The situation where V2G or SC is not provided is called the baseline scenario. When providing regulation up the TSO pays a fee for the electricity that is supplied by the aggregator. Compared to the baseline scenario, the aggregator makes a profit. When providing regulation down, the aggregator pays a fee to the TSO for the electricity that is bought and stored in the EVs. The price that an aggregator pays to provide regulation down and thus buying electricity should be lower than the normal electricity price in the baseline scenario in order to be profitable. Even though no actual money was received, it is still a profit due to the decrease of costs. In Figure 9 it can be seen during which periods V2G can make profits in comparison to the baseline scenario. An aggregator is able to provide V2G or SC services when the SOC is larger the required SOC and lower than the SOC of the baseline scenario (blue line). The required SOC depends on the capacity required by the EV owner when making a trip, and the normal charging durations. Calculations for the required SOC are provided in Chapter 6.

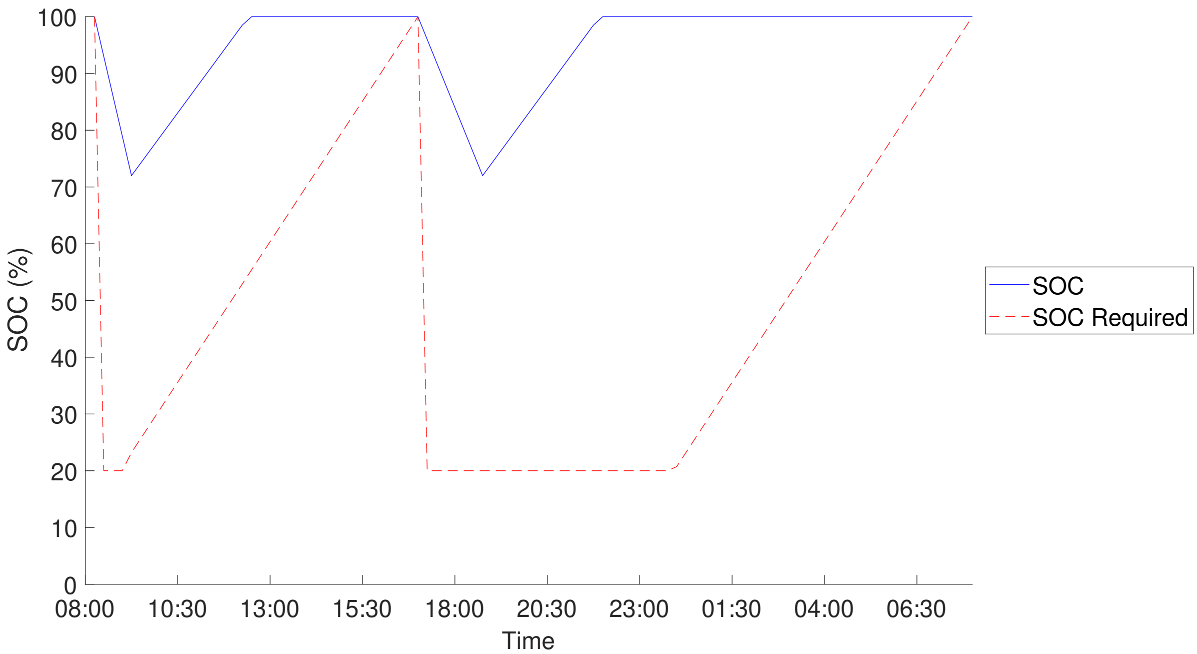

Figure 9: How profits can be made - V2G and SC possible between blue and red line considering a normal weekday [17]

In the literature, many studies have estimated the profitability of V2G. Each study took different practical considerations and markets into account. An overview of several of the estimations is given in Table 3.

Study	Location	Value range per EV	Service studied	Remunerations
Hoogvliet et al. [17]	Netherlands	€120-€750	Secondary reserve	Energy price
Kempton et al. [22]	California (USA)	$311-$720	Primary reserve	Capacity price
Codani et al. [6]	France	€193-€593	Primary reserve	Capacity price
Sortomme and El-Sharkawi [35]	Houston (USA)	$161-$635	Energy sales, primary reserve, secondary reserve	Capacity price
Fernandes et al. [11]	Spain	€122-€540	Reduction of system costs	Unspecified
Druitt and Früh [8]	UK	£150-£400	Storage and secondary reserve	Energy price
Jarfstorf and Wickert [18]	Germany	€8-€108	Secondary reserve	Capacity- and energy price

Table 3: Comparison of profits in previous studies [17]

3.6 Importance for net operators

Despite the aggregator's perspective of this study, it is important to note the effects of V2G and SC on the TSO, and electricity grid itself. V2G and SC have the ability to prevent several investments in grid infrastructure, peak power and storage facilities [13]. These preventions are not addressed in most algorithms calculating the profits for an aggregator, as the savings are hard to quantify. Yet, these conceptual savings should be kept in mind. As the electricity demand and the flexibility of demand keep increasing, a solution is desired which minimalizes investment costs. V2G and SC is a promising new concept which is able to provide both flexibility and high capacity, which takes away the need of investing in new power plants that are used only for peak power or other services. Power plants for peak power are idle most of the time, and therefore expensive [20, 35].

3.7 Summary

This Chapter provided the theoretical background required to establish a good understanding of the V2G and SC concepts. Three SQs have been answered throughout this Chapter, and a brief description of the answers is provided subsequently.

- SQ 1: *What are the V2G and SC concepts?*

The V2G concept uses EVs to provide electricity storage or supply in specific electricity markets. In the SC concept the EVs are only used as storage and not as a source of electricity.

- SQ 2: *What is an aggregator, and what is its role in the V2G and SC concepts?*

An aggregator is an entity that couples numerous different EVs, which each have unique battery characteristics and EV owner preferences, so that together they form a large storage or source of electricity. An aggregator is required for the V2G and SC concepts as a single EV does not have the capacity to make an impact for the grid in any meaningful manner.

- SQ 3: *How can profits be made in the V2G and SC concepts?*

Aggregators are able to make profits by providing regulating services to the electricity market. The regulating services are required for the electricity market to balance demand and supply.

In the following Chapter, the specifics of the Netherlands are addressed. As this thesis focusses on the Netherlands, the Dutch electricity market and EV statistics are used. As mentioned in this Chapter, the details of the electricity markets vary throughout the world, and therefore it is required to explain the details of the Dutch electricity in more detail in the next Chapter.

4 Specifics of the Netherlands

This thesis focusses on the Dutch environment, and the specifics of the markets and EVs are discussed in this Chapter. The previous Chapter described how the V2G and SC concepts originated and what the possibilities of V2G and SC are. However, for the simulation the characteristics of the Netherlands are required to get insights into how aggregators could perform in the Netherlands. One study in particular, by Hoogvliet et al. (2017), provided a solid first exploration of the profitability of an aggregator in the Netherlands. The authors found that potential profits range from €120 - €750 per vehicle.

- In Section 4.1 the specifics of the different Dutch electricity markets are described including the markets of interest for V2G and SC, the IDM and RRP market
- In Section 4.2 the limitations of the Dutch electricity are explained including market complexity and bidding requirements
- In Section 4.3 the statistics of the EVs in the Netherlands are examined including the currently most popular EVs
- In Section 4.4 a summary of the findings of this Chapter is provided including a short description of the answer to SQ 4

This Chapter is written using several documents from the website of TenneT, using the articles of Hoogvliet et al. (2017) and Tanrisever et al. (2015), a background report on the Dutch electricity market by the TU Delft [15], the document of Chang et al. (2016) for the description of the Dutch electricity market, and the implementation guide for making a RRP bid [41]. And this Chapter uses several documents of the website of Rijksdienst voor Ondernemend Nederland www.rvo.nl, and several other specific documents about battery characteristics.

4.1 Details of Dutch Power Market

The markets throughout the world are similar, and are divided following the structure described in Section 3.4. However, power the markets have different requirements per country. For example, in the United States an aggregator can bid for regulating services in the electricity market using a capacity price and an activation price. The aggregator receives the capacity price of the bid regardless of whether the bid is actually activated. This capacity price is used to ensure a certain amount of regulating capacity. If the bid is activated, i.e. call-off occurs, the regulating service has to be provided and the aggregator gets paid the additional activation price. Both of these bids can be adjusted by the aggregator in order to get approved and accepted by the TSO [3]. In Singapore though, the capacity bid is non-existent and the aggregator would only get paid when it is activated. This activation bid can be adjusted by the aggregator [29]. In this article the Dutch electricity market is of interest, and therefore the details and requirements are elaborated upon next. First, the history of the Dutch electricity market is shortly described, after which two important players on the electricity are examined and the interrelations of the parties are described using the Universal Smart Energy Framework, and finally the different markets are specified.

4.1.1 History

The Dutch electricity market is liberalized since 1998 when the Electricity Act was introduced. This enabled more freedom for individual customers and suppliers. The 1998 Electricity Act established a state-owned entity to serve as the TSO. In 2008 the state divided the medium- and low-voltage transmission grid (<110 kV), which resulted in the new entity Distribution System Operator (DSO). The distribution of electricity to the consumers is operated by the DSOs. Nine state-owned DSOs are in operation to supply in different geographical areas of the Netherlands. Even though the system operators have monopolies, due to state regulation the electricity price is kept as low as possible [39]. The electricity supply chain as briefly described can be seen in Figure 10.

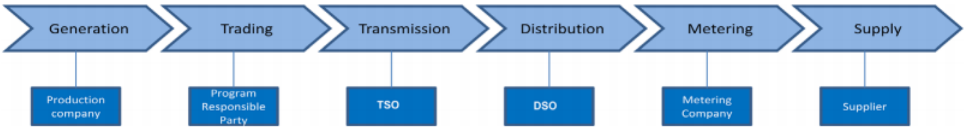

Figure 10: Supply chain of electricity [39]

4.1.2 System Operators

The TSO of the Netherlands is TenneT, a state-controlled monopoly. It is the backbone of the Dutch power grid and connects all regional networks with each other. The 110 kV, 150 kV, 220 kV and 380 kV are under control of TenneT, and these grids are also connected to the European network. In order to participate in the generation or trading of electricity, TenneT requires a T-prognosis and an E-program. The T-prognosis is the forecasted flow of electricity which is used by TenneT to ensure grid stability at all times by calculating the expected electrical flows through the system. The E-program is the net position of each participant in the market for each Program Time Unit (PTU). The E-programs are used to safeguard the balance of supply and demand of electricity. The programs are also used to calculate and settle imbalance payments after the physical delivery of electricity [40]. The DSOs are responsible for the construction, maintenance, management and development of the electricity grids that distribute the power from the high voltage grid to the consumers [39].

4.1.3 Program Responsible Parties

A Program Responsible Party (PRP) is a legal entity that manages at least one physical connection to the grid and is the party that interacts with TenneT. A PRP is responsible for forecasting their net demand, which is the difference between supply and demand that flows through its physical connection (E-Program), and the quantity that will be transported through certain transmission lines from their connection (T-Prognosis). According to the 1998 Electricity Act all firms can buy and sell electricity in the market without actually possessing a physical connection. However, it is obligatory to have a PRP permit or a contract with an official PRP in order to trade electricity. PRPs are obliged to pay imbalance costs when the realized net demand deviates from the forecasted demand submitted to TenneT in the E-Program. The imbalance costs a PRP has to pay in this case depends on the amount of deviation realized and the current market price of electricity at that specific moment [15].

Trading of electricity can occur in three markets, the futures market, the spot markets which include both the day-ahead market and the intraday market, and the imbalance market. Each market will be discussed in the following Sections, and will be assessed on its premises for V2G or SC. The different characteristics and requirements of the markets are visualized in Figure 11.

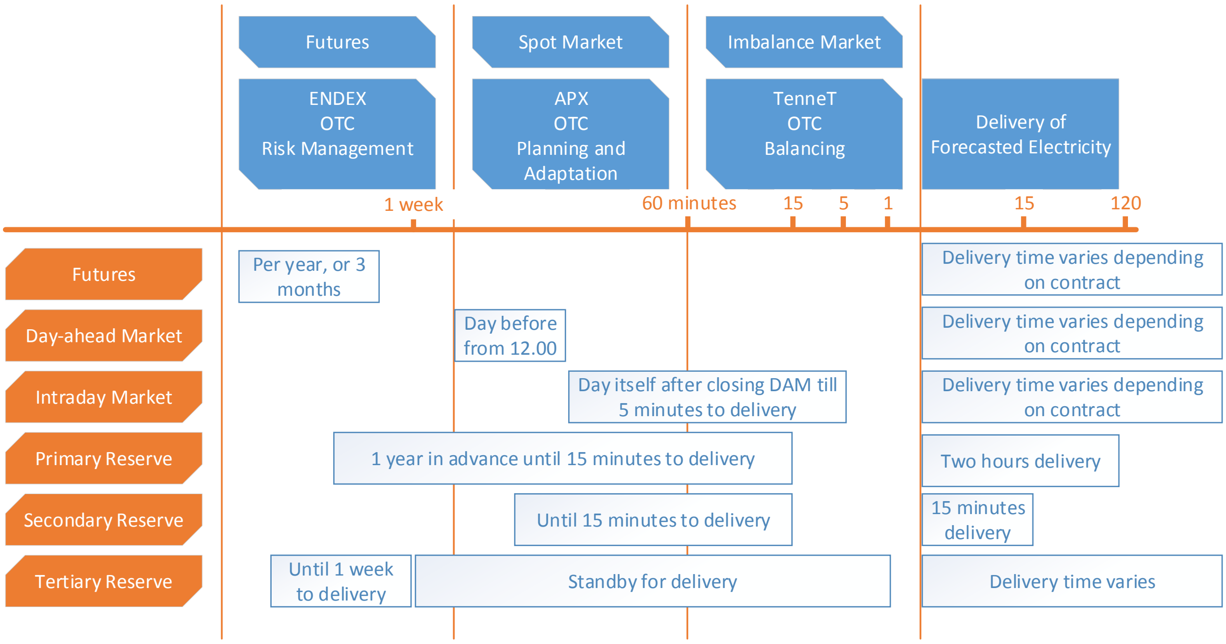

Figure 11: Distinction between markets, their brokers and time for bidding until delivery [5, 15]

4.1.4 Futures

The futures market resembles the baseload power market. The commodities traded in this market are handled in the exchange ICE-ENDEX or via brokers, the so-called OTC-contracts (Over The Counter). Trading in futures starts four years in advance of delivery day. This early trading coincides with speculations about the electricity price, as a capacity and a price have to be invoiced. A license is required to be able to trade on the exchange ICE-ENDEX [15]. This market however, as in line with literature about base and peak load power is not suitable for EVs. Therefore, the details about the bidding process and requirements are not elaborated in further detail.

4.1.5 Day-ahead Market

The Day-Ahead Market (DAM) trades in electricity where delivery is due for the next day. This market is also known as the spot market, and is traded via the EPEX, formerly known as the APX. The DAM operates using a double-sided blind auction system to obtain uniform pricing. The electricity is traded per hour, and for each hour the bids are sorted in descending demand and ascending supply prices. The market could be interesting for V2G. SC is not possible as it is the delivery of electricity. A minimum of 0.1 MW is required to bid on the day-ahead market [15]. As SC is not possible, and the market does not fully utilize the short-term, low-duration capabilities of V2G and SC, the DAM is not considered further in this study.

4.1.6 Intraday Market

On the Intraday Market (IDM) the electricity traded has to be delivered on the same day. Trading in the IDM is possible up to 5 minutes in advance of delivery time. The short-term notice could be interesting for V2G and SC considering the unpredictability of supply due to wind and solar energy and the unpredicitability of demand. Despite the market being regulated at the APX, much of the trading takes place in the bilateral OTC-market. A minimum of 0.1 MW is required to bid on the intraday market [15].

As the unpredictability of supply increases when the renewable energy sources have deeper penetration of the market, the prediction errors in the E-programs is expected to increase proportionally. The increase in errors will subsequently increase both the capacity of regulating services in the

IDM and RRP market and the settlement prices of these markets. The need for quick response, low-duration flexibility will become more important in the future. The IDM does not require much regulating capacity yet. Nevertheless, it is expected that the capacity required by the IDM will increase over the years [5, 15]

4.1.7 Imbalance Market

The imbalance market resembles the ancillary services in the Netherlands. This market is organized and controlled by TenneT, the TSO. The previous markets are meant to trade electricity, the imbalance market however is meant to control the balance of production and demand, and frequency. This market is meant for capacity bids with respect to regulation and responsive capacity. There are three types of reserves in the imbalance market, the primary, secondary and tertiary reserve.

The primary reserve has the function of restoring frequency disruption in the entire, internationally interconnected High-Voltage grid [17]. It is the first reserve to be called upon when there is a significant deviation in the frequency. On weekly basis biddings take place for the primary reserve. A bid is valid for a week. Moreover, the contracted capacity should be available within 30 seconds of notice. The minimum capacity to be able to bid is 1 MW. The incentive component is capacity based, and there is no compensation for the actual provided electricity [5]. The primary reserve is not considered ideal for an aggregator of V2G and SC as the bids must hold for a week, and as it does not remunerate the volume of energy delivered [17].

The secondary reserve, also known as the Regulation and Reserve Power (RRP) market, has the purpose of diminishing disruptions in the electricity balance which last at least 15 minutes. Bids can take place until one hour prior to delivery, and each bid is valid for one PTU. One can either make a single-bid ,i.e. only one 15 min block is bid, or a block-bid, i.e. multiple 15 min blocks are bid. Besides the bidding procedure, TenneT also has contracts for the secondary reserve market, which accumulate around 300 MW yearly. These contracts are compensated for the capacity available, and for the actual provided MW. These contracts are made with energy producers, which are obligated to have a certain amount of flexibility. Other parties, such as the PRPs, are able to bid voluntarily. These volutarily bids are only compensated for the actual provided MW. This reserve market is interesting for aggregators of V2G and SC as the short-duration and short bidding horizon allow for high accuracy of the bids.

The secondary reserve market is characterized by several requirements and compensations. First, the minimum bidsize is 4 MW and has a maximum of 200 MW [15]. Moreover, in order to bid, an aggregator should either be a licensed PRP or have a contract with a PRP which can make bids for them. Providing regulation constitutes of two services, regulation down and regulation up. These services should be bid symmetrically, implying that the capacity bid for regulation down services is equal to the capacity bid for regulation up services. The price for the PRP's imbalance is determined by the following factors:

- The direction of the PRPs' imbalance, i.e. providing regulation up or down
- The regulation state
- The height of incentive component
- The regulating prices
- The midprice, where the regulation state is 0

The direction of the PRP's imbalance can either be surplus or shortfall. With surplus the PRP is supplying in imbalance, with shortfall it is sourcing in imbalance.

The regulation states are determined per PTU, and are characterized by a number from 0-2 and a + or - sign indicating the four possible stages of regulation in a PTU [40].

- **0** Neither upward nor downward regulation is required
- **+1** Exclusively upward regulation is required
- **-1** Exclusively downward regulation is required

- **2** Both upward and downward regulation is required

The incentive component is €10 per MW [47].

The regulation prices are determined using a so-called bidladder. The bidladder is constructed for each PTU, and each bid represents one bidding party. The TSO sorts the bids in an economically efficient manner, i.e. ascending order w.r.t. price for RRP up and descending order w.r.t. price for RRP down. The settlement price which all parties, that are activated, receive is the highest or lowest bid that has been activated. For instance, considering the bidladder as in Figure 12, parties 1-7 would receive a settlement price of €100/MW h when 650 MW is required for RRP up.

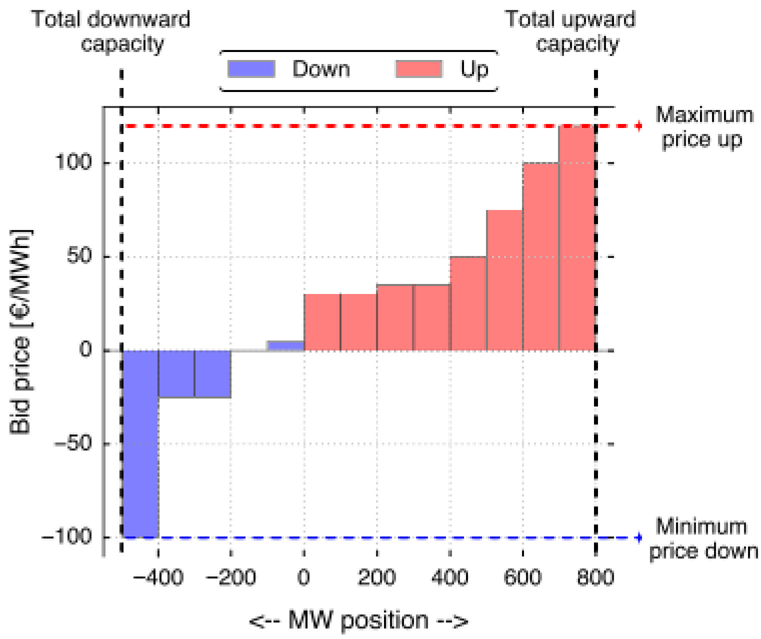

Figure 12: Illustrative price bidladder for TenneT [17]

Whether the PRP or the TSO is compensated for the imbalance is visualized in Table 4. The actual settlement prices are calculated per minute.

	Settlement price > 0	Settlement price < 0
Upward regulation power (+)	TenneT pays RRP supplier	RRP supplier pays TenneT
Downward regulation power (-)	RRP supplier pays TenneT	TenneT pays RRP supplier

Table 4: Payment in secondary reserve [41]

The tertiary reserve is for emergency situations. The capacity contracted by TenneT should be available at every possible moment, and has strict requirements. For instance, the capacity for emergency situations cannot be used for any other purpose, and the call-off or activation of it can last for hours. Moreover, the capacity should be at least 20 MW [5]. Therefore, this market is not suitable for V2G or SC where the capacity is used for other purposes as well. The total volume of each market and the average prices per MWh can be found in Table 5.

Market	Volume	Value
Primary reserve	96 MW (2015)	Capacity price: €4000/MW/week
Secondary reserve	300 MW (2015) + additional 240 GWh down (2014) and 224 GWh up (2014)	10% - €17/MWh 50% - €42/MWh 90% - €65/MWh
Tertiary reserve	350 MW (2015)	€15.000/MW/year
Intraday market	0,7 TWh (2013)	10% - €25/MWh 50% - €42/MWh 90% - €60/MWh
Day-ahead market	44,5 TWh (2014)	10% - €29/MWh 50% - €41/MWh 90% - €55/MWh
RRP market	66 TWh (2013)	€35 - €40/MWh

Table 5: Volumes and prices of electricity markets [5]

4.1.7.1 Example RRP bid of an aggregator

An aggregator does not have a contract with TenneT. Therefore, an aggregator should make a bid for each PTU. It is recommended that an aggregator bids using a single-bid instead of a block-bid, as this provides the highest reliability with regard to the capacity of the EV fleet. Since an aggregator does not have a contract with TenneT, it does not receive the incitement component.

In this example, the aggregator makes a single-bid of 6 MW for RRP up and 6 MW for RRP down. A bid for RRP up or down implies that the aggregator enables TenneT to use the capacity that is bid for regulating services in a specific PTU. The bid of the aggregator should also include a bid price. Two bid prices are made, for RRP down the bid price is -€100 and for RRP up the bid price is €100. The bid is made one hour in advance of delivery.

At the time of delivery, the bidlidder is constructed, as in Figure 12. In this specific PTU the direction of the PRPs' imbalance is 2. In this PTU both upward and downward RRP is required. For upward regulation 800 MW was required for balancing the discrepancies. For downward RRP 50 MW was required. The bidladder shows that for upward RRP a settlement price of €120 is rewarded, and that for RRP down a settlement price of €5 was rewarded. For RRP up, all parties with a bid price lower than or equal to €120 are activated and are rewarded with a settlement price of €120, regardless of the bid price. For RRP down all parties with a bid that is higher than or equal to €5 are activated and rewarded with the settlement price of €5, regardless of the bid price.

In Table 4 it is evaluated whether the aggregator has to pay TenneT for its services, or if TenneT has to pay the aggregator. The settlement price of upward regulation is larger than 0, i.e. TenneT pays the RRP supplier. The settlement price of downward regulation is also larger than 0, in this case the RRP supplier pays TenneT. If the settlement price of RRP down would become negative, TenneT pays the RRP supplier.

Whether an aggregator is activated is determined by the settlement prices as discussed above. The bid of the aggregator included bid prices of €100 for RRP up and -€100 for RRP down. The bid price for RRP up is lower than the settlement price, and thus is activated. The bid price for RRP down is not higher than or equal to the settlement price, and therefore is not activated. In this case, the aggregator receives 6 MW * €100/MW = €600 for the provided RRP up services.

4.2 Limitations Dutch Electricity Market on Bids

The liberalization of the Dutch electricity market provided businesses with an opportunity to compete for the production of electricity. Nowadays there are several large electricity providers such as Nuon and Essent which have pursued the economic opportunity. For new entries in the market, such as an aggregator, the market has a high barrier, and makes it therefore hard to compete. Several of these limitations that are of concern for the business case of an aggregator are discussed below.

The complexity of the electricity market is the first limitation. There are six different types of markets and these are controlled by three different parties, the ENDEX, the EPEX, and TenneT. The complexity of the electricity markets requires thorough knowledge about the electricity trade, operational requirements to active trade, and technical requirements for deployment of flexibility on the different markets. Moreover, the Over-The-Counter contracts are merely mentioned, and the details of it are unknown. These contracts might be interesting for an aggregator as these types of contracts require flexibility. In order to bid in the imbalance market an aggregator requires either a PRP license, or a contract with a PRP which will then bid for the aggregator. Costs of these licenses or contracts are unknown.

The second limitation is the availability of information, which is a consequence of the complex market structure. Multiple sources have to consulted in parallel to get an overview of the market. Moreover, the historical data is hardly available and generally requires a fee [39].

The technical requirements are the third limitation for an aggregator. Codani et al. (2014) examined ideal market requirements for V2G. The ideal market requirements for V2G are provided in Table 6. In the same Table the market requirements of the Netherlands is presented. The imbalance market controlled by TenneT requires a minimal capacity of 4 MW, however, this is not in accordance with the ideal market requirements for aggregators. In addition, the capacity which can be provided should be integer, implying an aggregator can only bid for instance 4, 5, 6MW. As 1 MW requires aggregation of a large number of EVs, it could be that the capacity of a large number of EVs is not used. The regulation speed which is required by TenneT is 7% of the total capacity per minute. The bid of an aggregator is valid for a period of 15 minutes. An even distribution of regulating services therefore is 100%/15=6,67%. The required regulation speed by TenneT of 7% is slightly higher than an even distribution of 6.67%. In order to meet this regulation speed demand, an aggregator should bid less capacity than possible. For example, if an EV has a connection of 3.7 kW, it could potentially have a capacity of 55,5kW per PTU for regulation up or down. Due to the regulation speed required by TenneT it can only bid 52,8kW though, which constitutes a decrease of almost 5% in capacity. Furthermore, the RRP market requires symmetrical bidding. Symmetrical bidding implies that bids for RRP down and RRP up are equal. V2G provides both bids RRP up and down, yet SC can merely generate bids for RRP down. Symmetrical bidding is therefore undesirable. The IDM does not have this limitation, and could therefore be interesting for an aggregator providing SC.

Type	Rules	Description	Conditions Codani et al. [6]	RRP market TenneT
Aggregation	Minimum bid size	Minimum capacity of RRP bid. Generally, TSOs employ minimum bid sizes between 0.1MW and 10 MW. Smaller minimum bid sizes are more favorable for the aggregation of EVs	0,1 MW	4 MW
	Interoperability between DSOs	TSO rules must allow for aggregation over multiple areas to increase odds of reaching the minimum bid size	Yes	No
	Type of aggregation	Telemetry vs. financial. Telemetry allows for combining bids and power flows from different locations. Financial only allows for the combining of bids	Telemetry	Telemetry
Payment	Nature of payment scheme	Market based vs. regulated. In market-based payment schemes all parties eligible for RRP provision can bid. In regulated payments schemes TSOs dispatch based on historical load share	Market-based	Market-based
	Completeness of payment scheme	The extent to which regulation services are remunerated	Complete	Complete
	Bonus for intense flexibility	The extent to which fast responding sources are rewarded	Yes	Considerably

Table 6: Compatibility of RRP market related to ideal market design [17]

4.3 Commuting and EV statistics

In weekdays commuting is the most apparent reason for EV owners to travel, in this case they travel from home to work and back home. The EV owners could charge their EV at home, at work or at both depending on the availability of a charging station. The loading patterns of EVs in the Netherlands can be seen in Figure 13 where the accumulated number of charging signals is represented by bars. As expected there are peaks for stopping and starting charging between 08.00-09.00 hour and 17.00-18.30 hour during weekdays. These peaks are most likely to be caused by the commuting of the EV owners. Other start and stop charging signals could be caused by unplanned trips or different work schedules. In the weekends the loading patterns are different, and seem to be more randomly. However, it can be said with reasonable certainty that the EV is plugged in from 20.00 till 07.00 hour [45].

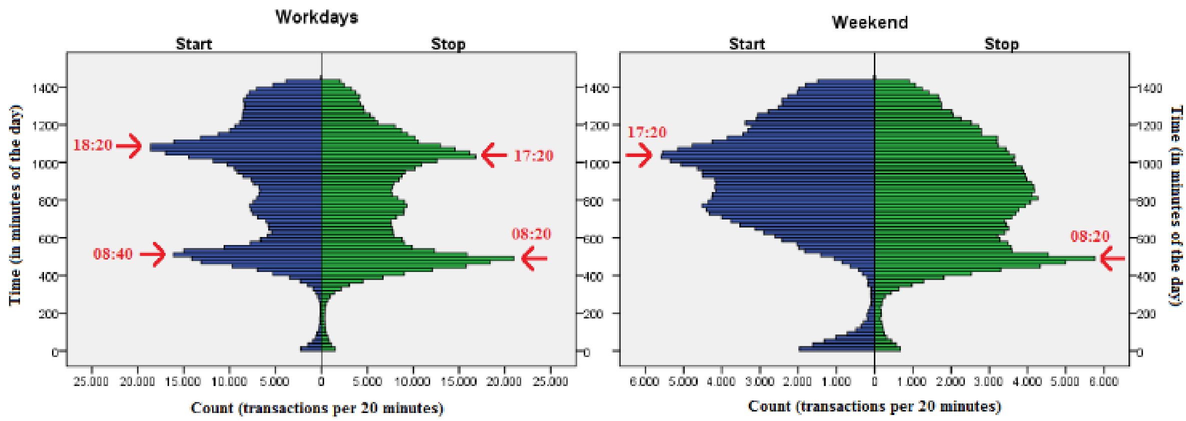

Figure 13: Loading Patterns in the Netherlands. On the left weekdays, on the right weekends [45]

In [17] three different EV owner patterns have been identified relating to charging customs. These can be categorized according to the availability of charging stations and are: Commuters (C), Residents (R) and Resident Commuters (RC). Commuters charge their EV during office hours, residents charge during the night and resident commuters charge their EV during each parking session. This is visualized in Figure 14, which describes the expected connection times of the different EV owner types. The driving patterns of the three EV owner types are similar during the weekdays.

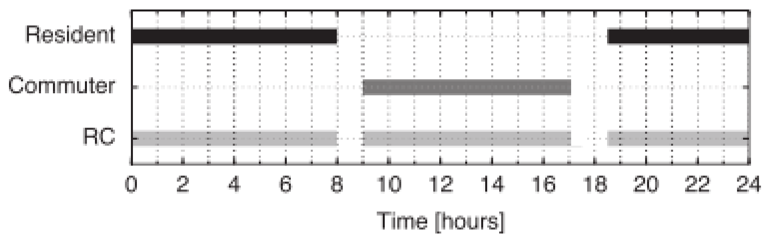

Figure 14: Connection times during weekdays for the different types of EV owners [17]

4.3.1 Statistics of EVs in the Netherlands

In the Netherlands a total of 418.641 new cars have been registered in 2017, of which 11.072 were EVs [31]. At the time of writing about 170.000 EVs are registered in the Netherlands [30]. The goals of the government are to have 200.000 EVs by 2020 and 1.000.000 by 2025 [25]. Moreover, the ambition is that 10% of all new passenger cars sold will have an electric powertrain and plug by 2020, this should be 50% by 2025 and 100% by 2030 [30].

The most popular EVs in the Netherlands are the Tesla Model S75, Renault ZOE and the Nissan Leaf, the most popular PHEVs on Dutch roads are the Mitsubishi Outlander, Volvo V60 Plug-in hybrid and the Volkswagen Golf. These EVs and PHEVs will be used in the simulation with their characteristics to estimate returns for an aggregator stationed in the Netherlands [30]. The characteristics of each vehicle are given in Table 7.

	Tesla	ZOE	Leaf	Outlander	V60	Golf
Battery capacity (kWh) [10]	75	41	40	12	11.2	8.7
Charging power (kW) [10]	17	22	6.6	3.7	3.7	3.7
Number on Dutch roads (May 2018) [30]	8.824	2.751	2.842	24.922	15.554	10.907
SOC reduction (%/trip) [17]	10	28	28	28	28	28
Battery replacement costs (€) [1]	12000	7000	6000	200	200	200

Table 7: Specifications of popular electrical vehicles in the Netherlands

4.4 Summary

This Chapter described the specifics of the Dutch electricity market and the EV and commuting statistics. In this Chapter, SQ 4 has been evaluated, and a short description of the findings is presented below.

- SQ 4: *How is the Dutch power market regulated?*

The Dutch power market is regulated according to the general market structure in Chapter 3. For V2G and SC the IDM and RRP market are interesting, as these market address and value the strengths of EVs, i.e. these markets are short-duration, quick response, and high-value.

Furthermore, the EV and commuting statistics of the Netherlands have been examined. The insights of this Chapter are used in the simulation in Chapter 7. In the simulation the Dutch electricity market is used to estimate potential profits. Furthermore, the six different EVs and PHEVs described in Table 7 are used as input for the EV characteristics.

5 Practical Considerations of V2G and SC Implementation

In this study the potential profit of an aggregator in the Netherlands is ought to be maximized considering several practical limitations. In the previous Chapter the specifics of the Netherlands with regard to V2G and SC have been described. In this Chapter the practical limitations are examined in order to obtain a realistic estimate of the potential profits.

The V2G concept was first mentioned in 1997 [19] and has since been the focus of research for many scholars. This has led to numerous conceptual frameworks, implementation plans and algorithms. Review of these articles has indicated that there are three major practical considerations for the implementation of V2G, namely: battery degradation, investment costs, and social barriers [38]. As the aim of this research is to incorporate the practical consideration into a profit maximization algorithm for aggregators, it is important to assess the implications of these challenges. Battery degradation and investment costs only affect the implementation of V2G, whereas social barriers also affect SC. After reading this Chapter, it should be clear why these three practical considerations are of major concern for an aggregator and the V2G and SC concepts.

- In Section 5.1 the practical consideration of battery degradation is explained
- In Section 5.2 the practical consideration of investment costs are elaborated
- In Section 5.3 the practical consideration of social barriers are specified. To test whether the V2G and SC concepts are possible with regard to the aggregation of numerous EVs a survey is conducted. The survey is used to test the willingness of EV owners to participate in the V2G and SC concepts
- In Section 5.4 the summary of this Chapter is provided including a brief description of the answer to SQ 5

5.1 Battery Degradation

Battery degradation occurs due to the deterioration of battery cells. This happens when the battery is charged or discharged. The irreversible chemical reaction that occurs in the battery will gradually increase the battery's internal resistance resulting in a reduced useable battery capacity [7, 38]. The deterioration of a battery depends on many different factors, including charging and discharging rates, voltage, Depth Of Discharge (DOD), temperature [38], humidity, and it also strongly depends on the battery chemistries [29].

The Equivalent Series Resistance (ESR) is a parameter used to predict the battery life cycle. Frequent battery charge and discharge cycles or a deep depth of discharge will result in an increased battery ESR which implies a lower lifespan of a battery. The battery ESR increases at low battery temperature and extreme state of charge. A battery state of charge should be kept between 30% and 90% of total battery capacity to prevent the increase in ESR [38]. The DOD, which is one of the most important indicator of battery lifetime is the DOD [29], and should be kept less than 60% [38].

Participation in V2G would lead to faster battery degradation as more charging and discharging cycles occur as a result of V2G. Therefore, it is important for an aggregator to compensate the EV owners for the additional battery degradation. The degradation rate increases as a result of V2G due to providing RRP up, i.e. the discharging of the EV. Charging an EV, i.e. regular charging or providing IDM or RRP down, does not result in an increased degradation rate, as this charging should occur anyway. Therefore, the degradation rate does not increase by participating in SC. The inflicted degradation costs to the EV, associated to providing IDM or RRP up, should be compensated by the aggregator, as these costs would not occur without participating in V2G. EV owners are not willing to participate in V2G if they are not compensated for the battery degradation costs, as will be confirmed by the survey in Chapter 7. The degradation costs associated to providing IDM or RRP up can be estimated using several calculations. To obtain a realistic estimate, the most important indicator of battery lifetime, the DOD, should be incorporated in the calculation for degradation costs.

5.2 Investment Costs

The second practical consideration for the implementation of V2G is the high investment costs that coincide with the physical implementation of V2G. The investment costs are necessary to upgrade the power system of the EV, including improvements in hardware and software infrastructure. The hardware infrastructure should contain a battery charger which allows bi-directional electricity flows. The software infrastructure includes the controlling and communication systems. The charging facilities have to be upgraded as well, to allow bi-directional electricity flows [38].

However, the exact height and details of the investments costs are unknown [29]. In the simulation the investment costs are therefore not considered. The investment costs depend on the height of the investment and the number of EVs and charging facilities that have to be upgraded. For an aggregator to be profitable, it should be noted that the investment costs in V2G hardware and software should be lower than the possible returns of V2G. SC could be performed regardless of the bi-direction facilities, and require no investment costs.

5.3 Social Barriers

In [36] it is concluded that attempts to overcome social barriers might be just as important as the studies relating to improving the technical performance of V2G. The barriers the V2G concept faces are not just technical, they encompass social barriers as well. The history of other energy transitions implies that these 'socio-technical' obstacles may be just as important to any V2G transition. In addition, as the social barriers are often harder to identify, they could be more difficult to overcome. The implementation of V2G, even when all technical problems have been resolved, could still be impeded by a lack of widespread public acceptance [36].

An aggregator should be able to couple thousands of EVs, as discussed in Section 3.2. This requires the participation of thousands of EV owners. The participation of EV owners is fundamental for the aggregator's business model. Without a large group of participating EV owners an aggregator cannot make an impact in the electricity markets. Yet, the social barriers associated to V2G and SC have prevented the public acceptance of the V2G technology. Despite the importance of public acceptance, the social barriers preventing acceptance have not received much attention in literature [28, 38]. Because an EV owner has to share the electricity of the EV's battery with the power grid, EV owners might think the SOC of the battery is insufficient for a trip at the time of departure. This driving range anxiety is one of the major challenges for the implementation of V2G. The lack of charging facilities makes the situation even worse. In order to reduce the driving range anxiety: a well-planned EV charging network is required [38], outside the scope of this work; And it is necessary to take into account the SOC of the EV and the EV owner's preferred SOC at the moment of departure. This is referred to as the minimal Guaranteed Driving Range (GDR) [3].

Another major challenge regarding the implementation of V2G and SC is how EV owners could be incited or obligated to plug-in their EV whenever possible to enable V2G or SC. An aggregator only possesses the capacity of an EV's battery if the EV is plugged-in. Even though cars generally drive only 1 hour a day, it does not imply that the EV is plugged-in for the remainder of the day. Moreover, due to the increased degradation rate of the battery, the battery has to be replaced more frequently than normal. This is another inconvenience preventing public acceptance of V2G. To incite the EV owners to participate in V2G, compensation might be required. This compensation could possibly be necessary to stimulate EV owners to plug-in their EVs, and to overcome the barriers caused by the inconveniences before. In [28] the willingness to participate in V2G of EV owners was tested using a contractual agreement. The authors concluded that EV owners are not willing to participate on a contractual agreement because EV owners are extremely sensitive to V2G restrictions. In the contracts it is agreed upon how many hours per day an EV owner is obligated to plug-in his/her EV. As this type of contract is not economically competitive, the authors propose a pay-as-you-go framework instead. This framework eliminates all contract requirements, and allows EV owners to provide V2G services on their terms. This framework could make V2G more attractive to EV owners [28].

5.3.1 Survey

The proposed pay-as-you-go framework might mitigate the social barrier related to V2G. This framework however, has not been examined among EV owners. For this purpose, in this thesis a survey among EV and potential EV owners is conducted. In this survey the central question is how an aggregator could potentially incite EV owners to participate in V2G and SC. One of the main objectives of this survey is to obtain a realistic estimation of the required compensation to incite EV owners. This incitement compensation will be used in the profit optimization problem. EV owners could be incited by a compensation [28], and it is expected that an incitement compensation is required for EV owners to participate in V2G or SC. This expectation is formulated in Hypothesis 1a (H1a).

H1a: *An incitement compensation is required for EV owners to participate in V2G or SC.*

The degradation costs associated with V2G should be compensated by the aggregator. This intuitively makes sense as the additional usage of the cars' battery would otherwise not have taken place. In literature almost all profit optimization problems account for the degradation costs in one way or another. The compensation could be based on actual provided energy times a price for the additional degradation [20, 35] or it could take into account several other factors of degradation such as DOD [3, 29]. The necessity of a degradation compensation for the costs associated to V2G is examined by questioning whether an EV owner is willing to participate in V2G without compensation. It is expected in H1b that EV owners are not willing to participate in V2G if they are not compensated for the additional degradation costs.

H1b: *A degradation compensation is required for EV owners to participate in V2G.*

The willingness to participate in V2G might also be affected by the EV owner's characteristics. These characteristics include among others age, gender and the degree of environmental awareness. According to [4, 32] consumers who are interested in EVs are environmentally sensitive, i.e. have a pro-environmental identity. Consumers that are aware of the environment, and who are actively trying to help the environment by buying an EV could also be more willing to participate in V2G or SC.

There are four human values considered to underline an individual's environmental beliefs and behaviors. These values are biospheric, indicating a person's concern for environment; altruistic, indicating a person's concern for others; egoistic, a person's concern for personal resources; hedonic values which reflects a person's concern for pleasure and comfort [2]. It is expected that:

H2a: *The willingness to participate in V2G or SC decreases when an EV owner scores high on hedonic values.*
H2b: *The willingness to participate in V2G or SC decreases when an EV owner scores high on egoistic values.*
H2c: *The willingness to participate in V2G or SC increases when an EV owner scores high on altruistic values.*
H2d: *The willingness to participate in V2G or SC increases when an EV owner scores high on biospheric values.*

The degradation compensation as discussed before is most of the time calculated by multiplying the amount of regulation up by a price for using additional battery capacity which is based on the replacement costs of the battery pack [3, 20, 29, 35]. This reasoning is based on the premise that an aggregator only has to pay for the amount of battery degradation which is actually caused by V2G. The expectation is that EV owners also apply this reasoning and that they require a degradation compensation for the time or amount that the battery is used for V2G. The incitement compensation in contrast, is likely to be dependent on the time the EV owner enables V2G or SC. This is expected because EV owners have to actively plug in their EVs for a certain period of time. The time that the car is available should be appraised by an aggregator. This reasoning is in line with how several electricity markets, for example the UK [23], Germany [3] and Dutch primary reserve [5] work. In these markets the provider of reserve power gets paid a capacity price, and are called capacity markets. This capacity price is a compensation for providing reserve capacity, and is paid regardless of whether there is an actual call-off, i.e. the capacity has to be delivered.

H3a: *EV owners wish incitement compensation based on the time they enable V2G or SC.*
H3b: *EV owners wish degradation compensation based on the time their EV is used for V2G.*

In [28], the contractual agreement between an aggregator and an EV owner was found to be economically infeasible as EV owners are extremely sensitive to the restrictions from this type of V2G framework. In addition, in [38] it was determined that one major social barrier for EV owners is the driving range anxiety. Taking these two notions into consideration it is expected that EV owners wish to get incitement compensation because their flexibility decreases when providing V2G, and the charging time increases when providing V2G. Other factors such as additional efforts or extra income could also be the determinant for EV owners to wishing incitement compensation.

H4a: *EV owners wish incitement compensation because their flexibility to use their EV decreases.*
H4b: *EV owners wish incitement compensation because the charging time increases.*
H4c: *EV owners wish incitement compensation because they have to make extra efforts.*
H4d: *EV owners wish incitement compensation because they could obtain an additional income.*

The EV owner's environmental beliefs and behaviors could not only have an effect on the willingness to participate in V2G and SC, but could impact the height of the incitement compensation. Using the same four human values as for Hypotheses 2, it is expected that:

H5a: *The height of incitement compensation increases when an EV owner scores high on hedonic values.*
H5b: *The height of incitement compensation increases when an EV owner scores high on egoistic values.*
H5c: *The height of incitement compensation decreases when an EV owner scores high on altruistic values.*
H5d: *The height of incitement compensation decreases when an EV owner scores high on biospheric values.*

5.3.1.1 Hypotheses

In Figure 15, the formulated hypotheses are visualized in a conceptual model. This model displays the possible relations between the various variables and elements. The willingness of EV owners to participate in V2G and SC is the result of several variables and elements that could be interrelated to each other. With this model the willingness of the EV owners to participate is tested by examining: whether (potential) EV owners are willing to participate, what their requirements are (including the height of the incitement compensation), and for what they would require to receive compensations. Next, the design of the survey, which is used to test the hypotheses, is discussed.

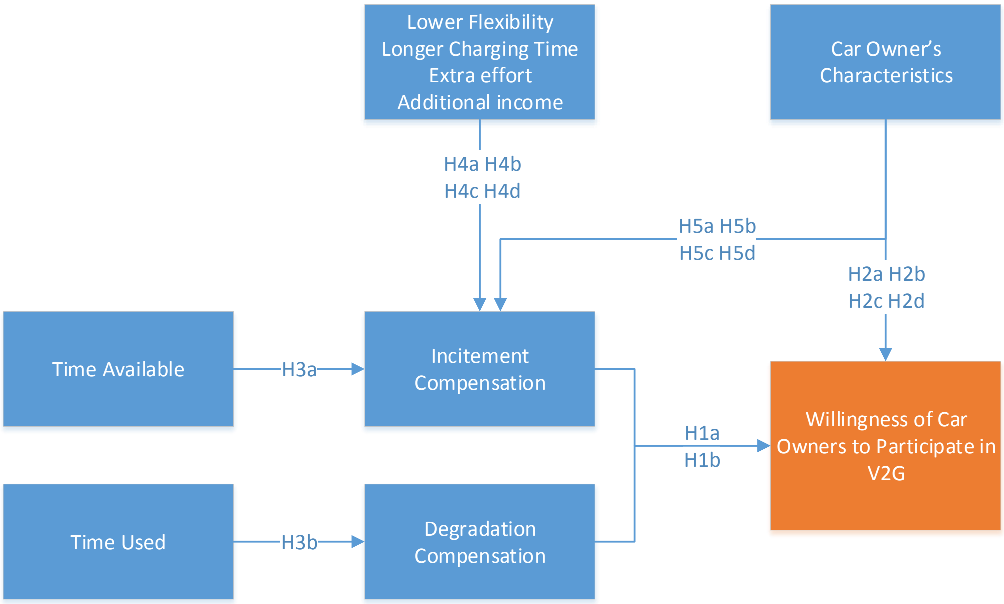

Figure 15: Conceptual Model for Questionnaire

5.3.1.2 Design of Survey

The objective of the survey with respect to this research about maximizing profits for an aggregator within V2G is to obtain insights into the wishes and requirements of EV owners. The social barriers relating to the implementation of V2G have not received as much attention as the profit optimization problems, whereas it might be equally important. If there are no EV owners willing to participate in V2G, then there is no profit for an aggregator to be maximized as there is no capacity to bid. The main insight obtained in this survey is how EV owners could be incited to participate in V2G. The incitement compensation required to participate is reflected in monetary benefits for the EV owner. The EV owners should indicate the height of the incitement compensation required for them to participate in V2G or SC. The height of the incitement compensation for V2G and SC is examined separately, as this could differ. The survey (in Dutch) is attached in appendix B. Participants were asked to indicate on a 7-point scale (1 totally agree to 7 totally disagree) if they agree with the statement/question.

The survey begins with two demographic questions about age and gender. It proceeds with several statements about social trends, to obtain insights into the four human values that underline an individuals' environmental beliefs and behaviors. The four human values considered are: biospheric, altruistic, egoistic, and hedonic values [2]. Participants were asked to indicate on a 7-point scale (1 not like me at all to 7 very much like me) how much the person in the description is similar to them.

In the next questions, several information about the perceived benefits of gasoline and electrical vehicles is asked. Seven key attributes are shown, for which the respondent has to indicate if this attribute is fitting for the type of vehicle. Among the key attributes [27], seven of them are: Price, is the type of car perceived expensive; environmental considerations, is the type of car perceived environmentally friendly; lifetime, does the car have a long perceived lifetime; range, is the perceived range high; performance, is the top speed and acceleration perceived as high or good; comfort, is the car seen as comfortable; status, is the social status perceived as high when driving that type of vehicle. This list of key attributes is not exhaustive, however, can describe the differences between the type of cars perceived by car owners/buyers. This is followed by the question: What do you consider when purchasing a new car? These questions describe what an individual finds important when considering to buy a new car.

Having described the values, behaviors and what is important for an individual relating to his/her vehicle, the SC and V2G concept are explained. First, it is stated that one should presume that they are in possession of an electrical vehicle, either EV or PHEV. It is explained that a car on average only drives for 1 hour a day, and that in the remaining 23 hours the battery of an EV could be used to stabilize the electricity grid. Because one vehicle does not have enough capacity to do so, an aggregator party is required. Then three questions follow, whether they are willing to participate in V2G, in SC and whether they are willing to plug-in their EV as long as possible. These questions are a baseline scenario to obtain an insight into whether an EV owner would be interested in the SC/V2G concepts. The respondents do not yet know about the incitement compensation.

The remainder of the survey focuses on the incitement compensation that is possibly required to motivate EV owners to participate. First, it is explained that the height of the incitement compensation is yet to be determined as well as its terms (flex-as-you-go vs contractual). It is explained why an incitement compensation might be required. Moreover, the degradation compensation is elaborated upon as well, as it is expected that without a degradation compensation EV owners are not interested in V2G.

First, it is examined whether they are expecting any degradation or incitement compensation at all. Then the means of compensation should be indicated. The compensation could be based on actual usage, on availability or on both. This question is used to test hypotheses 3a and 3b.

Second, several questions relating to practical SC/V2G implications for the EV owners are stated. These practical implications for an EV owner include among others the additional efforts that could be a result of V2G and SC. The practical implications for an EV owner could affect the willingness to participate.

From an aggregator's perspective, it would be interesting to know in advance at what time the EV owner is using his/her EV. This information can be used by an aggregator to make a bid with high certainty that the EV's capacity is available at that time. For this purpose, it is evaluated how long in advance an EV owner is able, and willing to indicate that he/she is using his/her EV. Another input that could be required from EV owners participating in SC or V2G is how they would like to charge their EV. Three charging options are possible: priority (no SC/V2G), normal (the EV is charged for the next planned trip), flexible (the EV will not be used by the owner for at least 24 hours). The last question relating to a practical implication of SC and V2G is to what SOC the battery should be charged for a normal planned trip. The lower the required SOC for a planned trip, the more freedom an aggregator has with respect to making bids.

Lastly, the height of the incitement compensation required for EV owners to participate in SC/V2G is asked. There are three incitement compensations examined: V2G-flex-as-you-go, V2G-contractual and Smart Charging. First the differences and implications of the three types is explained, after which the respondent could indicate using a slider what the height of the incitement compensation should be. The maximum height of the incitement compensation was set to be €500. The maximum incitement compensation would be infeasible with respect to the possible benefits an aggregator is able to make, see Table 3. The last remaining question, to test hypotheses 4, is for what an EV owner would actually require the incitement compensation. This question provides insights for an aggregator into what the EV owners find restricting about V2G and SC.

5.4 Summary

In this Chapter three practical considerations regarding the implementation and profit of V2G and SC have been identified. The identification of the practical considerations was the objective of SQ 5:

- SQ 5: *What are the practical considerations of profit maximization?*

There are three major practical considerations for the profits of an aggregator:

- Battery degradation costs related to V2G. The EV owner should be compensated for the inflicted additional battery degradation, which accounts to an extra cost for the aggregator. The battery degradation should be estimated as realistically as possible. Therefore, the DOD should be used in the calculations for the degradation compensation.

- Investment costs related to V2G. In order to establish the physical bi-directional power connection between an EV and the grid, investments in bi-directional hardware and software are required. The height of the required investments are unknown, and the investment costs are therefore not considered in the simulation model in Chapter 6, but will be discussed in Chapter 8. The investment costs should not exceed the potential benefits of V2G.
- Social barriers related to V2G and SC. The EV owners are reluctant to participate in V2G and SC due to driving range anxiety and other inconveniences. As the participation of EV owners is fundamental to the V2G and SC concepts, a survey was conducted among potential EV owners. This survey intents to obtain insights into how EV owners could be incited to participate in V2G and SC. In Chapter 7 the results of the survey are examined. One of the contributions of the survey to this work is an estimation of the incitement compensation required by EV owners. This is an additional cost the aggregator has to take into account, and that should be adopted in the formulation of the profit optimization model in Chapter 7

6 Profit Optimization Problem

In this Chapter the profit optimization problem is formulated mathematically. For this purpose, several problem formulation found in literature were examined in Section 6.1. The examination of the models resulted in a framework which is then used to formulate the problem in this study. The framework consists of: type of control; an objective function; market, price and battery constraints; and energy and costs calculations. In literature several optimization problems exists, e.g. [17, 29, 35], and these models have several interesting insights. These insights are described in Section 6.1.1.

In Section 6.2 the profit optimization model of this study is formulated. This model takes into account the practical considerations found in Chapter 5, and the specifics of the Netherlands described in Chapter 4. Multiple variables can be distinguished in the following equations. The detailed description of the variables can be consulted in the Nomenclature. In general the variables are described as follows:

- $E_i^{\cdots}(t)$ represents electricity
- $B_i^{\cdots}$ represents a battery characteristic
- $P^{\cdots}(t)$ represents the electricity price for the corresponding market
- $C_i^{\cdots}(t)$ represents costs
- $SOC_i(t)$ represents the current SOC
- $SOC_i^{\cdots}(t)$ represents EV owner preferences for the SOC
- α, η, δ, ϵ[...] represent a compensation factor, efficiency factor, probability factor, and expectation factor respectively

In Section 6.3 the summary of this Chapter is provided, including a short answer to SQ 7.

6.1 Existing profit optimization models

Many scholars have developed a profit maximization algorithm, and one that is accepted in the literature is one by Sortomme et al (2012). This algorithm is focused on maximizing V2G energy and ancillary services. First the algorithm is provided, after which it is explained conceptually.

$$\text{Maximize} \quad \forall i, t$$

$$Income - Costs \tag{1}$$

$$\text{Subject to:}$$

$$\sum_{t=1}^{time} \big((\epsilon[E_i^{V2G}(t)] \cdot \alpha_i(t) + \rho_i(t)) \cdot \eta_i + SOC_i^{initial} - SOC_i^{trip}(t^{trip}\big) \leq B_i^{cap} \tag{2}$$

$$\sum_{t=1}^{time} \big((\epsilon[E_i^{V2G}(t)] \cdot \alpha_i(t) + \rho_i(t)) \cdot \eta_i + SOC_i^{initial} - SOC_i^{trip}(t^{trip}\big) \geq 0 \tag{3}$$

$$\sum_{t=1}^{t^{trip}} \big((\epsilon[E_i^{V2G}(t)] \cdot \alpha_i(t) + \rho_i(t)) \cdot \eta_i + SOC_i^{initial} - SOC_i^{trip}(t^{trip}\big) \geq 0.99 B_i^{cap} \tag{4}$$

$$(E_i^{AP\downarrow}(1) + B_i^{POP}(1)\big) \cdot \alpha_i(1) \cdot \eta_i + SOC_i^{initial} \leq B_i^{cap} \tag{5}$$

$$(B_i^{POP}(1) - E_i^{AP\uparrow}(1) - E_i^{SR}(1) + \rho_i(1)) \cdot \alpha_i(1) \cdot \eta_i + SOC_i^{initial} \geq 0 \tag{6}$$

$$(B_i^{POP}(1) - E_i^{AP\uparrow}(1) - E_i^{SR}(1) + \rho_i(1)) \cdot \alpha_i(1) \cdot \eta_i + SOC_i^{initial} \geq SOC^{trip}(t^{trip}) \tag{7}$$

$$(E_i^{AP\downarrow}(t) + B_i^{POP}(t)) \cdot \alpha_i(t) \leq E_i^{V2G,max}(t) \tag{8}$$

$$E_i^{AP\uparrow}(t) \leq B_i^{POP}(t) + E_i^{V2G,max}(t) \tag{9}$$

$$E_i^{SR}(t) \leq B_i^{POP}(t) + E_i^{V2G,max}(t) - E_i^{AP\uparrow}(t) \tag{10}$$

$$E_i^{AP\downarrow}(t) \geq 0 \tag{11}$$

$$E_i^{AP\uparrow}(t) \geq 0 \tag{12}$$

$$E_i^{SR}(t) \geq 0 \tag{13}$$

$$B_i^{POP}(t) \geq -E_i^{V2G,max}(t) \tag{14}$$

$$B_i^{deg}(t) \geq 0 \tag{15}$$

$$B_i^{deg}(t) \geq C_i^{deg} \cdot \epsilon[E_i^{V2G\uparrow}(t)] \cdot \frac{\alpha_i(t)}{\eta_i} \tag{16}$$

$$\sum_{i \in V}^{n} B_i^{POP}(t) \leq \frac{E^{\epsilon,max} - E^{system}(t)}{E^{\epsilon,max} - E^{\epsilon,min}} \sum_{i \in V}^{n} E_i^{V2G,max}(t) \tag{17}$$

with

$$In = \sum_t \big((P^{R\downarrow}(t) \cdot E^{R\downarrow}(t) + P^{R\uparrow}(t) \cdot E^{R\uparrow}(t) + P^{RR}(t) \cdot E^{RR}(t)) \cdot \epsilon[EV](t)\big) + P^{El,charged} \sum_i \sum_t \big(\epsilon[E_i^{V2G}(t)] \cdot \epsilon[EV](t)\big) \tag{18}$$

$$C = \sum_i \sum_t \big(\epsilon[E_i^{V2G}(t)] \cdot \epsilon[EV](t)\big) + \sum_i \sum_t \big(Deg_i(t)\big) \tag{19}$$

$$\rho_i(t) = \left(\frac{B_i^{deg}(t)}{C_i^{deg}}\right) \frac{1 - \eta_i^2}{\eta_i} \tag{20}$$

$$\epsilon[E_i^{V2G}(t)] = E_i^{AP\downarrow}(t) \cdot \delta^{R\downarrow} + B_i^{POP}(t) - E_i^{AP\uparrow}(t) \cdot \delta^{R\uparrow} - E_i^{SR}(t) \cdot \delta^{SR} \tag{21}$$

$$E^{R\uparrow}(t) = \sum_{i \in V}^{n} E_i^{AP\uparrow}(t) \tag{22}$$

$$E^{R\downarrow}(t) = \sum_{i \in V}^{n} E_i^{AP\downarrow}(t) \tag{23}$$

$$E^{RR}(t) = \sum_{i \in V}^{n} E_i^{SR}(t) \tag{24}$$

$$\epsilon[E_i^{V2G\uparrow}(t)] = B_i^{POP}(t) - E_i^{AP\uparrow}(t) \cdot \delta^{R\uparrow} - E_i^{SR}(t) \cdot \delta^{SR} \tag{25}$$

$$C_i^{deg} = 0.042 \left(\frac{C_i^{battery}}{5000}\right) + \frac{1 - \eta_i^2}{\eta_i} \cdot P^{El,charged} \tag{26}$$

Control

The problem formulation in equations (1)-(26) maximizes profits for an aggregator by optimizing the bids to simultaneously provide V2G services in: Peak power, regulation up, regulation down, and spinning reserves. The formulation of the problem as a linear program can be solved quickly and efficiently for large groups of EVs [35]. The problem formulation is linear and convex as stated by the author. A convex model results in a global optimal solution. The model also uses a dynamic approach, implying that a time varying price is used for profit calculations instead of static average prices.

This problem formulation can be roughly divided in an objective function, 2 groups of constraints (market and battery), and 2 groups of calculations (energy and costs). The corresponding equations will be explained subsequently.

Objective Function

The objective function as in (1) maximizes the income minus the costs of V2G services. The objective function is constructed of several constants and most importantly, the decision variables.

In (18) and (19) the income and costs functions are described, which will be discussed in the costs calculations part. The decision variables are the $E_i^{AP\downarrow}(t)$, $E_i^{AP\uparrow}(t)$, and $E_i^{SR}(t)$ variables. The income and costs parameters are not described for time, but are dependent of time-varying variables in (18) and (19) and therefore do vary with time.

Market Constraints

Equations (8), (9) and (10) are required to prevent that more capacity is bid than there is actually available. Moreover, (10) prevents double booking of capacity, i.e. it avoids that spinning reserves can use the same capacity as regulation up.

Constraints (11)-(15) are constraints assuring that power draw, preferred operating point or battery degradation cannot become negative.

The last constraint of the profit maximization algorithm, (17), is a system loading constraint. This constraint ensures that the combined charging of the EVs does not add to the forecasted system peak load as well as limiting how much additional load can be added during other hours.

Battery Constraints

Constraints (2) and (3) are battery constraints. These constraints are required to restrict charging and discharging events from going beyond battery capacity limit or into a negative SOC respectively. The left hand side is equal for equations (2), (3). The left hand side for equation (4) differs only in the summation, the summation is not over all time but over the specific period when the EV makes a trip. The left hand side calculates the capacity that could be used for charging or discharging. The $SOC_i^{initial} - SOC_i^{trip}(t^{trip})$ determines the capacity left after the initial SOC is reduced by the capacity needed for a trip. The residual capacity is calculated using $(\epsilon[E_i^{V2G}(t)] \cdot \alpha_i(t) + \rho_i(t)) \cdot \eta_i$, and represents the expected power draw over all periods of time that the EV is connected to the grid. This is multiplied by a compensation factor for the number of EVs leaving unexpectedly in this period. The compensation factor $\alpha_i(t)$ is used in the optimization problem of this thesis, however it is adjusted to α_i, i.e. it does not depend on time or any calculation, it is used as a parameter. The discharge efficiency compensation factor is added next, after which the total is multiplied by the efficiency factor. This results in the expected power draw due to charging or discharging over a period of time. Adding up the initial SOC and subtracting the required capacity for the trip home results in a capacity which can be used for charging or discharging. This capacity however, should not exceed the maximum charge capacity of the vehicle, as in (2) or become negative (3) as this is physically impossible for the battery. The adaptation of these constraints into (4) is that the sum determines that at the time of departure for vehicle i, its SOC should be at least 99%.

In (5) it is constraint that the charging effects could exceed the maximum charging capacity in the next period. In constraints(6) and (7) it is prevented that the discharging effects will result in a capacity that is negative or lower than what is needed for a Trip respectively. These constraints differ from (2), (3) and (5) in the way that the power draw is calculated. In constraints (5)-(7) the power draw is calculated for the next period instead of for the complete period the EV is connected.

In (16) the battery degradation is calculated. The battery degradation should be larger or equal to the battery degradation costs. These costs constitutes of a degradation cost factor C_i^{deg} is calculated in (26). The battery degradation cost factor is multiplied by the discharging power draw, because degradation costs will only have to be paid for discharging. This is then multiplied by a compensation factor and an efficiency factor.

Energy Calculations

Equation (21) calculates the expected final power draw of the vehicle combining regulation and responsive services. This is done by adding the maximum additional power draw per type times its expected percentage of capacity per type of market. In (22), (23) and (24) capacity per market type is calculated. This capacity is used to bid into the electricity markets. Equation (25) is used to calculate the discharging capacity, this is required to estimate the battery degradation costs.

Costs Calculations

In (18) the income of the aggregator is calculated by adding up the bidding profits of the different markets multiplied by the expected percentage of EVs remaining at that period of time to perform V2G. And a factor for the energy which is sold to the vehicle owner for a certain price. This price could be higher than the actual price for electricity which is used to calculate the costs of the aggregator in (19). The cost consists out of the price for electricity plus the degradation costs for the vehicle owners. In (20) the term $\rho_i(t)$ is to account for the energy discharged from the battery due to the discharge efficiency, which is similar to the balancing term in the aggregator degradation costs [35]. The discharge efficiency could be simplified to $\epsilon[E_i^{V2G}(t)] \cdot \alpha_i(t) \cdot \frac{1-\eta_i^2}{\eta_i^2}$

The degradation costs are calculated in (26). Where the parameter 0.042 is the degradation cost of a kWh of energy throughput. The term it is multiplied with is the normalization of the battery replacement costs, $C_i^{battery}$ is the replacement costs divided by the normalization factor. The second term of the degradation cost is a balancing term multiplied by the aggregator price of energy to account for the differences in energy delivered to and taken from the battery compared to what is measured at the meter. This term is required so that there is no incentive for the aggregator to overcharge the customers.

6.1.1 Additional constraints from existing models

The model of Sortomme (2012) has a conceptual sound structure. However, in order to take additional practical considerations into account, and to incorporate the Dutch electricity market, the model should be adjusted. In this Section the changes required to the model of Sortomme (2012) are discussed.

Control

The model in [35] is a linear convex problem formulation. Another possibility for control, is Model Predictive Control (MPC). MPC has a number of advantages over traditional control schemes. These advantages include its ability to explicitly fulfill system constraints, natural handling of multi-variable systems and ability to handle dead-time [33, 34]. MPC minimizes the error from a set-point using a cost function [34]. To implement MPC the cost function of the model in [35] has to be adjusted. In depth explanation of the choice for MPC and the use of MPC can be found in Section 6.2.1.

MPC is described as: *"Model predictive control is a form of control in which the current control action is obtained by solving online, at each sampling instant, a finite horizon open-loop optimal control problem, using the current state of the plant as the initial state; the optimization yields an optimal control sequence and the first control in this sequence is applied to the plant."* [24].

This description encompasses the most important information for why MPC is used in this research: *MPC is a form of control in which the current control action is obtained by solving online [...] open-loop optimal control problem*, in this research that is, an online problem with dynamic properties is ought to be solved. The problem uses real-time data which is used to evaluate whether a bid is accepted or not; *At each sampling instant* that is, at each PTU; *A finite horizon*, that is, for a finite time horizon of one day and a planning horizon of 3 (the prediction horizon); *Using the current state of the plant as the initial state*, that is, the current SOC of the EV; *The optimization yields an optimal control sequence and the first control in this sequence is applied to the plant*, that is, the planning horizon consists of optimal bids per planning period, and only the first planning period (the grey block in Figure 16), i.e. the first bid, is added to the current SOC of the EV.

For the implementation of MPC a rolling horizon is used. The rolling horizon consists of a planning period, a planning horizon, and a time horizon. The planning period is the smallest period, and refers to one control in the optimal control sequence. The planning horizon refers to the complete control sequence, and is calculated at each sampling instant. This implies that MPC considers future actions as well. The time horizon is the number of time intervals MPC should evaluate. In Figure 16 the time horizon is three, as there are three blocks of planning horizons. The time horizon could easily expand, to for instance a time horizon of one day. The planning/prediction horizon should be determined in advance.

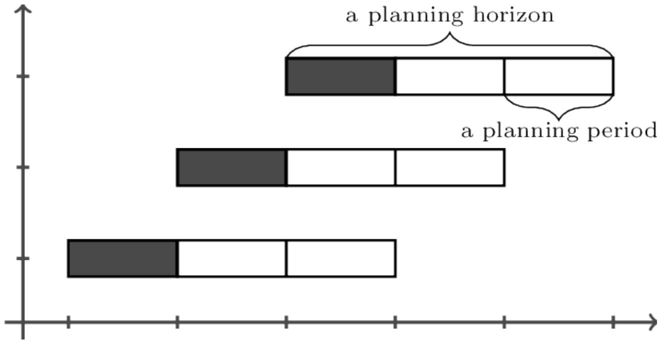

Figure 16: Conceptual visualization of a rolling horizon

Objective Function

Because MPC is used as a the control scheme, the objective function of income minus costs of one time period has to change in a summation of income minus costs over a certain time horizon. Generally, a cost function of MPC can be expressed as a quadratic equation such as [34]:

$$f(u,y) = \frac{1}{2}\sum_{k=0}^{N-1}\big((y(k)-y_{ss})_Q^2 + (u(k)-u_{ss})_R^2\big) \tag{27}$$

Where y_{ss} and u_{ss} are the steady state set-point of the output and input. A variant of MPC commonly used to optimize operational and other costs is the Economic Model Predictive Control (EMPC). With EMPC the costs can be expressed in a non-quadratic form [14, 34], e.g.:

$$f(u,v) = \sum_{k=0}^{N-1}\big(p(k)\cdot u(k)\big) \tag{28}$$

In the work of Sha'aban et al. (2017) the cost function described in (29) is used, which resembles a slightly modified version of the general EMPC cost function in (28).

$$\text{minimize} f = \sum_{k=0}^{N-1}\big(p(k)\cdot\delta(k)\cdot u(k) + wv(k)\big) \tag{29}$$

The term $\delta(k)$ was introduced as a tuning parameter to penalize the effect of the current or future tariff on the optimization problem. The terms v_k and w prevent infeasible solution as the slack variable v_k is penalized by a large value of w. In the problem formulation in section 6.2 the objective function is also a slightly modified version of the general EMPC cost function as well a variant of the objective function used in [34]. Other income and price parameters are used to oblige to the Dutch electricity market, and other costs variables are introduced. The general expression of both objective functions is similar though, minimizing the sum over time k, using a price variable, capacity variable, tuning parameter and costs.

Difference Equation

As previously mentioned, MPC minimizes the error from a set-point using a cost function. The set-point can be described by steady state variables of the input and output. MPC generally requires a difference equation. In [34] this is formulated as follows:

$$x(k+1) = Ax(k) + Bu(k) + Ed(k) \tag{30}$$

This notion is adopted in the problem formulation in section 6.2, where the output x in (30) has been replaced with the actual output, the SOC of the vehicle. The input u similarly has been replaced by E, the energy charged or discharged. The last term d is the driving parameter, which is the same in the problem formulation in this research.

SC or V2G Constraints

In [3] three types of charging patterns are distinguished: Regular charging, nonregular charging and nonregular discharging. This notion can be used to differentiate between normal charging, Smart Charging, and V2G.

Market Constraints

The market considered in the model of Sortomme (2012) focuses on the US, therefore the market constraints discussed for this problem formulation will not be used in the problem formulation of this research as this work focuses on the Dutch electricity market. Instead, the market constraints are deducted from Chapter 4 and from [17]. One of the market constraints that is important for the type of control, is the integer constraint of RRP bids. As the bids for RRP are required to be integer, the decision variables should be integer. Integer decision variables could result in a non-convex problem formulation. A non-convex problem formulation might not result in a global maximum or minimum, instead, a local maximum or minimum could be obtained. The result therefore, might not be the optimal result.

Price Constraints

Bidding prices are determined preemptively of actual energy provision. Pelzer et al. (2014) made a price-responsive dispatching strategy regarding V2G for the electricity market of Singapore. In this price-responsive strategy, bids are only made when the revenue of regulating services is higher than the variable costs. This price constraint is required to avoid financial losses. This is mathematically described as follows:

$$E_i^{\downarrow\uparrow}(t) = \begin{cases} E_i^{\downarrow\uparrow}(t), & E_i^{\downarrow\uparrow}(t) \cdot P^{\downarrow\uparrow}(t) > C^{var}(t) \quad \text{(31a)} \\ 0, & E_i^{\downarrow\uparrow}(t) \cdot P^{\downarrow\uparrow}(t) \leq C^{var}(t) \quad \text{(31b)} \end{cases}$$

However, this implies perfect knowledge about the prices in the future, or that bidding takes place at the exact moment of pricing. The Dutch electricity market required that bids are placed an hour in advance, therefore this constraint needs revision. As in the Netherlands a bid of the PRP has to include price for a given quantity, an aggregator should only construct a bid where the price for regulation is higher than the variable costs are. This also holds for the other markets. The concept of the constraint remains the same but it is adjusted to suit the Dutch electricity market.

Battery Constraints

The model of Sortomme (2012) considers several battery constraints in order to bid only the amount the battery is physically able to generate or store. The connection power of the grid to the vehicle though is not considered. The connection power is the amount of energy that can be transferred through the physical connection of the vehicle and the grid, and can be found in Table 7. The constraint of the connection power is as follows [3, 17]:

$$0 \leq E^{\downarrow,\uparrow}(t) \leq B^{cp} \tag{32}$$

Energy Calculations

The aforementioned problem formulation calculates the energy that can be bid per market type. However, this model does not include EV owner preferences. The need to include preferences of the EV owners is addressed in Section 5.3. The driving range anxiety among EV owners is one of the major challenges for V2G implementation. In [3] a minimal GDR is adopted to decrease the driving range anxiety. The height of the minimal GDR is indicated by the EV owners themselves. The minimal GDR resembles the SOC required for an EV owner to make an unplanned trip. The minimal GDR ensures that at every moment, if physically possible, the EV is charged to at least the SOC required to make an unplanned trip.

In [17] this minimal GDR is modified into a required SOC. The required SOC also includes the charging requirements for a planned trip. The minimal guaranteed driving range is for an unplanned trip, and the required SOC is for a planned trip. The required SOC is calculated as:

$$SOC^{req}(t) = SOC^{trip}(t^{trip}) - B^{cp} \cdot \eta_i \cdot (t^{trip} - t) \tag{33}$$

This energy calculation assumes knowledge about departure times. In the study of Hoogvliet et al. (2017) driving patterns were used in order to predict the charging times of EVs. This assumption is adopted, and the driving patterns used in this research were described in Section 4.3. When the departure time is known, the required SOC per time period can be calculated by subtracting the charging power from the required SOC for a planned trip.

In [17] transmission efficiency η_{tr} is introduced. This efficiency factor is required to allow for transmission losses . Transmission losses are, in the case of RRP down, undesirable. In the case of RRP up however, transmission losses can be considered as an advantage as a unit of power delivered at the low-voltage grid translates to a higher amount of power delivered to the high-voltage grid [17].

Costs Calculations

In equation (31) the price constraints are described. This constraint implies that the bid price should be higher than the variable costs. In [29] the variable costs are described as follows:

$$C^{var}(t) = C^{El,normal}(t) + C^{deg}(t) \tag{34}$$

Where $C^{El,normal}$ in (35) denotes the costs associated to purchasing the electricity with a normal price, and C^{deg} in (36) denotes the battery pack depreciation costs also called the degradation costs.

$$C^{El,normal(t)} = E^{\uparrow}(t) \cdot P^{El,normal} \tag{35}$$

$$C^{deg}(t) = \frac{B^{costs}}{\left(\left(\frac{145}{B^{DOD(t)}}\right)^{1/0.6844} \cdot B^{DOD(t)}\right) \cdot B^{cap}} \tag{36}$$

Where:

$$B^{DOD} = \frac{E^{\uparrow}(t)}{B^{cap}} \tag{37}$$

In this thesis the degradation costs are a function of the DOD, which is a more accurate calculation for the battery degradation costs than a standard parameter as in [35]. The degradation rate of the battery is influenced predominantly by the DOD [29].

One other cost that is not considered in [35] is the incitement compensation for the EV owners for V2G [28]. The incitement compensation is required to motivate EV owners to plug-in their EV in order to facilitate SC or V2G. The details, height and contractual agreements, are evaluated using the survey designed in Sections 5.3.1 and which is evaluated in Section 7.1.

Lastly, the actual calculation of benefits is different than the cost function in the objective function. Though Sortomme (2012) uses the same profit calculation, the calculation itself is not explicitly mentioned. Instead of calculating profits based on the income minus costs in the objective function, the profit calculation is actually the difference between the baseline scenario and the V2G scenario. In this research this difference is called the benefits with respect to the baseline scenario. The baseline scenario is the scenario without SC or V2G, i.e. the normal scenario. The benefits with respect to baseline scenario can be calculated as follows [17]:

$$Benefits = \sum_{t=1}^{T} \left(Profit^{RRP,t} - Profit^{baseline,t}\right) \tag{38}$$

Where $Profit^{baseline,t}$ is the scenario without SC or V2G, thus without income, incitement costs, and degradation costs and only regular charging costs.

$$Profit^{baseline,t} = \sum_{i \in V}^{n} \left(- E_i^{REG}(t) \cdot C^{El,normal}\right) \tag{39}$$

And $Profit^{RRP,t}$ is the SC or V2G scenario in the Dutch electricity market.

$$Profit^{RRP,t} = \sum_{i \in V}^{n} \Big(E_i^{RRP\downarrow,bid}(t) \cdot P^{RRP\downarrow,bid}(t) \cdot \delta^{RRP\downarrow}(t) + E_i^{RRP\uparrow,bid}(t) \cdot P^{RRP\uparrow,bid}(t) \cdot \delta^{RRP\uparrow}(t) \\ - \frac{C_i^{battery}}{\left(\frac{145.71}{B_i^{DOD}(t)}\right)^{\frac{1}{0.6844}} \cdot B_i^{DOD}(t) \cdot B_i^{cap}} - T_i^{charge}(t) \cdot C^{incite} - E_i^{REG}(t) \cdot C^{El,normal} \Big) \tag{40}$$

6.2 Profit Optimization Algorithm

In this Section the profit optimization algorithm of this thesis is formulated. This model is used in Chapter 7 for the simulation of the potential profits of an aggregator in the Netherlands. The profit optimization algorithm consists of three models. The first model encompasses the optimization of bids for the RRP market. The second model optimizes bids for the IDM. And the third model is a dispatching algorithm. The order of the models in line with the chronological order of the bidding procedure.

The algorithm in this research encompasses the conceptual ideas of Sortomme (2012) and also takes several notions of other scholars into consideration. These considerations are necessary to comply with the practical considerations of V2G as discussed in Chapter 5. The problem formulation of Sortomme (2012) is focused on the American electricity market, whereas the algorithm in this research is focused on the Dutch electricity market. As this research also ought to be as realistic as possible, dynamic real-time prices are used. Moreover, the degradation cost is not a fixed amount, but is dependent on the DOD as in equation (36). The incitement costs of SC and V2G are also used from the survey.

In Chapter 4 the practical implication of the Dutch Power Market have been described, including the bid time of 1 hour for RRP and 5 minutes for the IDM. These factors and limitations have to be accounted for in the algorithm design. Because of the differences in market requirements, and time horizon of the bid, an overview of the bidding procedure is visualized in Figure 17.

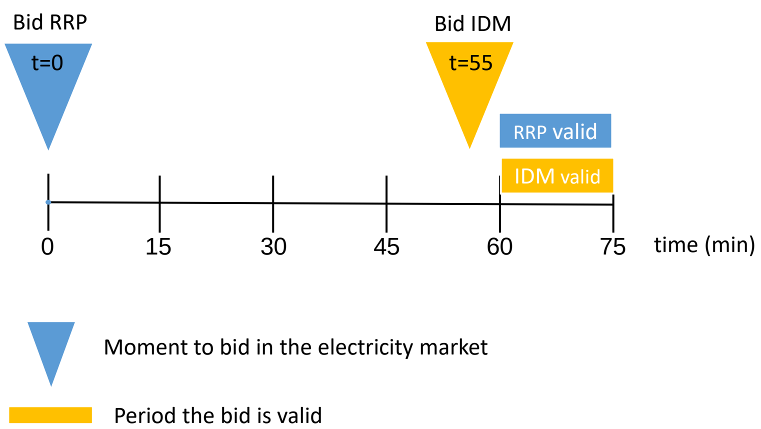

Figure 17: The bidding horizon of the different electricity markets in the Netherlands. Bidding for RRP should take place an hour in advance, and the bid is valid for 15 minutes or 1 PTU. Bidding for IDM should take place 5 minutes in advance, and the bid is valid for a period to be determined by the aggregator (in this example also 15 minutes).

Because there is a bidding horizon of an hour for RRP, and an aggregator cannot bid the same capacity multiple times in this bidding horizon. Previous bids have to be taken into consideration when making a bid. The RRP market should consider the previous bids that are valid for the four time periods in between the bid moment and until the current bid is valid. This also holds for the IDM, which has a small bidding horizon of only 5 minutes until dispatch. However, the IDM bid should take into account the RRP bids that hold for the coming periods, as these have already been made in the previous periods. The IDM bid should only consider RRP bids. The RRP bids to consider are the 5 previously made bids, that are valid for PTUs d, e, f, g, and h. At the moment of bidding for IDM, these RRP bids have already been made. An overview of the different PTUs to consider when making a bid is shown in Figure 18.

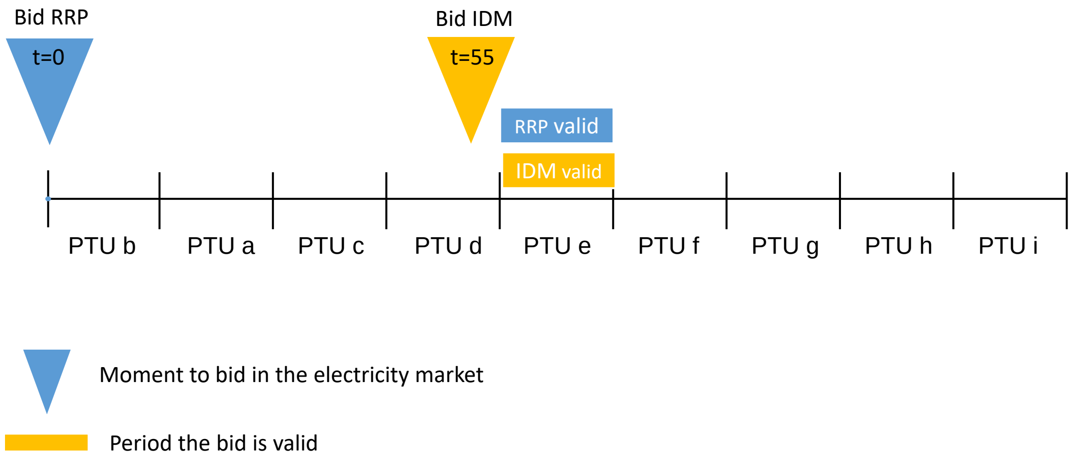

Figure 18: The impact of the bidding horizon on the possible bids of an aggregator. A bid for RRP should consider the bids that were previously made for RRP and that are valid for PTU a, b, c, and d. A bid for IDM should consider the bids that were previously made for RRP and that are valid for PTU d, e, f, g, and h.

Next, the algorithm maximizing profits in the RRP market is provided after which it is explained per equation why the equation is relevant and what its purpose is. Then, the algorithm maximizing profits in the IDM market is provided with explanation. And finally, the dispatching algorithm is formulated with explanation.

6.2.1 RRP Market

In Chapter 4 it was discussed that an aggregator could bid both RRP and IDM services. In this Section the problem formulation of the RRP market is presented. Bidding for this market should take place one hour in advance. Therefore, the profit maximization problem at time t=0 produces optimal bids for t=60, where the time steps are in minutes. This model is used in Chapter 7 to simulate the potential profits of an aggregator in the Netherlands incorporating several practical considerations.

$$\underset{E_i^{RRP\downarrow,bid},E_i^{RRP\uparrow,bid}}{\text{Minimize at t=0 for t=60, k=15 minutes}}$$

$$-\sum_{k=4}^{PredictionHorizon}\sum_{i\in V}^{n}\Bigg(\bigg(E_i^{RRP\downarrow,bid}(k)\cdot P^{RRP\downarrow,bid}(k)\cdot\delta^{RRP\downarrow}(k)+E_i^{RRP\uparrow,bid}(k)\cdot P^{RRP\uparrow,bid}(k)\cdot\delta^{RRP\uparrow}(k)$$
$$-\frac{C_i^{battery}}{\left(\frac{145.71}{B_i^{DOD}(k)}\right)^{\frac{1}{0.6844}}\cdot B_i^{DOD}(k)\cdot B_i^{cap}}-T_i^{charge}(k)\cdot C^{incite}-E_i^{REG}(k)\cdot C^{El,normal}\bigg)\Bigg) \quad (41)$$

Subject to:

$$SOC_i(k+1)=A\cdot SOC_i(k)+B\cdot E_i(k)+F\cdot D_i(k) \quad (42)$$

$$\text{If} \quad {}_i=1 \quad (43)$$

$$\sum_{i \in V}^{n} \left(E_i^{RRP\downarrow,bid} \cdot \frac{\alpha_i}{\eta_i \cdot \eta_{tr}} \right) \geq 4MW \tag{44}$$

$$P^{RRP\downarrow,bid}(k) < P^{El,normal} \tag{45}$$

$$E_i^{RRP\downarrow,bid}(k) \cdot \frac{\alpha_i}{\eta_i \cdot \eta_{tr}} + \sum_{K=1}^{4} \left(E_i^{RRP\downarrow,bid}(k-K) \right) \leq B_i^{cap} - SOC_i(k) \tag{46}$$

$$E_i^{RRP\downarrow,bid}(k) \cdot \frac{\alpha_i}{\eta_i \cdot \eta_{tr}} + \sum_{K=1}^{4} \left(E_i^{RRP\downarrow,bid}(k-K) \right) \geq B_i^{cap} - SOC_i^{req}(k+1) \tag{47}$$

$$\frac{E_i^{RRP\downarrow,bid}(k)}{15} \leq 0.95 \cdot B_i^{cp} \tag{48}$$

$$E_i^{RRP\downarrow,bid}(k) \geq 0 \tag{49}$$

$$\text{If} \quad \phi_i = 1 \tag{50}$$

$$\sum_{i \in V}^{n} \left(E_i^{RRP\uparrow,bid}(k) \cdot \frac{\alpha_i \cdot \eta_i}{\eta_{tr}} \right) \geq 4MW \tag{51}$$

$$\sum_{i \in V}^{n} \left(E_i^{RRP\uparrow,bid}(k) \cdot P^{RRP\uparrow,bid}(k) \right) > \sum_{i \in V}^{n} \left(C_i^{var}(k) \right) \tag{52}$$

$$E_i^{RRP\uparrow,bid}(k) \cdot \frac{\alpha_i \cdot \eta_i}{\eta_{tr}} - \sum_{K=1}^{4} \left(E_i^{RRP\uparrow,bid}(k-K) \right) \leq SOC_i(k) - SOC_i^{req}(k+1) \tag{53}$$

$$\frac{E_i^{RRP\uparrow,bid}(k)}{15} \leq 0.95 \cdot B_i^{cp} \tag{54}$$

$$E_i^{RRP\uparrow,bid}(k) \geq 0 \tag{55}$$

With:

$$A = 1, \quad B = \Delta k \cdot \eta_i, \quad C = 1, \quad F = -\Delta k \cdot \eta_d \tag{56}$$

$$E_i(k) = \begin{cases} E_i^{REG}(k), & \text{if} \quad SOC_i(k) \leq SOC_i^{req}(k+1) \vee \quad {}_i = 0 \quad \text{(57a)} \\ E_i^{RRP\downarrow,bid}(k) - E_i^{RRP\uparrow,bid}(k), & \text{if} \quad SOC_i(k) > SOC_i^{req}(k+1) \quad \text{(57b)} \end{cases}$$

$$E^{req}(t^{trip}) = B_i^{cp} \cdot \eta_i \cdot (t^{trip} - t) \tag{58}$$

$$E_i^{REG}(k) = B_i^{cp} \tag{59}$$

$$B_i^{DOD}(k) = \frac{E_i^{RRP\uparrow,bid}(k)}{B_i^{cap}} \tag{60}$$

$$C_i^{var}(k) = \frac{B_i^{cost}}{\left(\frac{145.71}{B_i^{DOD}(k)} \right)^{\frac{1}{0.6844}} \cdot B_i^{DOD}(k) \cdot B_i^{cap}} + E_i^{RRP\uparrow,bid} \cdot P^{El,normal} \tag{61}$$

$$\sum_{i \in V}^{n} \left(E_i^{RRP\downarrow,bid}(k) \right) = \sum_{i \in V}^{n} \left(E_i^{RRP\uparrow,bid}(k) \right) \qquad E_i^{RRP\uparrow,bid}, E_i^{RRP\downarrow,bid} \; is \; integer \tag{62}$$

$${}_i = \begin{cases} 1, & \text{if normal or flexible charging has been selected} \quad \text{(63a)} \\ 0, & \text{if priority charging has been selected} \quad \text{(63b)} \end{cases}$$

$$\phi_i = \begin{cases} 1, & \text{if V2G has been selected} \quad \text{(64a)} \\ 0, & \text{if SC has been selected} \quad \text{(64b)} \end{cases}$$

$$SOC_i^{req}(t) = \begin{cases} SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}), \text{if } SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}) \geq SOC_i^{GDR} & (65a) \\ SOC_i^{GDR}, \qquad \text{if } SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}) < SOC_i^{GDR} & (65b) \end{cases}$$

$$E^{req}(t^{trip}) = B_i^{cp} \cdot \eta_i \cdot (t^{trip} - t) \tag{66}$$

$$Profit^{RRP}(t) = \sum_{i \in V}^{n} \Big(E_i^{RRP\downarrow,bid}(t) \cdot P^{RRP\downarrow,bid}(t) \cdot \delta^{RRP\downarrow}(t) + E_i^{RRP\uparrow,bid}(t) \cdot P^{RRP\uparrow,bid}(t) \cdot \delta^{RRP\uparrow}(t)$$
$$- \frac{C_i^{battery}}{\left(\frac{145.71}{B_i^{DOD}(t)}\right)^{\frac{1}{0.6844}} \cdot B_i^{DOD}(t) \cdot B_i^{cap}} - T_i^{charge}(t) \cdot C^{incite} - E_i^{REG}(t) \cdot C^{El,normal}\Big) \tag{67}$$

$$Benefits = \sum_{t=1}^{T} \left(Profit^{RRP,t} - Profit^{baseline,t} \right) \tag{68}$$

Model Predictive Control

MPC is used in the optimization model as a controller because MPC allows for hard constraints on the inputs during all time intervals. In nearly every application there is a prevalence of natural arising hard constraints on the limits of the system. This requires a control method to handle those constraints. Among only a few suitable methods, MPC is one that is important for control engineers where the plants that are being controlled are sufficiently slow to permit its implementation [24]. In the case of bidding RRP, the bidding horizon is an hour, with 15 minutes intervals between each bid, making this model sufficiently slow for implementation.

As previously mentioned, MPC allows for hard constraints on the inputs, which is required in this model to fulfill the constraints in the optimization algorithm. The in the problem formulation of RRP are hard constraints on the inputs. These constraints can be modelled using MPC, whereas for example a Linear Quadratic Regulator would not allow for such constraints to be modelled.

Moreover, MPC is used to take into account future actions, this is achieved using a control sequence. For SC and V2G there is only a finite capacity to be bid for RRP, as the batteries are physically limited by their nature. If no future actions are considered, the first bid made will be the maximum capacity possible as this would maximize profits for that period. However, if the aggregator bids maximum capacity immediately, it has no capacity left to bid in subsequent hours, resulting in no profits in those periods. With MPC future actions are also considered, and therefore maximum capacity will not be bid immediately, but spread out over the prediction horizon resulting in more conservative and stable bids, which in turn could lead to more reliable income.

Here, an important notion about the use of MPC in the case of V2G bids should be made. In the optimization problem of bidding, it is assumed that the bid is accepted, resulting in a different SOC for the next step in the prediction horizon. This will lead to the more conservative and less volatile bids as discussed above. However, what is not considered in the optimization problem is the acceptance of the bid. This has to do with the time horizon of the bidding procedure. Bidding RRP has to take place an hour in advance of call-off, when the settlement prices are unknown. Therefore, it is unknown at the moment whether the bids are actually accepted resulting in a real change in the SOC. The MPC sequence considers the best case scenario, i.e. that all bids are accepted. This notion is important since the predicted behavior might not always be the same as the actual behavior in this case. It is not always the case that all bids are accepted. In establishing the prediction horizon in Section 7.2.1 the consequences of this imperfect knowledge is shown. In short, a longer prediction horizon with more conservative bids does not necessarily result in greater benefits as sometimes the greedy bids from a short prediction horizon are lucky when evaluating the call-off for the bid.

Centralized Controller

Another notion on the type of controller besides MPC is the use of a centralized controller. Despite the fact that the bids of RRP up or down are made for each EV specifically, there are also several requirements ((44),(51) and (62)) which hold for the complete problem. These constraints are meant to oblige to the market constraints, and cannot be achieved by one single EV. The complete problem formulation should be taken into account for these constraints. When the optimization problem becomes large, which is likely to happen considering thousands of EVs are required in order to generate enough capacity to make a valid bid in the RRP market, a distributed controller could save on computing time. A distributed controller could split the problem in multiple smaller subproblems, where the problem is simulated for e.g. only one EV. In Chapter 8 the idea of a distributed controller is elaborated upon further. For now, since only 6 EVs are simulated, a centralized controller suffices with respect to computation times.

Objective Function

Equation (41) is the objective function of the profit optimization algorithm. The variables to optimize are $E_i^{RRP\downarrow,bid}$ and $E_i^{RRP\uparrow,bid}$. The summation goes over time and the number of EVs. The time summation is used for MPC, as the model should be optimized for several time steps depending on the length of the prediction horizon. The optimal prediction horizon has to be determined at the beginning of the analysis, and is based on both the profits and computing time. As the prediction horizon increases, the computing time is likely to also increase. The summation over all EVs is used to calculate the total profits for an aggregator, and not per EV.

The first line of the objective function in (41), comprises the sources of income of the aggregator, including the income of RRP down capacity times the RRP down price and the RRP up capacity times the RRP up price. These variables can differ each time step depending on the constraints.

The second line of the objective function comprises the cost components. Three cost components are considered, the degradation costs, the first terms, the incitement costs, the second terms, and the regular energy costs for charging normally is the third term. The calculation for the degradation costs are adopted from Pelzer et al. (2014), and represent realistic varying degradation costs based on the RRP up bid and DOD. The RRP up bid therefore has a direct impact on the degradation costs, and should be considered in the objective function. The incitement costs are calculated based on the availability of the EV and the price EV owners would like to receive. This price is determined in the analysis of the survey. The availability of the EV implies that if the EV can be used for SC or V2G the EV owner should get a compensation, i.e. not for when the EV is actually used as otherwise the EV owners are not willing to participate in SC or V2G as found in the survey. The last term covers the normal charging costs for when the EV is not completely charged using RRP down. One cost component that is not included in the objective function are the depreciation costs of the investment in bi-directional V2G software and hardware which are required to make V2G physically possible. These costs have to be taken into account when calculating total profits for a year.

In the objective function the probability factors $\delta^{RRP\downarrow}(k)$ and $\delta^{RRP\uparrow}(k)$ from (29) are also adopted. These probability factors relate to the bid prices $P^{RRP\downarrow,bid(k)}$ and $E_i^{RRP\uparrow,bid(k)}$ respectively. The algorithm uses MPC, and in the MPC model it is assumed that the bids made are accepted. To compensate for the unpredictability of the actual call-off the probability factors $\delta^{RRP\downarrow}(k)$ and $\delta^{RRP\uparrow}(k)$ are introduced. These factors take a value larger or equal to 0 and smaller or equal to 1, resembling a probability of acceptance between 0% and 100%. The more likely it is that a bid gets accepted the higher the probability factor. In Figure 19 an illustrative example of the use of the probability factor is shown. At time period 1 a bid of €99 for $P^{RRP\downarrow,bid(1)}$ is highly likely to be accepted, resulting in a $\delta^{RRP\downarrow}(1)$ of 1. In the second period a lower $P^{RRP\downarrow,bid(2)}$ price of €79 is bid, which increases the potential benefits to be made if the bid is accepted (seethe bidladder in figure 12). The probability that the bid is accepted however, is lower since other parties could bid higher prices, resulting in a $\delta^{RRP\downarrow}(2)$ of 0.9 or 90%.

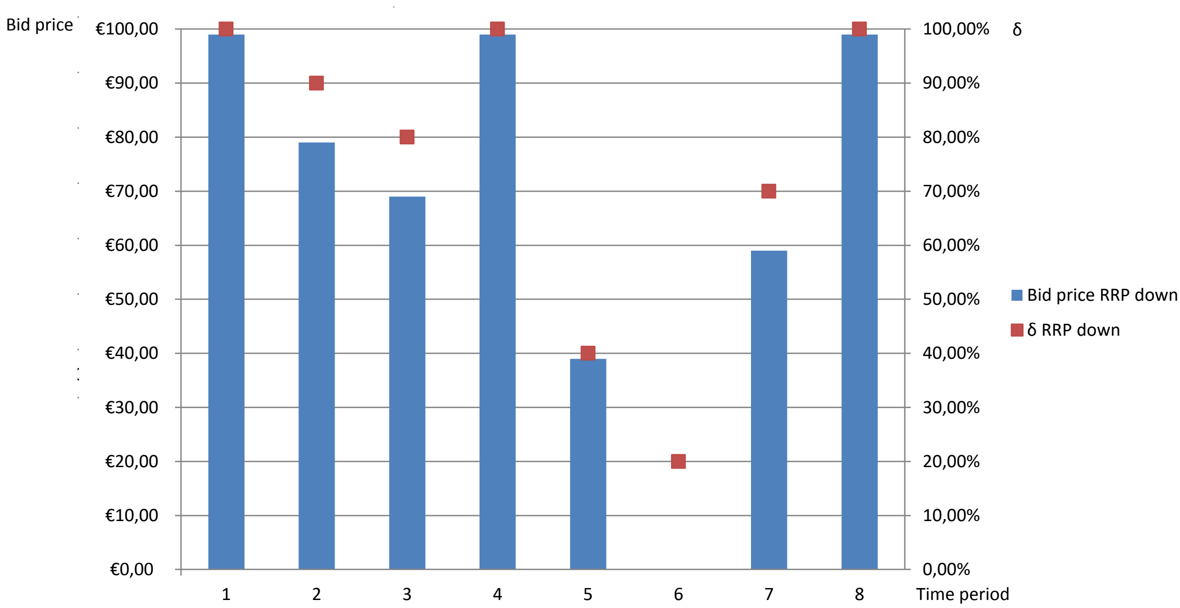

Figure 19: Illustrative probability factor δ for RRP down bid prices

Difference Equation

In equation (42) the SOC of the next period is calculated by adding the energy of RRP or regular charging or subtracting the driving energy from the current SOC. This is the difference equation of the model. In reality it cannot occur that a vehicle is both connected to the grid and driving, in the simulation this is prevented using a decision tree model as in Figure 29.

SC or V2G Constraints

In the next equation (43) it is evaluated whether the EV owner has indicated to be willing to participate in SC or V2G. If one is willing to participate in providing RRP down $\psi_i = 1$. In equation (50) it is evaluated whether the EV owners has indicated to be willing to participate in V2G, i.e. providing RRP up as well, if so $\phi_i = 1$ and then also constraints (51)-(55) hold. If an EV owner only wants to participate in SC, i.e. $\phi_i = 0$, these constraints do not hold and the objective function is only optimized over constraints (44)-(48), excluding the RRP up bid.

Market Constraints

There are several constraints arising from the requirements of the RRP market, including constraints (44), (51), (48), and (54). Equations (44) and (51) are required as TenneT does not accept bids which are below 4 MW. For this purpose, an aggregator has to couple thousands of EVs. Constraints (48) and (54) are required to satisfy the market constraint that a regulation speed of 7% of the total capacity per minute is required, as discussed in Section 4.2. To oblige by this constraint only 95% of the total capacity can be bid.

Price Constraints

There are price constraints for both RRP down and RRP up in equations (45) and (52) respectively. The constraint on the RRP down price in (45) is declared because the price for the bid should be lower than the normal electricity price of €0.10/kWh as otherwise providing RRP down would not be profitable. The price for RRP down, if positive, has to be paid to TenneT to buy the electricity, if this price is lower than the normal electricity price benefit with respect to the baseline scenario can be made, see Section 4.1.7 for the detailed description of the RRP market. The price for RRP up in 52 should be larger than the variable costs in equation 61, composed of the degradation costs and normal electricity price. The degradation costs are caused by providing RRP up and should therefore be included in the price to make a profit eventually. The degradation costs component is adopted from [29]. Moreover, as energy is sold, it might in the end have to be bought back from the grid. To compensate for these possible additional charging costs the bid price should take this possibility into account to be profitable in the end.

Battery Constraints

There are three constraints relating to the battery of the EV, (46), (47) and (53). Two constraints are required when bidding for RRP down. When bidding for RRP down the capacity bid plus the four previous bids should be larger smaller than the maximum battery capacity minus the current SOC as otherwise the physical limitations of the battery could be exceeded. The capacity bid for RRP down plus the four previous bids should however, also be larger than the required SOC of the period after providing RRP, as otherwise the EV might not be fully charged in time for the trip.

For RRP up the bid capacity minus the four previous bids should not be more than the difference in the current SOC and the required SOC of the next period. If a higher capacity is bid, there might not be enough battery capacity for an unplanned trip, the minimal GDR, or it is not able to charge in time for a planned trip.

The Dutch electricity market is designed such that bids have to be made one hour in advance, and hold for 15 minutes. Because an aggregator has limited capacity in the relatively small car batteries, the four bids before the current bid have to be taken into account as well when calculating left-over capacity. For example, if there is no consideration of the previous bids, an aggregator could potentially bid RRP down capacities equal to the connection power. If much RRP down is required, and all bids in the 5 consecutive periods are accepted, the bid capacity could exceed the maximum battery capacity. Because an aggregator in the Netherlands makes bids one hour in advance, it has to take into account the previous bids as well, so that the physical limitations are not violated which in reality would result in high penalties.

Energy Calculations

The energy calculations for the model are described in equations (57), (59), (60), (62), (62), (63), 64) and, (58). In (57) the energy provided to the difference equation is calculated. The energy provided could either be regular charged energy as in equation (59), or RRP provided energy. It depends on the required SOC which energy is provided. In (58) the required SOC is calculated, the required SOC determines how much SOC is required at each time step to ensure there is enough capacity for the car owner when they choose to drive. The required SOC idea and calculations are adopted from [17].

Equation 60 calculates the DOD which is required to calculate the degradation costs component. Whether to use the constraints for SC or V2G is determined by equations (63) and (64), these values are dependent on the preference of the EV owners.

The equality in (41) is actually a market constraint stating that the capacity of RRP down bid should be equal to the capacity of RRP up bid, and should both be integer. It is important to note that, due to the integer constraint in (62) the problem becomes non-convex. A non-convex problem might not result in an optimal solution if a solution is obtained at all. The non-convexity of the problem formulation is further discusses in Section 7.2.1.1.

Costs Calculations

In (61) the calculation for the variable costs are given, which consists of the degradation costs component and the regular charging costs. This is used to establish the price for RRP up. In equation (67) the profit of the RRP at time t is calculated. This profit is used to calculate the benefits with respect to the baseline scenario in equation (68).

6.2.2 IDM

In Chapter 4 it was discussed that an aggregator could bid both RRP and IDM service. In this Section the problem formulation of the IDM is presented. The model is comparable to the model for the RRP market in the previous Section. The differences are caused by the different bidding horizon, and the implications be explained after the formulation is presented. The profit optimization algorithm for IDM should be used 5 minutes in advance of the actual provision as required by the market. Simulation for IDM should take place after the RRP simulations, in order to be able to take into account the last RRP bids.

Minimize at t=55 for t=60, k=chosen by aggregator

$$E_i^{IDM\downarrow,bid}, E_i^{IDM\uparrow,bid}, P^{IDM\downarrow,bid}, P^{IDM\uparrow,bid}$$

$$-\sum_{k=1}^{PredictionHorizon} \sum_{i\in V}^{n} \Bigg(\Big(E_i^{IDM\downarrow,bid}(k)\cdot P^{IDM\downarrow,bid}(k)\cdot \delta^{IDM\downarrow}(k) + E_i^{IDM\uparrow,bid}(k)\cdot P^{IDM\uparrow,bid}(k)\cdot \delta^{IDM\uparrow}(k)$$

$$\frac{C_i^{battery}}{\left(\frac{145.71}{B_i^{DOD}(k)}\right)^{\frac{1}{0.6844}} \cdot B_i^{DOD}(k)\cdot B_i^{cap}} - T_i^{charge}(k)\cdot C^{incite} - E_i^{REG}(k)\cdot C^{El,normal}\Big)\Bigg) \tag{69}$$

Subject to:

$$SOC_i(k+1) = A\cdot SOC_i(k) + B\cdot E_i(k) + F\cdot D_i(k) \tag{70}$$

$$\text{If} \quad {}_i = 1 \tag{71}$$

$$\sum_{i\in V}^{n} \big(E_i^{IDM\downarrow,bid}\cdot \frac{\alpha_i(k)}{\eta_i\cdot\eta_{tr}}\big)\cdot 10^{-1} \geq 0.1MW \tag{72}$$

$$P^{IDM\downarrow,bid}(k) < P^{El,normal} \tag{73}$$

$$E_i^{IDM\downarrow,bid}(k)\cdot\frac{\alpha_i(k)}{\eta_i\cdot\eta_{tr}} \leq B_i^{cap} - SOC_i(k) - \sum_{K=0}^{4}\big(E_i^{RRP\downarrow,bid}(k+K)\big) \tag{74}$$

$$E_i^{IDM\downarrow,bid}(k)\cdot\frac{\alpha_i(k)}{\eta_i\cdot\eta_{tr}} \geq B_i^{cap} - SOC_i^{req}(k+1) - \sum_{K=0}^{4}\big(E_i^{RRP\downarrow,bid}(k+K)\big) \tag{75}$$

$$\frac{E_i^{IDM\downarrow,bid}(k)}{15} \leq B_i^{cp} \tag{76}$$

$$E_i^{IDM\downarrow,bid}(k) \geq 0 \tag{77}$$

$$\text{If} \quad \phi_i = 1 \tag{78}$$

$$\sum_{i\in V}^{n} \big(E_i^{IDM\uparrow,bid}(k)\cdot \frac{\alpha_i(k)\cdot\eta_i}{\eta_{tr}}\big) * 10^{-1} \geq 0.1MW \tag{79}$$

$$\sum_{i\in V}^{n} \big(E_i^{IDM\uparrow,bid}(k)\cdot P^{IDM\uparrow,bid}(k)\big) > \sum_{i\in V}^{n}\big(C_i^{var}(k)\big) \tag{80}$$

$$E_i^{IDM\uparrow,bid}(k)\cdot\frac{\alpha_i(k)\cdot\eta_i}{\eta_{tr}} \leq SOC_i(k) - SOC_i^{req}(k+1) + \sum_{K=0}^{4}\big(E_i^{RRP\uparrow,bid}(k+K)\big) \tag{81}$$

$$\frac{E_i^{IDM\uparrow,bid}(k)}{15} \leq B_i^{cp} \tag{82}$$

$$E_i^{IDM\uparrow,bid}(k) \geq 0 \tag{83}$$

With:

$$A = 1,\ \ B = \Delta k\cdot\eta_i,\ \ C = 1,\ \ F = -\Delta k\cdot\eta_d \tag{84}$$

$$E_i(k) = \begin{cases} E_i^{REG}(k), & \text{if} \quad SOC_i(k) \leq SOC_i^{req}(k+1) \vee \quad {}_i = 0 \quad (85a) \\ E_i^{IDM\downarrow,bid}(k) - E_i^{IDM\uparrow,bid}(k), & \text{if} \quad SOC_i(k) > SOC_i^{req}(k+1) \quad (85b) \end{cases}$$

$$E_i^{REG}(k) = B_i^{cp} \tag{86}$$

$$B_i^{DOD}(k) = \frac{E_i^{IDM\uparrow,bid}(k)}{B_i^{cap}} \tag{87}$$

$$C_i^{var}(k) = \frac{B_i^{cost}}{\left(\frac{145.71}{B_i^{DOD}(k)}\right)^{\frac{1}{0.6844}} \cdot B_i^{DOD}(k) \cdot B_i^{cap}} + E_i^{IDM\uparrow,bid} \cdot P^{El,normal} \tag{88}$$

$$\psi_i = \begin{cases} 1, & \text{if normal or flexible charging has been selected} \quad (89a) \\ 0, & \text{if priority charging has been selected} \quad (89b) \end{cases}$$

$$\phi_i = \begin{cases} 1, & \text{if V2G has been selected} \quad (90a) \\ 0, & \text{if SC has been selected} \quad (90b) \end{cases}$$

$$SOC_i^{req}(t) = \begin{cases} SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}), & \text{if } SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}) \geq SOC_i^{GDR} \quad (91a) \\ SOC_i^{GDR}, & \text{if } SOC_i^{trip}(t^{trip}) - E^{req}(t^{trip}) < SOC_i^{GDR} \quad (91b) \end{cases}$$

$$E^{req}(t^{trip}) = B_i^{cp} \cdot \eta_i \cdot (t^{trip} - t) \tag{92}$$

The problem formulation of the intraday market is similar to the RRP market. There are two major differences between the two problem formulations, besides the change in variable from RRP to IDM. The major differences are due to the different market constraints, and additional battery constraints.

Market Constraints

The intraday market differs from the RRP market in capacity requirements and equality requirements. For the IDM market a bid is valid from 0.1 MW and upwards instead of the 4 MW in the RRP market. This change in requirement is reflected in constraint (79). Moreover, the IDM does not require that bids for $IDM^{\downarrow}$ is equal to $IDM^{\uparrow}$. The bids are also valid for a period determined by the aggregator. Where the RRP market requires the bid to be valid for 15 minutes, the IDM bid can be valid for the duration of a period chosen by the aggregator. Moreover, the IDM does not require a regulation speed of 7% of the total capacity. The constraint that merely 95% of total capacity can be bid is therefore redundant.

Battery Constraints

The battery constraints in equations (74), (75) and (81) also change with respect to the RRP model. The changes in these constraints are due to the bidding horizon in Figure 18. As the bids for RRP have to be made an hour in advance, and the bids for IDM only 5 minutes in advance, the bid for IDM has to take previous RRP bids which hold for the upcoming periods into account. There are five periods of RRP the IDM bid should consider. A bid for IDM cannot, likewise for subsequent RRP bids, overlap bidding capacity as then the possibility exists that the aggregator cannot provide the bid capacity. As the aggregator can bid for a chosen period, the IDM bid does not have to take into account previous IDM bids. The IDM bids should be constructed such that the bids of IDM and RRP would not overlap.

6.2.3 Dispatching

In the dispatching phase of the bidding horizon it is evaluated whether or not a bid has been accepted and thus the bid energy has to be provided. The bid is accepted if it is either higher or lower than the settlement price for charging and discharging respectively. If the bid is not accepted and no regular charging is required then there is no energy provided to the vehicle.

At t=60

$$SOC_i(t+15) = A \cdot SOC_i(t) + B \cdot E_i(t) + F \cdot D_i(t) \tag{93}$$

$$
E_i(t) = \begin{cases} E_i^{REG}(t), & \text{if} \quad SOC_i(t) \leq SOC_i^{req}(t+15) \vee \quad {}_i = 0 & \text{(94a)} \\ E_i^{RRP\downarrow,bid}(t), & \text{if} \quad P^{RRP,bid\downarrow}(t) \geq P^{RRP,settle\downarrow}(t) & \text{(94b)} \\ -E_i^{RRP\uparrow,bid}(t), & \text{if} \quad P^{RRP,bid\uparrow}(t) \leq P^{RRP,settle\uparrow}(t) & \text{(94c)} \\ E_i^{RRP\downarrow,bid}(t), & \text{if} \quad P^{RRP,bid\downarrow}(t) \geq P^{IDM,settle\downarrow}(t) & \text{(94d)} \\ -E_i^{IDM\uparrow,bid}(t), & \text{if} \quad P^{IDM,bid\uparrow}(t) \leq P^{IDM,settle\uparrow}(t) & \text{(94e)} \\ 0, & \text{else} & \text{(94f)} \end{cases}
$$

6.3 Summary

The profit optimization models formulated in this Chapter are used in the next Chapters to simulate and evaluate the benefits of an aggregator. This Chapter provided an answer to SQ 7:

- SQ 7: *How can the practical considerations be incorporated in a profit maximization algorithm?*

To answer this SQ, in Section 6.1 existing models in literature were examined. The conceptual framework of Sortomme et al. (2012) was used as the foundation for the profit optimization algorithm of this work. Furthermore, in this Section several other important constraints, such as the price-responsive constraint from Pelzer et al. (2014), and the required SOC from Hoogvliet et al. (2017), were described.

In Section 6.2 the problem formulations of this thesis were provided. Three models have been formulated, one for the RRP market, one for the IDM, and one for dispatching. The first two algorithms use MPC, in order to take future bids into account. As the bidding procedures differ per market, the profit optimization models do not run simultaneously. In Figure 17 the bidding horizon is visualized. The bidding horizon is important for the aggregator, as the aggregator should oblige by the rules of the electricity markets. Bids are not accepted if they are late.

7 Results

In this Chapter the results of the analysis are provided. This Chapter consists of two main segments, the results of the survey, and the results of the simulation. The results of the survey are presented first, as the outcome of the survey is used in the simulation. In this Chapter, SQ 6 and SQ 8 will be discussed.

- In Section 7.1 SQ 6 is discussed. In this Section the survey designed in Section 5.3.1 is examined using the hypotheses formulated. The hypotheses are tested using linear regressions and correlations. The main objective of the survey is to obtain an insight in the height of the required incitement compensation by EV owners
- In Section 7.2 the potential profits of an aggregator in the Netherlands are estimated. The estimation is made using a simulation in Matlab using the CVX software. The RRP profit optimization model formulated in Chapter 6 is used for the simulation. The inputs of the various parameters are described in Section 7.2.1.3, and follow from the literature study in Chapters 4, 5 and the results of the survey described in Section 7.1
- In Section 7.3 the summary of the results are presented including a short description of the answers to SQ 6 and SQ 8

7.1 Survey

In Section 5.3.1 the design and relevance of the survey have been discussed. In 2018 an online questionnaire was conducted. Participants were recruited through email and/or social media. In total, 111 Dutch individuals volunteered to participate in the survey, of which 73 fully completed. From this respondent group 83 completed the survey until the height of incitement compensation question, and are useful to explore interrelationships and correlations between the several variables. SPSS was used to test the hypothesis and to examine other correlations.

First, the means of all questions will be discussed in the same order as for the survey. Using a Likert scale the means of the respondent group well represents how individual EV owners might consider the issue. The means are reported in bar plots, containing the means, upper and lower bound with on y-axis the Likert scale from 1-7. Second, bivariate correlations are evaluated for which we report the correlation value in a Table, and discuss the significant values. A correlation is significant when the significance two tailed value is below 0.05. Lastly, hypotheses 2, 4, and 5 are evaluated using a linear regression method for which we report the regression coefficients, the 95% confidence interval of the means, and the impact value B.

In the group of 83 respondents, 61 or 73% of the respondents were male and 22 or 27% female, with an average age of 31, and a Standard Deviation (SD) of the mean of 13,62. In Figure 20 the Means (M) of the values underlying a person's beliefs and behavior are provided, including the Upper Bound (UB) and Lower Bound (LB). The values underlying a person's beliefs and behavior are constructed from 3 to 5 statements. In question 3 of the survey these statements were presented to the participants. The respondent group scored high on hedonic (M=6,11) and altruistic (M=5,26) values, indicating that the respondents value pleasure and comfort, and that they have a high concern for others respectively.

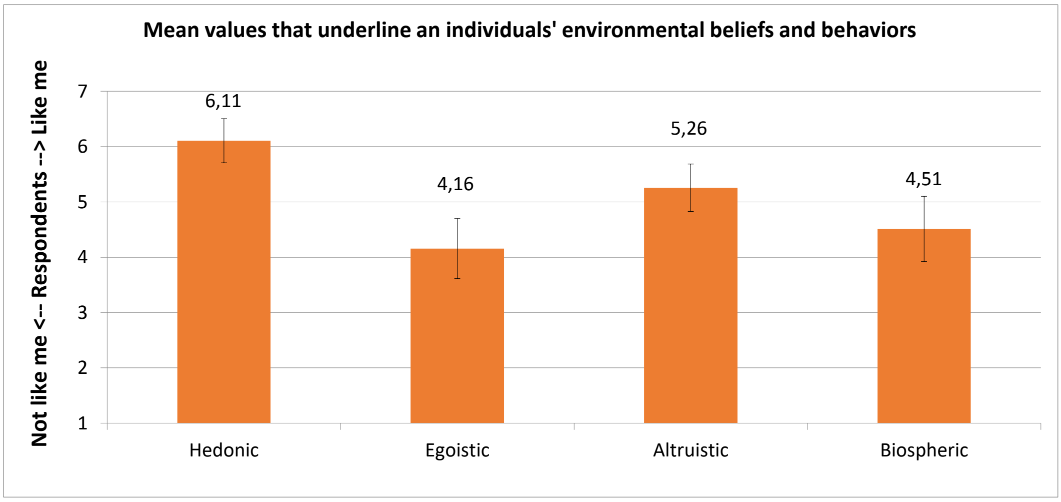

Figure 20: Means of values underlying a person's beliefs and behavior

7.1.1 Means

When describing the means, the mean values are plotted in a bar graph, where the y-axis displays the Likert scale from 1 to 7. In the Likert scale1 indicates that the respondents totally disagree with the statement, and 7 indicates that the respondents totally agree with the statement, unless stated otherwise. The M value is presented in the graph above the bars.

The means of the questions 4 and 5, relating to the descriptions of the different type of vehicles, are visualized in Figure 21. There is a clear difference in the respondents group about the perceived attributes of the two different types of vehicles. The price of an EV is seen as expensive (M=5,89), whereas the price for a gasoline vehicle is normal (M=3,71). Also the environmental performance shows a large difference between the two means. The EV with a value of M=5,26 is significantly larger M=2,57 for the gasoline vehicle. Another large discrepancy is seen in the potential range of the vehicle, the EV has a perceived low range (M=2,66) compared to the range of a gasoline vehicle (M=5,29). The social status also shows a relatively large difference. The EV has a higher perceived social status (M=4,37) than the gasoline vehicle (M=3,43). This could indicate that people who score high on egoistic values are more likely to own an EV.

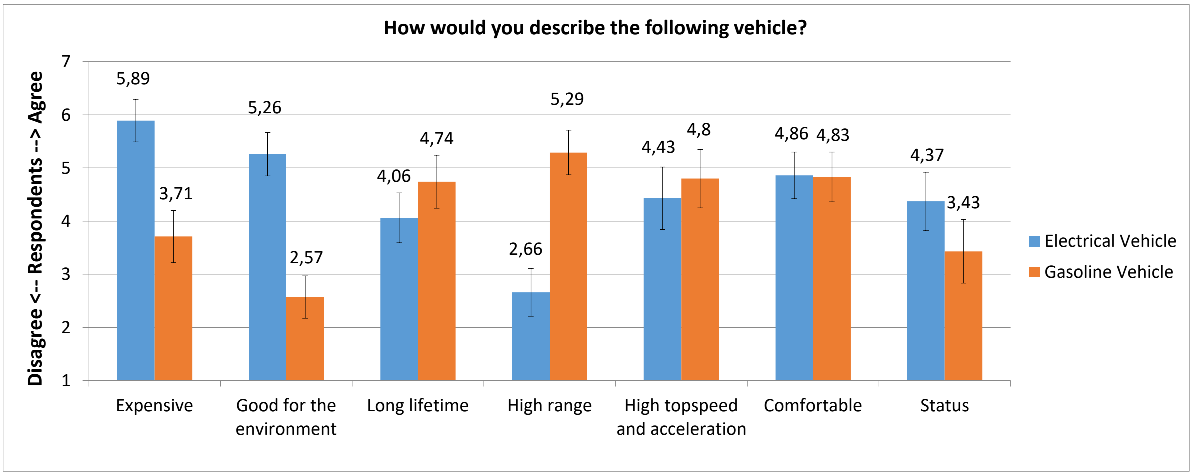

Figure 21: Means of the description of the two types of vehicles

What respondents consider when buying a vehicle shows what they find most important when buying a new vehicle. In Figure 22 the means of question 8 are shown. Three aspects of the seven key attributes are considered most when buying a new vehicle: Price (M=5,69), lifetime (M=5,31), and comfort (M=6,06). In the group of 83 respondents, only 2 are in possession of an EV. A reason for this could be that the respondents group perceives an EV as expensive, which is one of the aspects considered most. Moreover, the respondents group do not greatly consider environmental performance (M=3,91), which is one the key attributes of an EV.

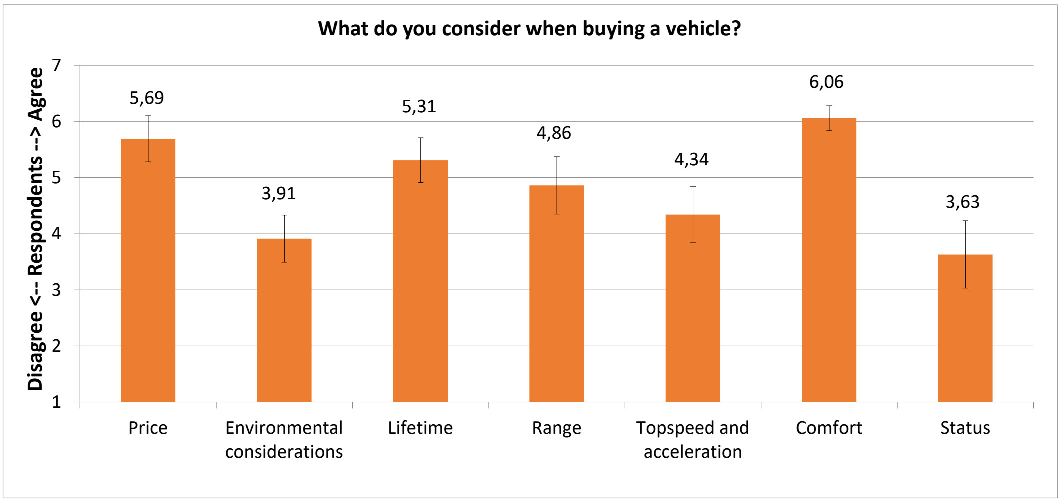

Figure 22: Means of the purchasing considerations

The means of questions 14 and 16 are presented in Figure 23. This question is used to test hypotheses 3a and 3b:

H3a: *EV owners wish incitement compensation based on the time they enable V2G or SC.*
H3b: *EV owners wish degradation compensation based on the time their EV is used for V2G.*

The degradation compensation is expected when the EV is actually used (M=5,46) for providing V2G services. This confirms hypotheses 3b. The basis of the incitement compensation however, is more interesting. From an aggregator point of view, it would be beneficial to only pay the EV owner when the battery is actually used. The means of being payed on availability (M=5,09) and on actual usage (M=5,09) are exactly the same. Hypothesis 3a can therefore not be confirmed. As there is no clear difference between the means of availability basis and usage basis, the incitement compensation in the simulation in Section 7.2 will be based on the hours the EV owner enables SC or V2G, i.e. on the hours available. Providing the incitement compensation based on availability will likely result in a larger group of participating EV owners since the compensation is more reliable and could be slightly higher. The reliability of the compensation is higher for availability based than for usage based, as for availability the EV owner will always be compensated when plugged in for SC or V2G, whereas with usage it depends on whether there actual SC or V2G has occurred.

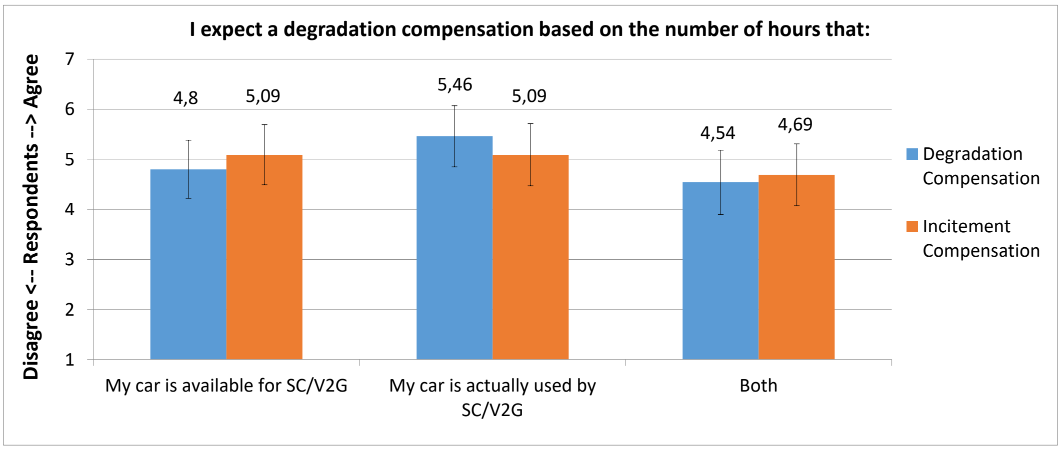

Figure 23: Means of the basis of the degradation and incitement compensation

One of the key insights of this survey is to evaluate the willingness to participate in SC or V2G. The willingness to participate in SC or V2G has been tested in questions 10, 11 and 15. The results of these three questions are shown in Figure 24. The willingness to participate in SC (M=5,09) and V2G (M=5,03) before the premise of an incitement compensation was explained, was slightly higher for SC. Reason for this could be that SC is less inconvenient for EV owners than V2G. When the premise of an incitement compensation was explained, the willingness to participate in SC/V2G marginally increased (M=5,14). Despite the marginal increase, it is still expected that an incitement compensation is required to obtain a large group of participating EV owners. Without the support of EV owners, V2G and SC are not possible.

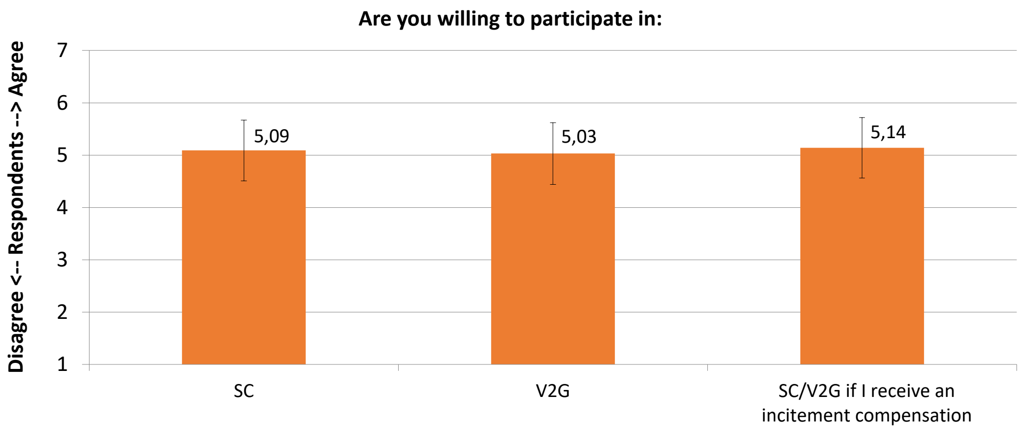

Figure 24: Means of the willingness to participate

The main objective of the survey was to get an insight in the height of incitement compensation required to obtain a large and reliable group of EV owners willing to participate. The mean incitement compensations are M=€338,31 for V2G-flex-as-you-go, M=€393,77 for V2G-contractual, and M=€265,09 for SC. These values indicate, in accordance with the expectation in [28], that V2G-contractual is less desirable for EV owners than V2G-flex-as-you-go. Concluding from the means, it seems that EV owners are more willing to participate in V2G-flex-as-you-go than in V2G-contractual.

Of the complete sample group, 17 respondents indicated that they would require an incitement compensation of €500 to be willing to participate in V2G or SC. This was the maximum value respondents were able to indicate, and this number was chosen to be infeasible. Since this was the maximum value the respondents could indicate, it is likely that this height of incitement compensation is not enough to incite those EV owners. They merely indicated €500 for a lack of a higher compensation. It could even be that these respondents are simply not willing to participate in V2G or SC at any costs.

For these reasons, the responses indicating €500 as desirable incitement compensation were ignored for the calculation of the actual height of incitement compensation. The means of the incitement compensation for the sample group without the respondents who indicated to require the maximum possible incitement compensation are given in Figure 25. The incitement compensation without those indicating €500 is about €65 lower in the categories V2G-flex-as-you-go (M=€257,55) and SC (M=202,45) but only €30 lower for V2G-contractual (M=360,50), indicating that V2G-contractual would require a substantial higher incitement compensations than the other forms of V2G. It is concluded that V2G-contractual is not desirable for EV owners and aggregators.

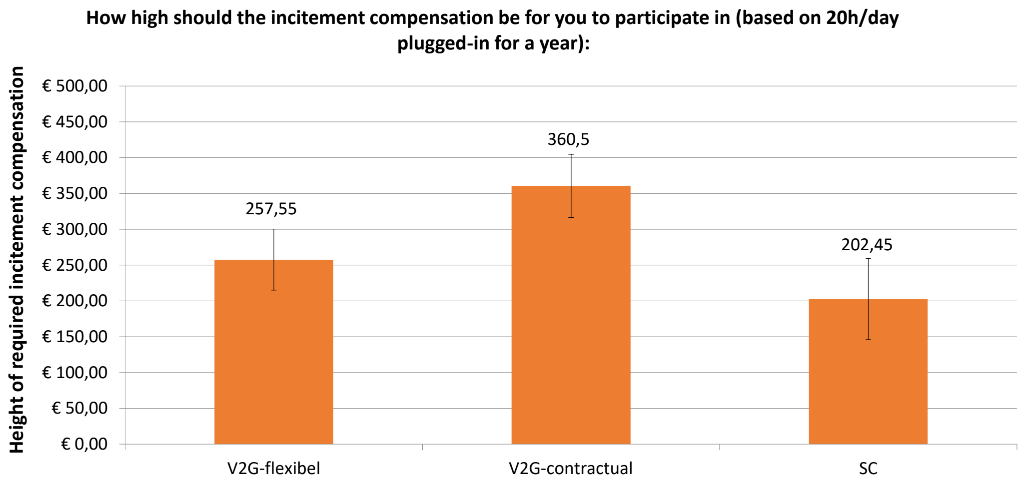

Figure 25: Means of the height of incitement compensation for sample group without respondents indicating maximum compensation

The means of question are shown in Figure 26. EV owners mostly require the incitement compensation for the perceived lower flexibility (M=5,6) and longer charging times (M=5,34), and not necessarily for additional income (M=3,29). This is in accordance with findings from the literature study in Section 5.3, where it was found that the driving range anxiety and lower flexibility were two of the main limitations to the implementation of V2G.

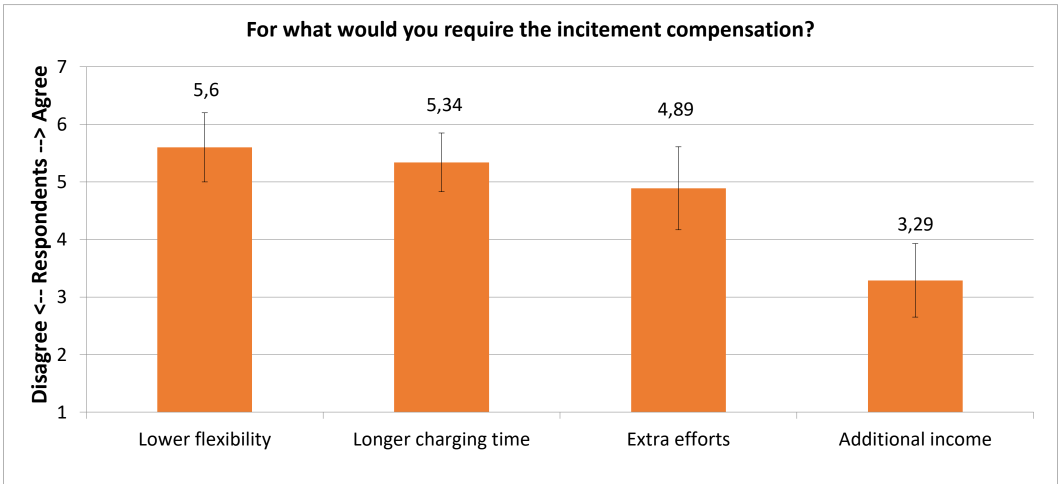

Figure 26: Means of the necessity of the incitement compensation

7.1.2 Relations

In this Section the linear regression relations and correlations between the variables are examined. First, it is checked whether a correlation is present. If there is a correlation between variables, it is examined whether a regression analysis indicated a relationship between the variables.

7.1.2.1 Bivariate Correlation

In this part of the analysis of the survey, correlations between several variables are examined. First, an example using the correlation output of SPSS is provided, after which the only the important values are reported. The remainder of the figures of the bivariate correlations can be consulted in Appendix B.

Hypothesis 1 and 3

To test hypothesis 1a (H1a), first bivariate correlations are examined. In Figure 27 the correlation output of SPSS is provided to test hypothesis 1a. In this test the correlation between the willingness to participate in V2G or SC and the requirement of an incitement compensation is evaluated. If an incitement compensation is required for EV owners to be willing to participate in V2G or SC then there should be a significant correlation between the two variables. One should look for the significance 2-tailed (Sig) value in the Figure.

Both the willingness to participate in V2G (Sig=0,000) and SC (Sig=0,000) are strongly related to the willingness to participate in V2G or SC if an incitement compensation is received. The willingness to participate in V2G does not correlate with the basis for the incitement compensation, i.e. an incitement compensation calculated on the number of hours used or available.

Moreover, from this test found additional support for H3a. The willingness to participate in V2G or SC if an incitement compensation is received correlates to premise that the incitement compensation is based on the available hours of the EV (Sig=0,000). Moreover, the willingness to participate in SC, also shows a strong correlating with an incitement compensation based on the hours of availability (Sig=0,007).

Correlations

		Willingness to participate in V2G -Q10	Willingness to participate in SC - Q11	Willingness to participate in V2G or SC if an incitement compensation is received - Q15	I expect a degradation compensation for V2G - Q13	I expect a degradation compensation for the availability - Q14a	I expect a degradation compensation for the usage - Q14b	I expect a degradation compensation for both - Q14c
Willingness to participate in V2G -Q10	Pearson Correlation	1	,754**	,440**	,244*	0,063	0,208	0,135
	Sig. (2-tailed)		0,000	0,000	0,027	0,576	0,063	0,229
	N	83	83	82	82	81	81	81
Willingness to participate in SC - Q11	Pearson Correlation	,754**	1	,434**	,353**	0,136	,295**	0,133
	Sig. (2-tailed)	0,000		0,000	0,001	0,225	0,007	0,236
	N	83	83	82	82	81	81	81
Willingness to participate in V2G or SC if an incitement compensation is received - Q15	Pearson Correlation	,440**	,434**	1	,465**	,296**	,368**	,222*
	Sig. (2-tailed)	0,000	0,000		0,000	0,007	0,001	0,046
	N	82	82	82	82	81	81	81
I expect a degradation compensation for V2G - Q13	Pearson Correlation	,244*	,353**	,465**	1	,306**	,473**	,263*
	Sig. (2-tailed)	0,027	0,001	0,000		0,006	0,000	0,018
	N	82	82	82	82	81	81	81
I expect a degradation compensation for the availability -	Pearson Correlation	0,063	0,136	,296**	,306**	1	-0,039	,482**
	Sig. (2-tailed)	0,576	0,225	0,007	0,006		0,728	0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for the usage - Q14b	Pearson Correlation	0,208	,295**	,368**	,473**	-0,039	1	,590**
	Sig. (2-tailed)	0,063	0,007	0,001	0,000	0,728		0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for both - Q14c	Pearson Correlation	0,135	0,133	,222*	,263*	,482**	,590**	1
	Sig. (2-tailed)	0,229	0,236	0,046	0,018	0,000	0,000	
	N	81	81	81	81	81	81	81

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 27: SPSS output bivariate correlation between willingness to participate in V2G or SC and incitement compensation

To test H1b, the output Figure in 59 is used. This hypothesis is focused on the question whether EV owners are willing to participate in V2G if no degradation compensation is given. As expected, a moderate correlation between the willingness to participate in V2G and the expectation of a degradation compensation for V2G is found (Sig=0,027).

From the values in the same Figure, likewise H3a, H3b can be tested as well. The willingness to participate in V2G (question 10) does not have a correlation with the requirement of a degradation compensation for the usage (Sig=0,063). In addition, the willingness to participate in V2G does not correlate with the degradation compensation based on availability (Sig=0,0575) or both (Sig=0,229) either. In the literature though, this relation has been well accepted [35, 17, 29]. The Sig=0,063 value for correlation between the willingness to participate in V2G and the requirement of a degradation compensation for the usage is only marginally larger than a significant correlation. Therefore, a degradation compensation based on the usage of the EV is used in the simulation.

Hypothesis 2

For hypotheses 2, the egoistic values, altruistic values and biospheric values are tested for correlation with the willingness to participate in V2G or SC. The SPSS output of this test is visualized in Figure 61. Multiple correlations are identified. A person's hedonic value is positively correlated to the willingness to participate in V2G/SC if an incitement compensation is received (Sig=0,010). A person's egoistic value is positively correlated to the willingness to participate in SC (Sig=0,013). The altruistic values and believes are correlated to the willingness to participate in both V2G (Sig=0,039) and SC (Sig=0,012). The final correlation identified is between a person's biospheric values and the willingness to participate in SC (Sig=0,012). All these relations are positive correlation. H2a and H2b thus should be refined.

Hypothesis 4

Hypotheses 4 are also evaluated using a test to identify possible correlations between the variables in the hypotheses. Figure 62 shows the output of test for correlation between the heights of incitement compensations and the reasons for which the incitement compensations are required (lower flexibility, longer charging time, extra efforts, and additional income). Two significant correlations are present: the height of the incitement compensation for V2G-flex-as-you-go and SC correlates to both longer charging times (Sig=0,001) and (Sig=0,004) respectively as in H4b, and to additional efforts (Sig=0,000) and (Sig=0,001) respectively as in H4c. Surprisingly, no significant correlation was found for the lower flexibility and height of incitement compensations.

Hypothesis 5

For hypotheses 5, the egoistic values, altruistic values and biospheric values are tested for correlation with the height of incitement compensation required for V2G-flex-as-you-go, V2G-contractual and SC. The SPSS output of this test is visualized in Figure 63. This test shows a significant correlation between the hedonic values of an EV owner and the height of incitement compensation for V2G-flex-as-you-go (Sig=0,009) and SC (Sig=0,045) as in H5a. No significant correlations were found between: The egoistic values and the height of incitement compensation for V2G-flexible (Sig=0,302) or SC (Sig=0,167) as in H5b; the altruistic values and the height of incitement compensation for V2G-flexible (Sig=0,344) or SC (Sig=0,750) as in H5c; and the biospheric values and the height of incitement compensation for V2G-flexible (Sig=0,346) or SC (Sig=0,842) as in H5d.

Other

Another interesting correlation which was discovered, is the correlation (Sig=0,000) between the willingness to participate in V2G or SC and the willingness to indicate charging type. The significance values can be found in Figure 60. This is interesting as the more willing the EV owner is to participate, the more willing the EV owner is to also participate in other services to support better usage of V2G and SC, such as indicating charging type.

7.1.2.2 Linear Regression

Previously, the correlations have been examined. In this part these correlation are tested for a possible linear regression. A linear regression indicates a stronger relationship than a correlation. The linear regression relation also uses the significance two-tailed value. If this value is lower than 0.05, the linear regression analyses indicates that there is a relation between the two variables.

If the linear regression analysis indicates a relation, the B value expresses the impact of this relation is. An increase of 1 on scale x results in an increase of B on scale y, if all other factors are held constant, and where B is the B value in the SPSS output. Only hypotheses 2, 4 and 5 were tested with the linear regression method.

Hypothesis 2

First, hypotheses 2 are tested using the linear regression analysis. The analysis of hypothesis 2 uses the EV owner's values and believes, i.e. the hedonic, egoistic, altruistic and biospheric values, and the willingness to participate in V2G and SC. The SPSS output of one of three the tests is used as an example for the interpretation of the linear regression analysis, and is shown in Figure 28. For the linear regression analysis a dependent variable should be chosen, in this case the willingness to participate in V2G or SC. The willingness to participate is evaluated in three questions, therefore, three tests with three different dependent variables are performed.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients			Correlations		
		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part
1	(Constant)	0,840	1,634		0,514	0,609			
	Hed	0,544	0,247	0,264	2,205	0,030	0,283	0,244	0,240
	Ego	-0,017	0,178	-0,011	-0,096	0,924	0,086	-0,011	-0,010
	Alt	0,181	0,227	0,095	0,800	0,426	0,157	0,091	0,087
	Bio	0,010	0,165	0,007	0,060	0,952	0,074	0,007	0,007

a. Dependent Variable: Willingness to participate in V2G or SC if an incitement compensation is received

Figure 28: SPSS output linear regression method with the dependent variable Q15 - Willingness to participate in V2G or SC when an incitement compensation is received versus the variables hedonic, egoistic, altruistic and biospheric values

The linear regression analysis indicates a moderate positive relationship between the hedonic value and the willingness to participate in SC or V2G and SC when an incitement compensation is received (Sig=0,030 and B=0,544). The B value implies that when an individual scores 1 point higher on the Likert scale for hedonic values, he or she is 0,544 more in agreement with the statement of willingness to participate in V2G or SC when an incitement compensation is received, provided that the other factors are held constant. Contradictory to H2a, the willingness to participate in V2G or SC increases instead of decreases as hypothesized for persons who score high on hedonic values. H2a is accepted, however instead of decreasing willingness, the willingness increases when a person scores high on hedonic values.

Hypothesis 4

Second, hypotheses 4 are tested using the linear regression analysis. This analysis also uses three tests. In these tests the dependent variables are the height of incitement compensations for V2G-flex-as-you-go, V2G-contractual, and SC. The variables used to test the linear regression are lower flexibility, longer charging time, extra efforts, and additional income. The SPSS outputs can be found in Appendix B in figures 67, 68, and 69.

The linear regression analysis indicates a strong positive relationship between extra efforts and the height of the incitement compensation as in H4c for: V2G-flex-as-you-go (Sig=0,000 and B=34,971), V2G-contractual (Sig=0,002 and B=24,228), and SC (Sig=0,029 and B=22,733).

A regressed relationship is also found between longer charging time and the height of the incitement compensation as in H4b for: V2G-flex-as-you-go (Sig=0,045 and B=17,566), V2G-contractual (Sig=0,004 and B=24,865). No relationship was found between longer charging time and SC (Sig=0,056).

The strongest regressed relationship is between extra efforts and the height of incitement compensation. H4b also found support from the linear regression analysis. Therefore, H4b and H4c are accepted.

Hypothesis 5

Lastly, hypotheses 5 are evaluated using the linear regression model. The dependent variables again are the height of incitement compensations for V2G-flex-as-you-go, V2G-contractual, and SC. The other variables of this hypothesis are the hedonic, egoistic, altruistic, and biospheric values. The corresponding Figures in Appendix B are Figures 70, 71, and 72. The linear regression analysis for hypotheses 5 showed support for H5a and H5b.

The linear regression analysis indicates a strong positive relationship between hedonic values and the height of the incitement compensation for: V2G-flex-as-you-go (Sig=0,005 and B=62,244), V2G-contractual (Sig=0,048 and B=41,182), and SC (Sig=0,013 and B=63,214). It would be expected that the B value of the V2G-contractual scenario would be larger than for the V2G-flexible and SC scenario, however it is not. This behavior could be caused by the maximum incitement compensation of €500. Respondents could not indicate a higher compensation for the V2G-contractual scenario when they actually wanted that.

A regressed relationship is also found between egoistic values and the height of the incitement compensation for SC (Sig=0,048 and B=-34,659). This is striking, as one would expect that individuals with high egoistic values would generally require a higher incitement compensation. The negative B value however, implies otherwise. This could be caused by respondents who scored high on egoistic values tried to leave a good impression by scoring low on the incitement compensation.

7.1.3 Survey Input for Simulation

In conclusion, the survey provided several interesting insights into the preferences of EV owners relating to the participation in V2G and SC. For the simulation it is important to get an indication of the height of the incitement compensation. First of all, it should be mentioned that EV owners are not willing to participate in V2G without a degradation compensation. The degradation compensation should be provided when the battery of the EV is used for providing IDM or RRP down. Second, the incitement compensation should be provided for the number of hours an EV owner enables V2G or SC.

- Incitement compensation required for V2G: €257,55/year for charging 20 hours/day - €0.035/hour
- Incitement compensation required for SC: €202,45/year for charging 20 hours/day - €0.028/hour

7.2 Simulation

With a simulation one can estimate the performance of a model. The simulation can be used to test the behavior of the system. The more realistic the simulation is made the better the results reflect real life performance of the system. To test the performance of the profit maximization algorithm in equations (41)-(62), a simulation is made. This simulation provides an estimate of the potential benefits an aggregator in the Netherlands is able to make.

In the following Sections first, the design of the simulation is explained, after which the relaxations and assumptions are stated. Relaxations and assumptions are necessary as the real life scenario is too complex to model, and some data is not available. Second, the input data for the normal scenarios are provided, after which the performance of the normal scenarios are elaborated upon. Lastly, a sensitivity analysis is performed to test the robustness of several assumptions and different scenarios.

7.2.1 Design of Simulation

The simulation is done in Matlab R2017a using the CVX toolbox. CVX is a software that can be used in Matlab for disciplined convex programming, and turns Matlab into a modeling language, allowing constraints and objectives to be specified [12]. Sortomme et al. (2012) and Hoogvliet et al. (2017) among other scholars also used CVX to simulate the V2G optimization problems.

The profit maximization algorithm for RRP in equations (41)-(62) is first evaluated for convexity. As the CVX software is explicitly designed for disciplined convex programming, it has to be verified if the algorithm is convex.

As mentioned in the algorithm design, the algorithm for RRP is non-convex. The market requires $E_i^{RRP\downarrow/\uparrow,bid/provided}(k)$ to be integer as discussed in section 4.1.7. Integer decision variables turn the algorithm into a non-convex problem formulation. Moreover, the switching variable of $E_i^{REG}(k)$ and $E_i^{RRP\downarrow/\uparrow,bid/provided}(k)$ depending on the $SOC_i^{req}(k+1)$ is also a non-convex notation when evaluating the complete algorithm as a series of constraints. To still implement the algorithm using CVX several relaxations should be made.

To resolve the issue with the switching variable, instead of simulating the profit maximization algorithm for the complete time horizon for all EVs, the problem is divided in smaller convex problems using the decision tree model in Figure 29. This model evaluates per time step, per EV whether to do nothing, charge normally or make a bid in either RRP down or RRP down and up for SC and V2G respectively after which the bids are either accepted or not. By breaking down the complete problem in small individual problems, the profit optimization subproblem can be treated as a convex model. The simulation first verifies whether the EV is connected to the grid or not. If it is connected, it determines whether priority charging has been chosen, i.e. no SC or V2G is desired by the EV owner, or whether the EV has to charge normally to oblige to the required SOC constraints. If this is not required, then for SC RRP down can be bid, where for V2G both RRP down and up can be bid. Then it is evaluated whether the bid is accepted, and if so the RRP down/up is provided, see Figure 29. Using this decision tree model, there is no need for a switching variable.

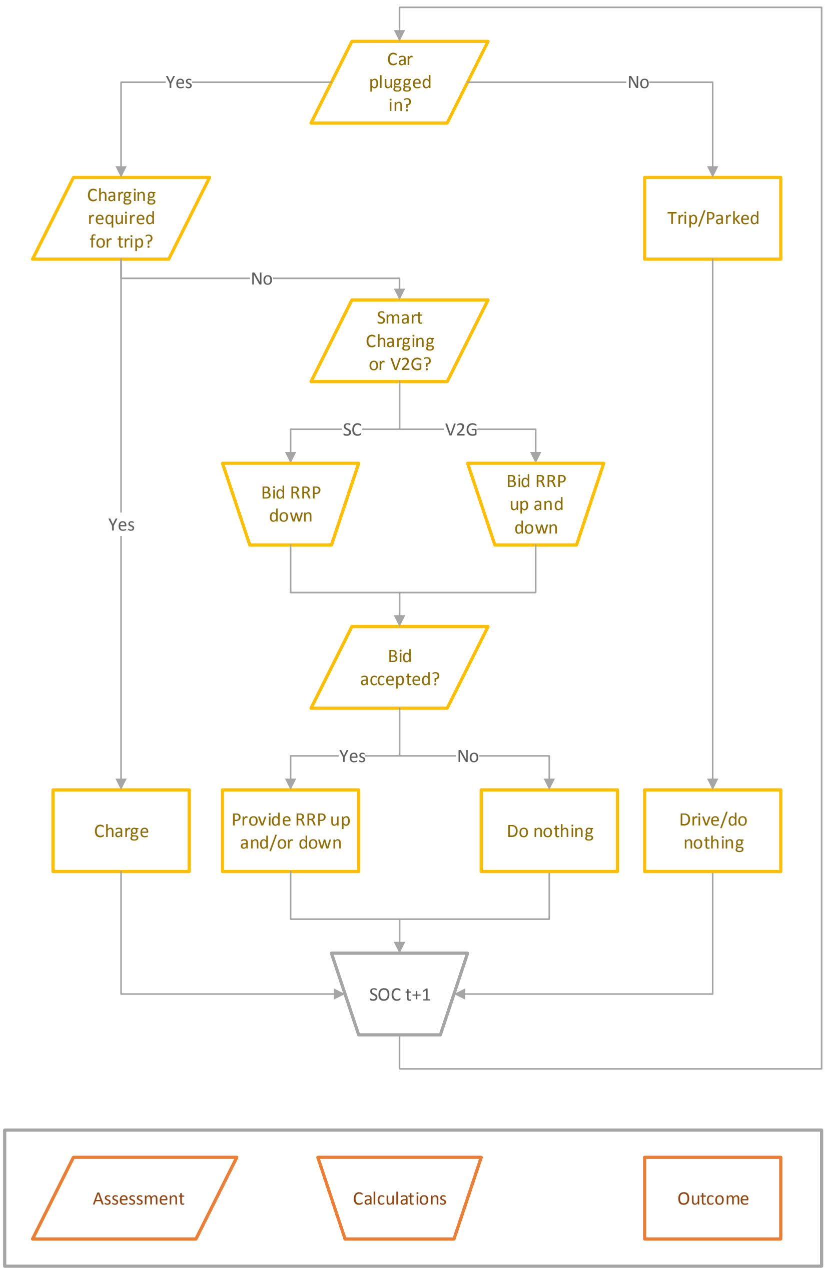

Figure 29: Schematic decision tree model overview RRP scenario [17]

7.2.1.1 Relaxations

As CVX is explicitly designed for disciplined convex programming it has to be verified if the algorithm is convex or not. As $E_i^{RRP\downarrow/\uparrow,bid/provided}(k)$ is integer due to the market constraints for the imbalance market as discussed in section 4.1.7 the algorithm is non-convex. Moreover, the switching of $E_i^{REG}(k)$ and $E_i^{RRP\downarrow/\uparrow,bid/provided}(k)$ depending on the $SOC_i^{req}(k+1)$ is also a non-convex notation when evaluating the complete algorithm as a series of constraints.

The problem formulation, despite using the decision tree model, is still non-convex due to the integer market constraints. To still be able to implement the algorithm using CVX several relaxations are made. First of all, the $E_i^{RRP\downarrow/\uparrow,bid/provided}(k)$ variable is relaxed, implying that the variable can take all possible positive values instead of only integer values.

CVX also did not allow for the degradation costs component to be used in the objective function due to convexity issues. Therefore, the costs calculations of the degradation costs in the objective function (41) are not taken into consideration. After evaluation of the results in Section 7.2.2 the absence of the degradation costs component can be justified. In Figure 38 it can be seen that the degradation costs component is only a small portion of the total cost function. It is expected that the results do not differ significantly from the results obtained when using the degradation costs component in the objective function. The objective function for the RRP model then is as follows:

$$-\sum_{k=4}^{PredictionHorizon}\sum_{i\in V}^{n}\Big(\Big(E_i^{RRP\downarrow,bid}(k)\cdot P^{RRP\downarrow,bid}(k)\cdot\delta^{RRP\downarrow}(k)+E_i^{RRP\uparrow,bid}(k)\cdot P^{RRP\uparrow,bid}(k)\cdot\delta^{RRP\uparrow}(k)$$
$$-T_i^{charge}(k)\cdot C^{incite}-E_i^{REG}(k)\cdot C^{El,normal}\Big)\Big) \tag{95}$$

Other relaxations that were made for the simulation are:

- The bid prices $P^{RRP\downarrow/\uparrow,bid}(k)$ are assumed to be constant over time for easier implementation. Differences in bid prices are evaluated in the sensitivity analysis
- The benefits were simulated using 6 EVs (3 EVs and 6 PHEVs as in Table 7) instead of e.g. 10.000 EVs for the realistic scenario due to computational time considerations
- The market constraints for a minimum bid of 4 MW (equations (44) and (51)) are relaxed as 6 EVs are not able to generate such capacity
- The market constraint for equal RRP up and down bids (equation (62)) is relaxed as this constraint is infeasible for 6 EVs
- The IDM is not considered as the data for the IDM is not available, simulating the IDM could be done in future work

7.2.1.2 Subproblems

Having described all relaxations, the subproblems that follow from the decision tree model are formulated. The decision tree model in Figure 29 separates the optimization problem formulated in equations (41)-(62) in Section 6.2.1, into two smaller subproblems. The decision tree model evaluates whether SC or V2G has been selected by the EV owner, this indication is an EV owner preference. CVX is able to provide a solution for the two subproblems, which could imply that the subproblems are convex. However, it is still possible that the solution provided by CVX is a local optimum.

- If SC has been selected, i.e. $\psi_i = 1$ and $\phi_i = 0$ then only subproblem 1 is optimized.
- If V2G has been selected, i.e. $\psi_i = 1$ and $\phi_i = 1$ then subproblems 1 and 2 are optimized separately. Subproblem 1 results in the RRP down bid, and subproblem 2 results in the RRP up bid.

Subproblem 1:

$$\underset{E_i^{RRP\downarrow,bid}}{\text{Minimize at t=0 for t=60, k=15 minutes}}$$

$$-\sum_{k=4}^{PredictionHorizon}\sum_{i\in V}^{n}\Big(\Big(E_i^{RRP\downarrow,bid}(k)\cdot P^{RRP\downarrow,bid}(k)\cdot\delta^{RRP\downarrow}(k)-T_i^{charge}(k)\cdot C^{incite}-E_i^{REG}(k)\cdot C^{El,normal}\Big)\Big) \tag{96}$$

Subject to:

$$SOC_i(k+1)=A\cdot SOC_i(k)+B\cdot E_i^{RRP\downarrow,bid}(k)+F\cdot D_i(k) \tag{97}$$

$$E_i^{RRP\downarrow,bid}(k)\cdot\frac{\alpha}{\eta_i\cdot\eta_{tr}}+\sum_{K=1}^{4}\left(E_i^{RRP\downarrow,bid}(k-K)\right)\leq B_i^{cap}-SOC_i(k) \tag{98}$$

$$E_i^{RRP\downarrow,bid}(k)\cdot\frac{\alpha}{\eta_i\cdot\eta_{tr}}+\sum_{K=1}^{4}\left(E_i^{RRP\downarrow,bid}(k-K)\right)\geq B_i^{cap}-SOC_i^{req}(k+1) \tag{99}$$

$$\frac{E_i^{RRP\downarrow,bid}(k)}{15}\leq 0.95\cdot B_i^{cp} \tag{100}$$

$$E_i^{RRP\downarrow,bid}(k)\geq 0 \tag{101}$$

Subproblem 2:

$$\underset{E_i^{RRP\uparrow,bid}}{\text{Minimize at t=0 for t=60, k=15 minutes}}$$

$$-\sum_{k=4}^{PredictionHorizon}\sum_{i\in V}^{n}\left(\left(E_i^{RRP\uparrow,bid}(k)\cdot P^{RRP\uparrow,bid}(k)\cdot\delta^{RRP\uparrow}(k)-T_i^{charge}(k)\cdot C^{incite}-E_i^{REG}(k)\cdot C^{El,normal}\right)\right) \tag{102}$$

Subject to:

$$SOC_i(k+1)=A\cdot SOC_i(k)+B\cdot E_i^{RRP\uparrow}(k)+F\cdot D_i(k) \tag{103}$$

$$E_i^{RRP\uparrow,bid}(k)\cdot\frac{\alpha\cdot\eta_i}{\eta_{tr}}-\sum_{K=1}^{4}\left(E_i^{RRP\uparrow,bid}(k-K)\right)\leq SOC_i(k)-SOC_i^{req}(k+1) \tag{104}$$

$$\frac{E_i^{RRP\uparrow,bid}(k)}{15}\leq 0.95\cdot B_i^{cp} \tag{105}$$

$$E_i^{RRP\uparrow,bid}(k)\geq 0 \tag{106}$$

7.2.1.3 Input Data and Assumptions

For the normal scenarios several input data is required including real-time historic prices, required SOC of the vehicles and type of drivers. Also the prediction horizon should be established to see what prediction horizon will maximize profits using model predictive control. The data that is used as input in the simulation for the normal scenarios is elaborated subsequently. As sometimes the input data is unknown or varies per source, assumptions about several inputs have been made.

Three normal scenarios are distinguished, the baseline scenario is the scenario where the EV owners do not choose to provide any SC or V2G services, i.e. only driving and normal charging occurs. The profit of all other scenarios is compared to the profits of the baseline scenario. The other two normal scenarios to calculate the monetary benefits are the V2G scenario and SC scenario, where the EV indicated to participate in V2G or SC respectively.

For the normal scenarios the prices of a random day in 2017 is used. The day begins at 08.00 AM and ends at 07.59 AM the next day. The prices of first weekdays of autumn 2017 (25/26-09-2017) are used in the normal scenarios. The normal raw electricity price is €0.10 per kW [17], relating to a normal electricity price of €100,- per MW. As the price for RRP down should be lower than the normal electricity price, a RRP down bid price of €99,- per MW is used. For RRP up the price should be higher than the normal electricity price plus the compensation for the degradation costs. The degradation cost depends on several factors including the DOD and the battery pack replacement costs. Therefore, it is not unlikely that the degradation costs are different for the 6 different EVs. Since only one RRP up price can be bid, the normal RRP up price has to be assumed The highest price for degradation costs are used, in order to make the provision of RRP up profitable for all EVs. Simulation revealed that the degradation costs component equals around €45,-/MW of RRP up. The total price RRP up used in the normal scenario is €145,-/MW.

There are three type of drivers defined by [17], resident commuters, commuters, and residents. Resident commuters are able to charge both at home and work, commuters can only charge at work, and residents can only charge at home. For the normal scenario the charging patterns of resident commuters are considered. The planned trips of resident commuters occur from 08:00 till 09:00 and from 17:00 till 18:30 as in Figure 13. For the other hours, the EVs are available for SC and V2G services.

The required SOC for a trip, as seen in the survey does not always have to be 100% for the EV owners. In the normal scenario however, it assumed that the required SOC for a planned trip is 100%. The minimal GDR for the normal scenario is 20%. The required SOC for a trip depends on the type of EV, and is 10% for the Tesla and 28% for the other EVs and PHEVs, as in Table 7. As a RRP up or down bid is valid for an hour and 15 minutes after the time of bidding, bidding cannot take place after one hour and 15 minutes before a trip, as otherwise there is no capacity to provide the energy since all EVs are driving. The driving efficiency of the vehicles is assumed to be equal for all EVs, and is 94%. The connection power is as in Table 7, and the charging efficiency of all EVs is assumed to be 98%. The transmission efficiency is set at 92 % in accordance with [17].

The simulation is dynamic, implying that real-time historic data is used to verify if a bid is accepted or not. A bid is valid for 15 minutes, but each minute it is estimated by TenneT whether RRP is required, and how much is required. To take computation time once more into consideration the RRP in the simulation is evaluated per 15 minutes. Per 15 minutes both the minimum and maximum settlement price is evaluated. When the bid price is accepted, it is assumed that all capacity bid is actually provided. In the normal scenarios the maximum prices of this 15 minute interval are used to calculate the benefits.

The time horizon of the simulation is one day. The optimal prediction horizon used in the simulation using MPC is deterministically set to be 3 using the data below (Table 8), taking into consideration both optimal benefits and computation time. Because it is not known in advance if a bid gets accepted or not, a larger prediction horizon does not always result in higher benefits. For example, take the first weekday of spring in 2017, where benefits are exceptionally high. In this case it is better to take a low prediction horizon resulting in non-conservative bids which in the end, result in the highest benefits w.r.t. the baseline scenario. However, in the first weekday of autumn 2017 the benefits with respect to the baseline scenario do increase as the prediction horizon increases. In a normal day, the benefits increase when making more conservative bids. Despite the efforts of MPC to take future bids into account, it does not always result in higher benefits for V2G or SC. Sometimes it seems random as for when the benefits are the largest. To take into account computation time as well, which were about 360 s for a prediction horizon of 1,2 and 3, 3.600 s and 50.000 s for a prediction horizon of 4, a middle of the road prediction horizon of 3 was chosen which has a relatively low computing time and decent benefits. The advantage choosing a prediction horizon of 3 with respect to a prediction horizon of 1 is that the bids are more regulated resulting in more flexibility as well. The disadvantages are that the bids have a lower maximum value, which could hurt profits if a lucky bid gets accepted. The same reasoning applies for the advantages and disadvantages of a prediction horizon of 3 instead of a prediction horizon of 4, however the additional advantage of choosing a prediction horizon of 3 is that the computation time is significantly lower.

Prediction Horizon	1	2	3	4
First weekday spring 2017	21,83	€20,54	€19,57	€19,97
First weekday autumn 2017	€5,11	€4,78	€5,21	€5,17
Warmest day in 2017	€5,39	€5,31	€5,43	€5,29
Coldest day in 2017	€3,61	€3,58	€3,56	€2,88

Table 8: Specifications of popular electrical vehicles in the Netherlands

7.2.2 Monetary Benefits

The monetary benefits are calculated using the input data discussed above. For these scenarios the input data is maintained constant to evaluate the differences between the baseline scenario, the SC scenario, and the V2G scenario under normal circumstances. An overview of the benefits with respect to the baseline scenario can be found in Table 9.

	Tesla	ZOE	Leaf	Outlander	V60	Golf
Profits baseline	-€1,81	-€2,77	-€2,70	-€0,81	-€0,76	-€0,58
Benefits V2G	€1,91	€2,12	€1,20	€0,03	€0,00	-€0,04
Benefits SC	€0,44	€0,60	€0,67	-€0,22	-€0,24	-€0,33

Table 9: Overview of benefits for the first weekday of autumn 2017 (25/26-09)

Baseline scenario

In the baseline scenario no SC or V2G is performed. All other scenarios are compared to this baseline scenario, to evaluate whether an aggregator is able to make benefits. Benefits is explicitly mentioned instead of profit, as profit is generally interpreted as income - costs. The benefits of a scenario are the profits of the scenario - the profits of the baseline scenario. As the baseline scenario does not have any income and only regular charging costs, the profit of the baseline scenario is negative. The SOC of the different EVs under the baseline scenario is visualized in Figure 30. Only 3 out of the 6 EVs are plotted in this Figure, as most EVs show similar behavior and the plot gets hard to read. The EVs plotted are a Tesla, which drives for only 10% of its battery capacity; the ZOE, a normal EV; and the Outlander, a PHEV. The required SOC is plotted as well in the Figure. In the baseline scenario however, the EV take a trip, and when plugged-in the EV charges normally with a rate equal to the connection power of the EV.

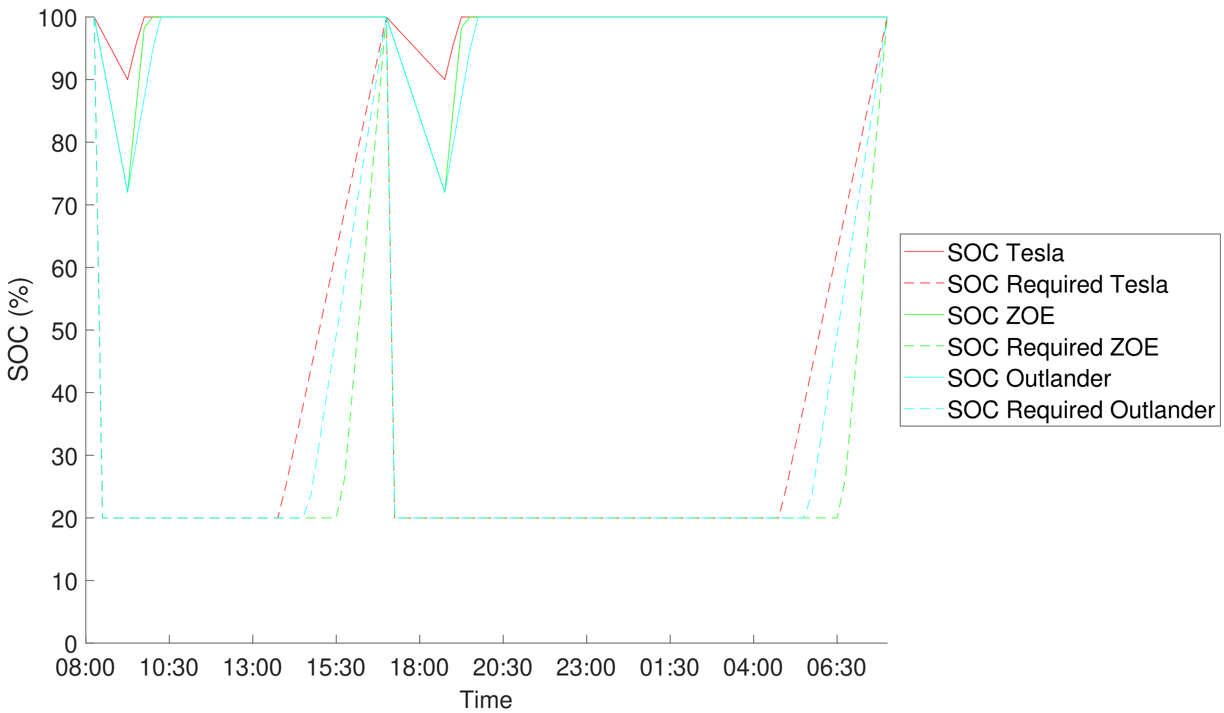

Figure 30: SOC of three vehicles under the baseline scenario

In Figure 31 the amount of charged and discharged energy is visualized. The accumulated positive and negative should have a net result of 0, implying that an EV charges the same amount as that it discharges. The profits associated to the baseline scenario are: €-1,81, €-2,77, €-2,70, €-0,81, €-0,76, and €-0,59 for the Tesla, ZOE, Leaf, Outlander, Golf, and V60 respectively. The costs are only the regular charging costs, constituted of the capacity of charging needed times the normal electricity price of €0,10/kWh.

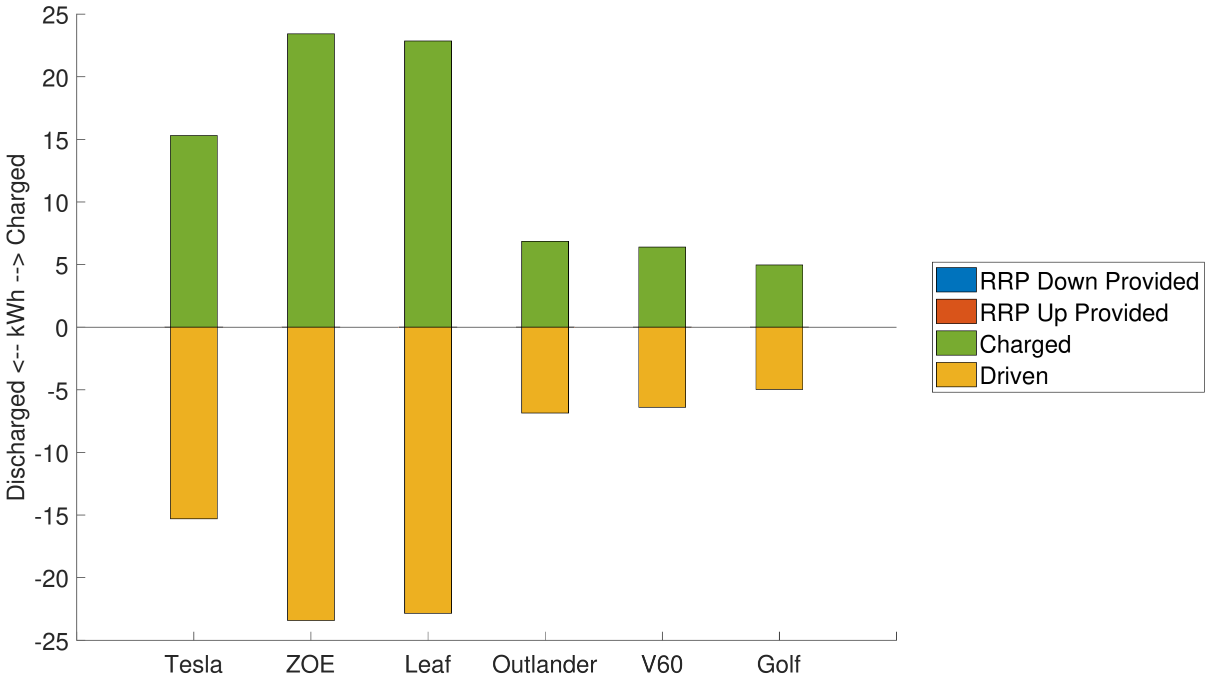

Figure 31: Breakdown of charging and discharging in the baseline scenario

V2G

In the V2G scenario both RRP up and down services are provided. In Figure 29 it is determined whether V2G has been selected by the EV owners, if so, bids are made in both the RRP up and down market. If the bid is accepted, RRP up/down is actually provided. In Figure 32 it can be seen that for the three EVs the SOC goes up and down in the periods RRP is possible. The SOC goes up when it is providing RRP down services, and goes down when RRP up is provided.

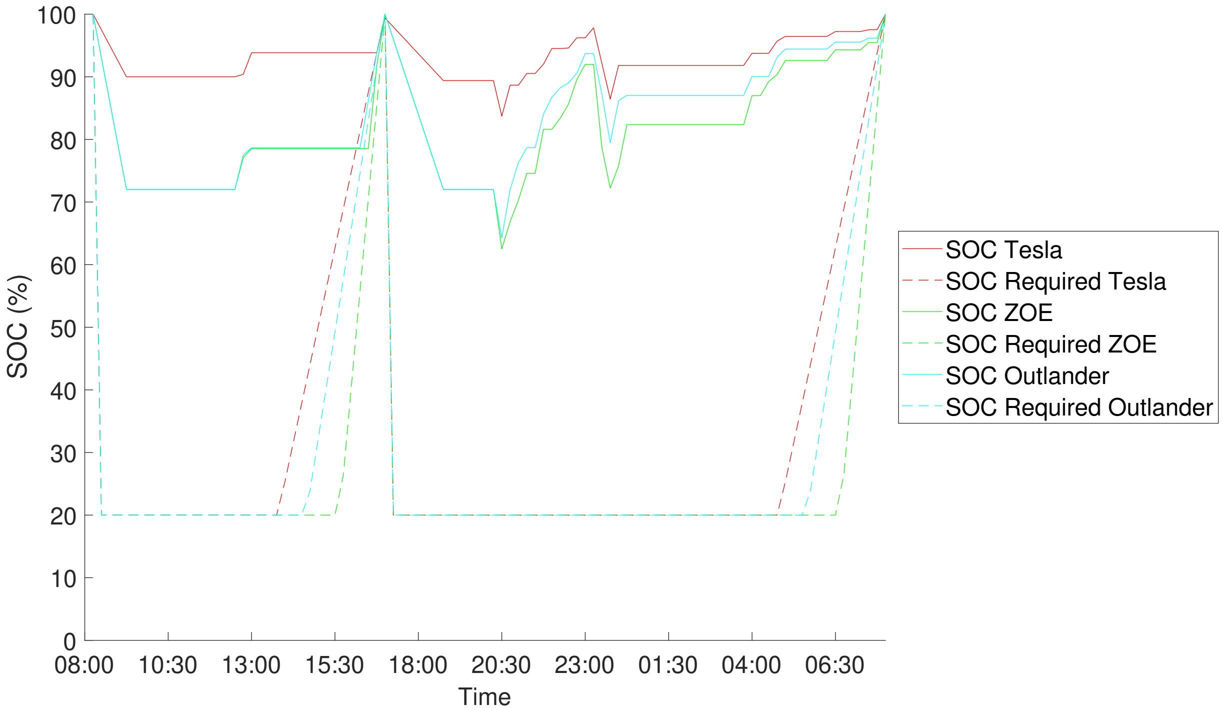

Figure 32: SOC of three vehicles under the V2G scenario

In Figure 33 a breakdown of the bids and the accepted bids is visualized for the first weekday of autumn in 2017. This graph shows the SOC in kWh instead of % like in Figure 32. On the y-axis on the right hand side the bid size is projected. The size steps are the same for both y-axes, therefore, the height of an accepted is the same height as the increase or decrease of the SOC an hour later. The SOC changes an hour and fifteen minutes later, as the bid has to be made an hour in advance and the provision of RRP takes gradually place for the 15 minutes after.

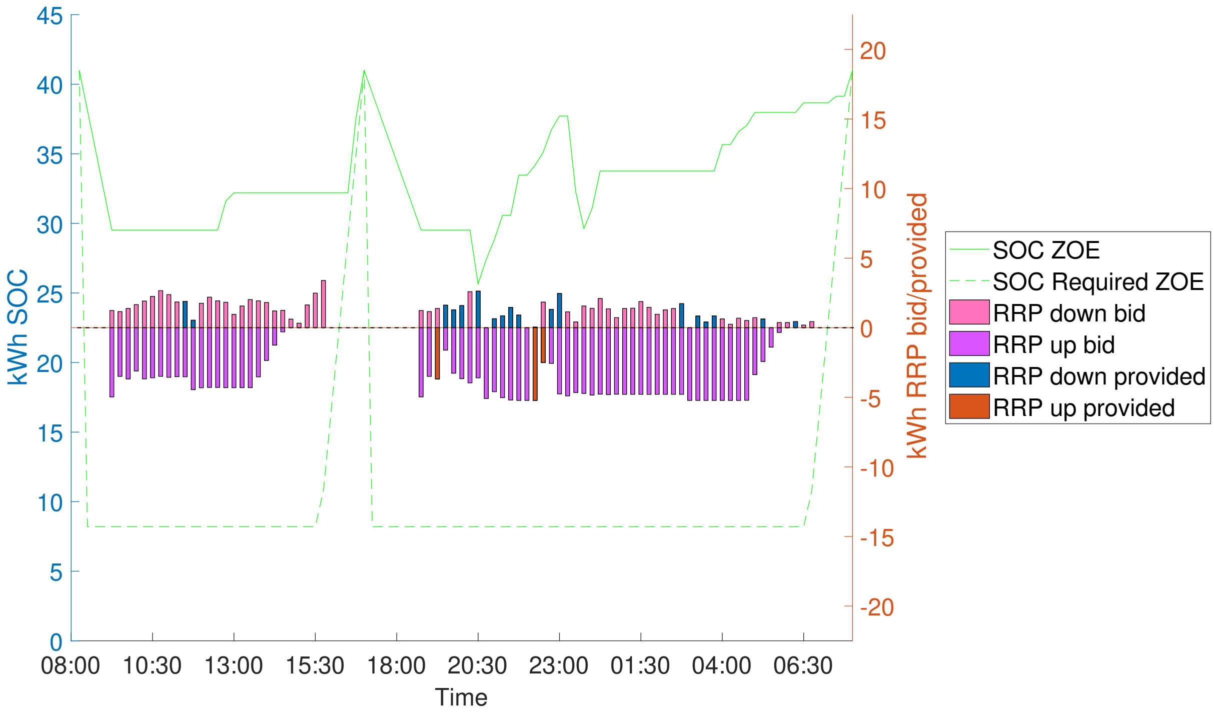

Figure 33: Bids and SOC of the ZOE in the V2G scenario

The electricity flows as a result of driving, charging and providing RRP is visualized in Figure 34. This breakdown plot shows for each EV the amount of kWh charged and discharged as a consequence of driving, charging or providing RRP. It can be seen that less regular charging is required than in baseline scenario. This is due to the accepted RRP down bids. The total energy flow through the battery increases however, as caused by the additional discharging due to the accepted RRP up bids. Remarkable as well is that the Tesla has provided less RRP down than the ZOE, yet more RRP up. This is most likely due to the fact that the Tesla only uses 10% of its battery capacity for a trip, and therefore does not have as much capacity for charging but does have a large capacity spare to be used for RRP up.

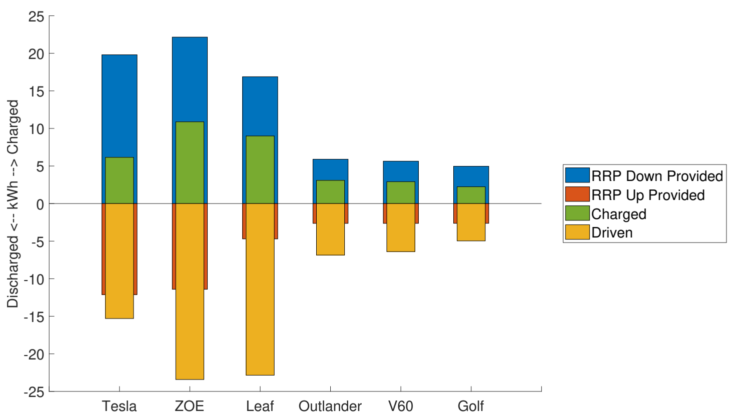

Figure 34: Breakdown of charging and discharging in the V2G scenario

Figures 35 and 36 display the total amount of bid capacity for RRP and the number of times that

RRP or regular charging was required. The figure displaying the total amount of bid capacity follows the same trend line as Figure 34, showing the highest bid capacity for the ZOE. However, different from the actual energy flow is the amount of capacity RRP up bid. We see that the Tesla has a lower total amount of RRP up bid than the ZOE, however it provides more RRP up than the ZOE. This discrepancy could be explained by the timing and acceptance of the bids. As the EVs have different behavior of the SOC, the Tesla could, in this scenario, be lucky that a high bid at a time where the ZOE could only make a low bid, was accepted. Accepted RRP up bids do not occur regularly, see Figure 36. Only 3 RRP up bids have been accepted in the first weekday of autumn in 2017. Moreover, the number of RRP down also differs for the three EVs. The Tesla has the lowest amount of accepted RRP down bids, as it has the least freedom for charging. The difference between the ZOE and Leaf, who have the same spare capacity for charging, could be explained by the difference in connection power. The ZOE has a higher connection power, and might be fully charged at an earlier stage than the Leaf, refraining the ZOE from making additional RRP down bids. In addition to the fully charged state of the EVs, the Leaf also has the highest number of regular charging periods, which could be explained by the same reasoning as for the RRP down bids. The Leaf has a lower connection power, and also a large battery capacity. Multiple periods of regular charging are thus required to fully charge the battery of the Leaf.

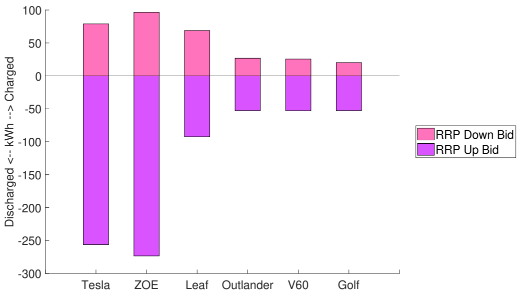

Figure 35: Total amount of RRP up and down bid in the V2G scenario

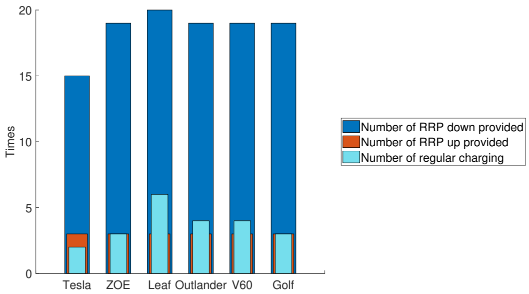

Figure 36: Number of times that RRP was performed and that regular charging was required in V2G scenario

Having discussed the energy flows of the EVs, the monetary benefits resulting from these energy flows are plotted in Figure 37. In this Figure the income of RRP up and down is represented by the green bars. Note that the profits for RRP down are all negative. This implies that electricity has been bought from TenneT. As a result, the total profits might become negative. However, the profits of the scenario are not the most important performance indicator. The important performance indicator is the benefits with respect to the baseline scenario. The benefits with respect to the baseline scenario are the profits of the V2G scenario minus the profits of the baseline scenario. In this case the benefits of all EVs are positive, whereas the benefits for the PHEVs are near €0. Even though the profits of EVs is not always positive, e.g. the Leaf has negative profits, the profits in the V2G scenario are higher than the profits in the baseline scenario. The benefits are thus not necessarily an actual profit, but could also represent a cost savings. The benefits of the PHEVs however, are as said close to €0, where the Outlander has a marginal profit and the Golf has a marginal loss. The reason for this could be assigned to the lower available capacity for bids, as the capacity of the batteries are smaller. Furthermore, it could also be caused by the lower connection power. Due to the lower connection power there is a limit on what the PHEVs can bid, and as bids are only accepted occasionally, the capacity provided is not enough to make a profit.

A breakdown of the different cost components is shown in Figure 38. It can be seen that the incitement costs and the regular charging costs resemble the largest part of the costs, and that the degradation costs contain just a small fraction of the total costs. Since the degradation costs is only a small part of the total costs, it is reasonable to leave it out of the objective function in the subproblems.

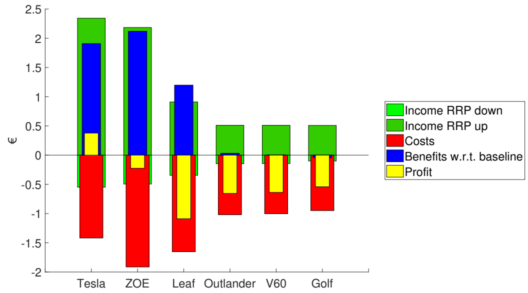

Figure 37: Breakdown of benefits and costs in the V2G scenario

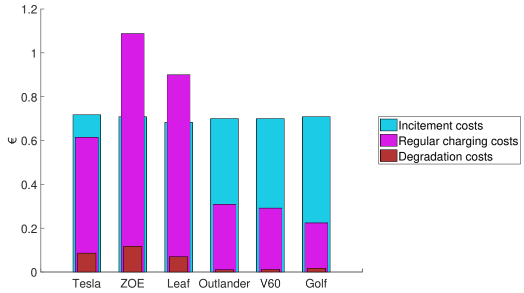

Figure 38: Breakdown of the different cost components in the V2G scenario

Smart Charging

For the SC scenario the same Figures as for the V2G scenario are shown, in order to obtain a structure comparison of the differences between the two scenarios. First, the SOC of the three EVs are shown in Figure 39. From this Figure it can be seen that with SC the EVs are only charging. In Figure 40 it can be verified that only RRP down bids are made during the day. The RRP down bids are smaller and fewer than in the V2G scenario since there is no additional discharging of the vehicles due to RRP up.

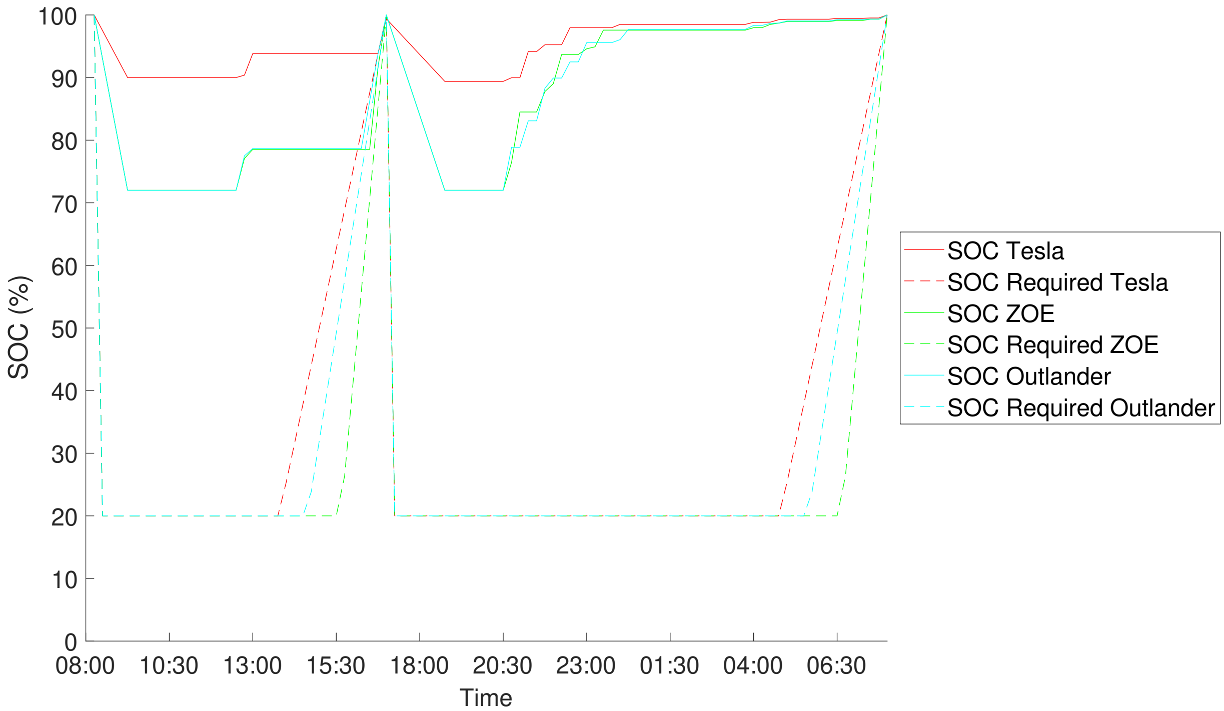

Figure 39: SOC of three vehicles in the SC scenario

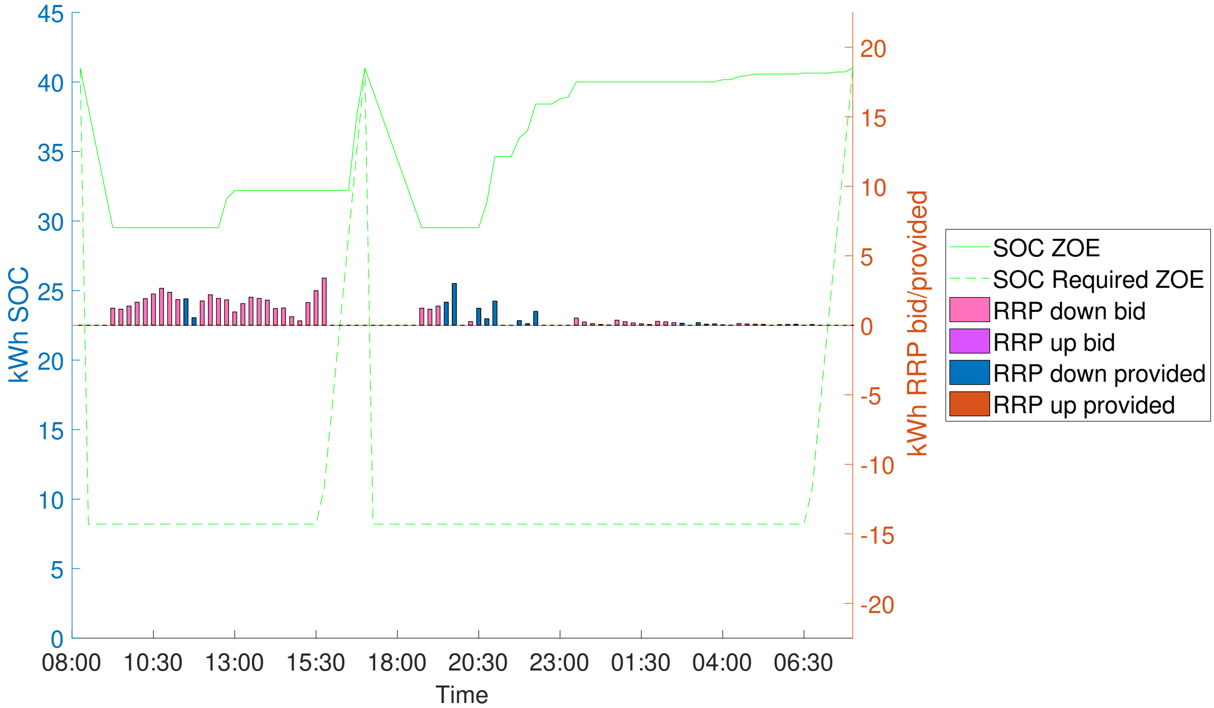

Figure 40: Bids and SOC of the ZOE in the SC scenario

The total amount of energy flow through the battery in the SC scenario is the same as for the baseline scenario. However, not all energy is regularly charged, but some RRP down has also been provided see Figure 41.

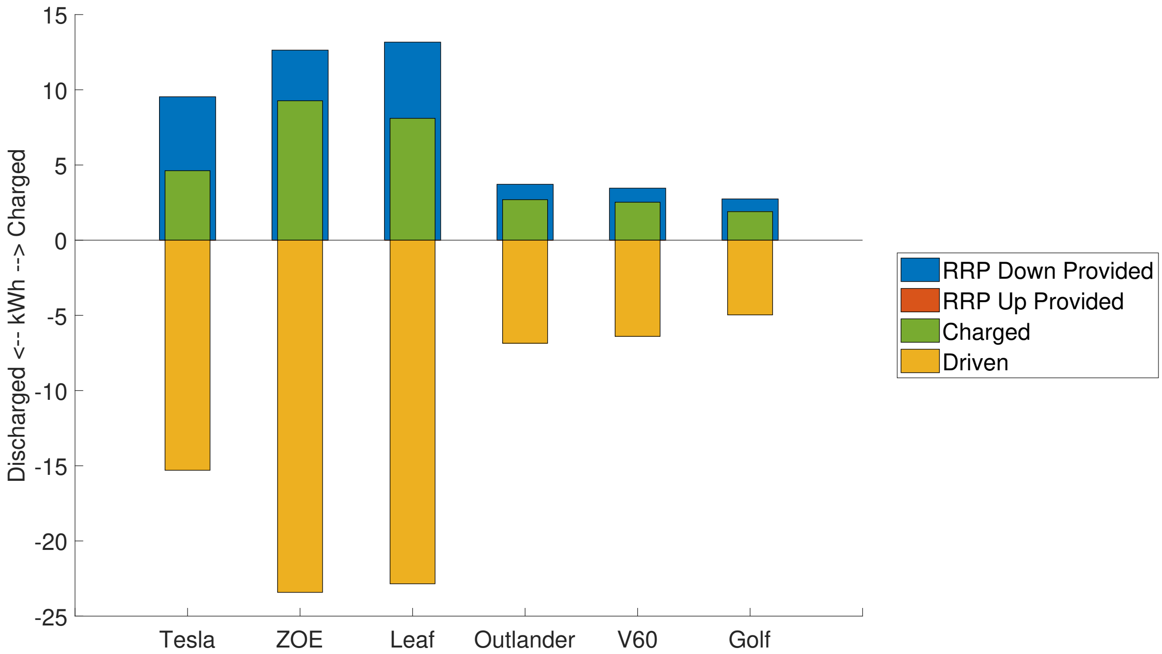

Figure 41: Breakdown of charging and discharging in the V2G scenario

In the next two Figures it can also be seen that only RRP down has been bid, and that the total bid capacity is lower than the total bid capacity in the V2G scenario following the same reasoning as discussed previously. It can also be seen that for all EVs except the Golf, the number of times RRP down is provided is the same or lower than within the V2G scenario. Only the Golf provided more times RRP down than in the V2G scenario. This could be caused by the height of the bids for RRP down which are lower than in the V2G scenario, suggesting that the Golf had more times spare capacity for providing RRP down.

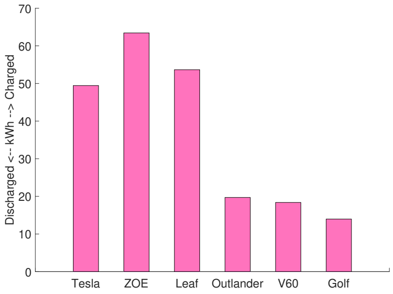

Figure 42: Total amount of RRP up and down bid in the V2G scenario

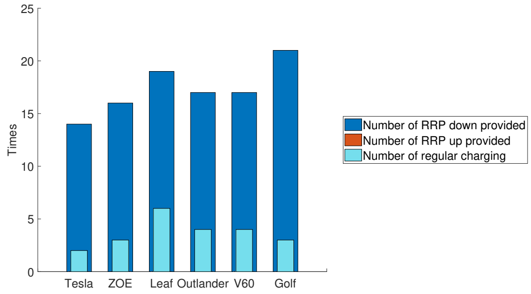

Figure 43: Number of times that RRP was performed and that regular charging was required in V2G scenario

The benefits and costs calculations are again shown in the two Figures next to each other in Figures 44 and 45. In the breakdown of benefits, it can be clearly seen that none of the PHEVs are able to make a benefit with respect to the baseline scenario. Even though one might expect SC to be more beneficial to EV owners as no discharging is required, thus no degradation compensation is required, the SC scenario is not beneficial for PHEV since the incitement costs are outweigh the profits. Also for the normal EVs the profits are significantly lower than in the V2G scenario, e.g. the Tesla profit is €1.91 for V2G and only €0.44 for the SC scenario. A reason for the low benefits in the SC scenario could be that the incitement compensation for SC is not half of the incitement compensation required for V2G, even though in theory only half of the benefits can be achieved. Another reason could be that RRP up is more profitable than RRP down in this specific day, resulting in lower benefits when only RRP down can be bid. Besides, the bids of RRP down should be lower in the SC scenario compared to the V2G scenario, since no additional discharging occurs, resulting in lower incomes.

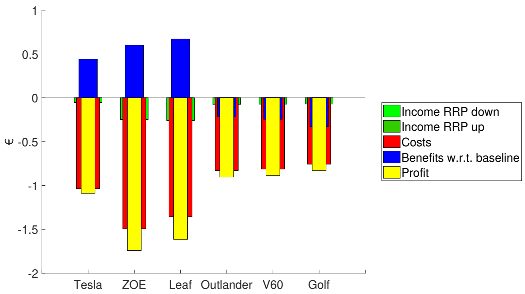

Figure 44: Breakdown of benefits and costs in the V2G scenario

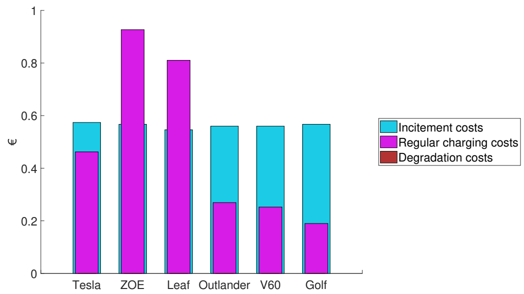

Figure 45: Breakdown of the different cost components in the V2G scenario

7.2.3 Sensitivity Analysis

In this Section the input data, as discussed in Section 7.2.1, is altered to examine the effects of different possible scenarios. The input data for the previous analysis included assumptions regarding EV owner preferences and characteristics. If the preferences or characteristics change, this could impact the monetary benefits. For each scenario it is first discussed which factors are changed, after which the corresponding monetary benefits are presented.

Alternative Trip Preferences of EV Owners

The first scenario reflects question 19 of the survey. This question related to the required SOC at the beginning of a planned trip. In the normal scenarios before, it was assumed that the required SOC at the beginning of a planned trip should be 100%. However, the survey showed that not all EV owners would require a SOC of 100% at the beginning of such trip, see Figure 46.

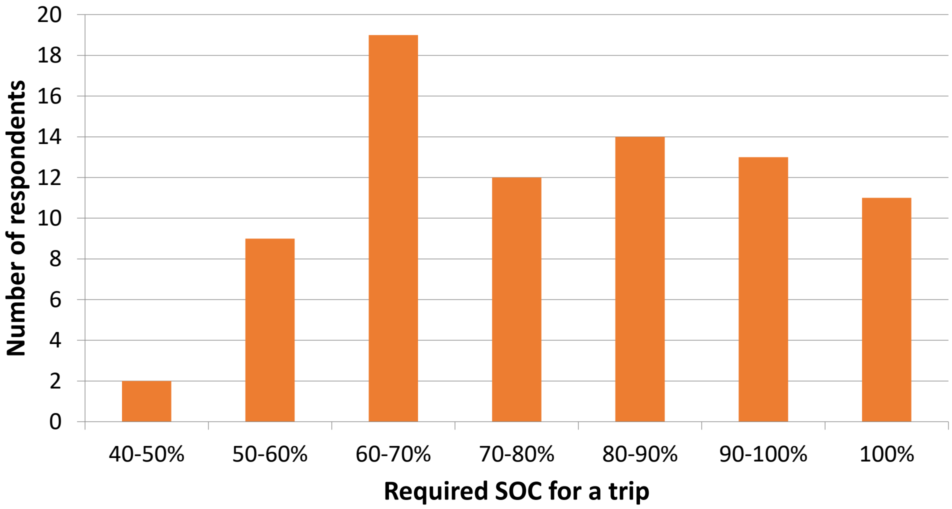

Figure 46: Means required SOC at the beginning of a planned trip

When an EV does not require a SOC of 100% there is more time to generate bids. Besides, there is also more spare capacity which could be bid. These two relations lead to higher benefits when less SOC is required for a planned trip. In Figures 47 and 48 this relation is visualized. In accordance with [17], most benefits can be made between 100% SOC and 70% SOC for a planned trip. After this relatively steep increase in benefits, the additional benefits to be made flatten.

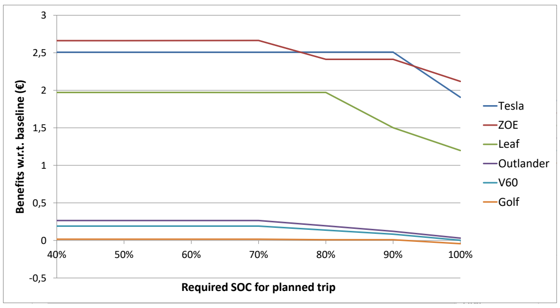

Figure 47: V2G benefits under alternative required SOC for a planned trip

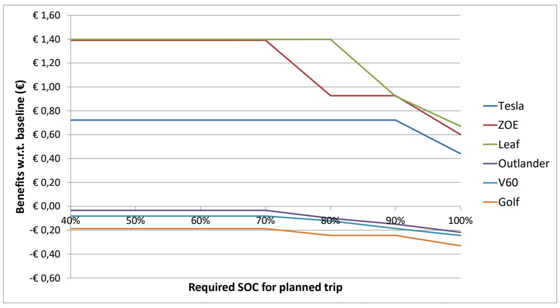

Figure 48: SC benefits under alternative required SOC for a planned trip

Alternative Bidding Strategies

In the normal scenario bid prices of €99 and €145 were applied for RRP down and RRP up respectively. However, by changing the bids SC or V2G could become more profitable. If a relatively high price for RRP down is accepted, benefits are not significant. If a lower bid price for RRP down is used, the bid price is not accepted when the settlement price is relatively high, and the capacity remains available for other bids in more profitable periods. The same reasoning accounts for the RRP up bid, but the bid price should increase instead of decrease in order to make more profitable bids. The results are shown in Figures 49, and 51.

For RRP down the benefits first increase until the bid price is €39, decreasing the bid further results in fewer benefits. The benefits increase by lowering the bid first, as the less profitable bids are cancelled freeing up capacity for more profitable periods. However, after a bid of €39 the benefits decrease once more, as only few bids are accepted, see Figure 50. In closer examination a bid price of €43 was found to be optimal. For this bid price both the ZOE and V60 could make one additional bid that was accepted. For RRP up the benefits do not increase by increasing the bid price, as there are few bids accepted 52. If more RRP up is required in a day, e.g. during the warmest day of the year, it is expected that by increasing the RRP up bid price the benefits will increase as well likewise RRP down in this day.

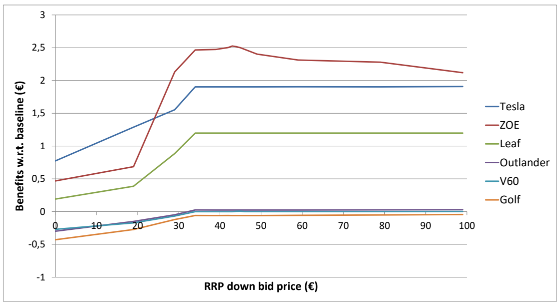

Figure 49: V2G benefits under alternative RRP down bid prices

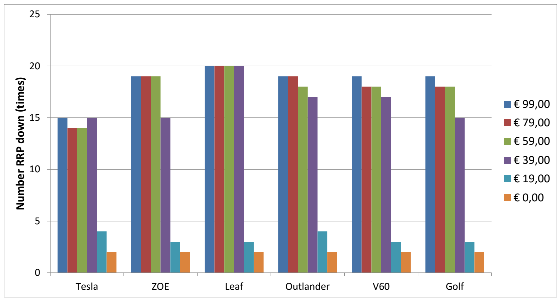

Figure 50: Times RRP down was provided under varying RRP down bid prices

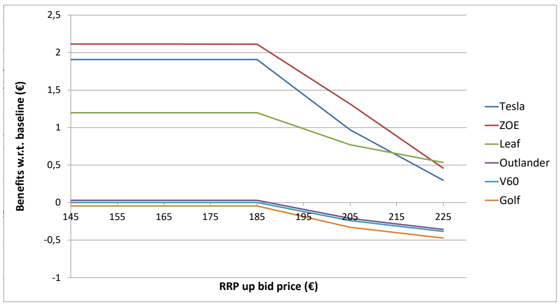

Figure 51: V2G benefits under alternative RRP up bid prices

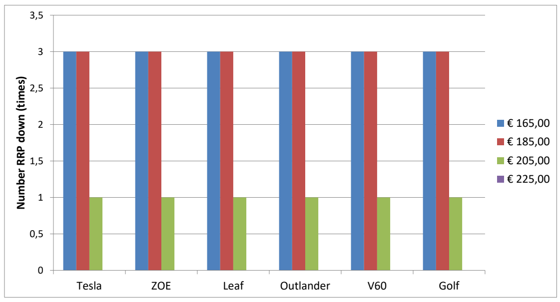

Figure 52: Times RRP up was provided under varying RRP up bid prices

Normal Connection Power

The connection power found in literature for the Tesla, ZOE and Leaf were supercharge connections. The normal 240 V connection at home can only provide a connection of 3,7 kWh though. If this is the only connection available for the EV owner the benefits change as well. In the normal scenarios the difference in benefits between the ZOE and Leaf were great, see Figure 9. This difference can be largely assigned to the difference in connection power. Table 10 shows that this is indeed the main cause for the difference in the benefits between the two cars. If the connection power is the same, 3,7 kWh, the benefits are almost equal. The small difference is due to the different battery capacities, where the battery capacity of the ZOE is slightly larger than the Leaf's capacity resulting in larger bids.

7.3 Summary

In this Chapter, the survey and the optimization problem have been analyzed. The survey, designed in Chapter 5, and analyzed in this Chapter provides an answer to SQ 6. Analysis of the survey

	Tesla	ZOE	Leaf	Outlander	V60	Golf
Benefits V2G	€0,48	€0,87	€0,84	€0,03	€0,00	-€0,04
Benefits SC	€0,25	€0,65	€0,61	-€0,22	-€0,24	-€0,33

Table 10: Monetary benefits for the different EV with a normal connection power of 3,7 kWh

was done using SPSS, several correlations and linear regression relationships have been identified. The analysis of the profit optimization problem provides an answer to SQ 8. Matlab was used to simulate the profit optimization model designed in Chapter 6. For the purpose of simulation, several relaxations were required, these are discussed in Section 7.2.1.1.

- SQ 6: *How can EV owners be incited to participate in the V2G and SC concepts?*

The survey showed that EV owners are willing to participate in SC or V2G if they would be compensated for it. The compensation is required as they perceive participating in SC and V2G required extra efforts and will increase the duration of charging. An incitement compensation of €202,45 per year for charging 20 hours per day is required for SC, and an incitement compensation of €257,55 per year for charging 20 hours per day is required for V2G. This results in an incitement compensation of €0,028 per hour of enabling SC, and €0,035 per hour of enabling V2G.

Other interesting insights of the survey are:

- EV owners do not require a fully charged, i.e. 100% SOC, EV for a planned trip
- Respondents are sensitive for price and comfort of an EV when considering to buy a new vehicle
- The higher the willingness of an EV owner is to participate in V2G or SC, the more likely the EV owner is willing to participate in support services such as indicating time of departure and charging type
- No support was found for H1b, implying that EV owners do not require a degradation compensation. It is argued however, that the degradation compensation is regardless of the survey
- Surprisingly, no support was found for H4a. The incitement compensation is not required for the lower flexibility as a result of V2G or SC

.

The survey is concluded by a reflection of the hypotheses. In Section 5.3.1 5 hypotheses have been formulated. In the analysis support for hypotheses *H4b, H4c and H5a* was found using a linear regression method. Support for hypotheses *H1a, H2a, H2b, H2c, H2d, H3a, H3b, H4b, H4c, and H5a* was found using bivariate correlation.

- SQ 8: *What is the impact of the practical considerations on the profits of an aggregator?*

The benefits that an aggregator could possibly make depends on many factors, including V2G or SC, types of EVs, bidding strategies, day of the year, connection power and EV owner preferences. The practical considerations described in Chapter 5 suggested that for the simulation degradation compensation and incitement compensation should be included. These costs result in lower benefits an aggregator is able to make. The incitement compensation is a major costs component for an aggregator, and for SC in particular this limits the profitability significantly. Moreover, PHEVs are less profitable than EVs in all scenarios.

In the analysis only single days were examined, whereas literature generally reports on yearly benefits. If the benefits for the random day are extrapolated by multiplying the benefits with 365 days, the following yearly monetary benefits could be achieved:

	Tesla	ZOE	Leaf	Outlander	V60	Golf
Benefits V2G	€697,15	€773,80	€438,00	€10,95	€0,00	-€14,60
Benefits SC	€160,60	€219,00	€244,55	-€80,30	-€87,60	-€120,45

Table 11: Overview of yearly benefits using extrapolated date of the first weekday of autumn 2017

8 Discussion

In this Chapter several of the limitations imposed in this research are discussed. The limitations are required to narrow the scope of the research. This Chapter examines the limitations, and evaluates the possible impacts the limitations could have on the results.

8.1 TSO approach

This research aimed at maximizing the profits for an aggregator. As discussed in Chapter 2 the objectives of an aggregator and the TSO are somewhat contradictory. The TSO perspective is aimed towards congestion management and prevented costs relating to investments in additional infrastructure. Congestion management focuses on enabling electricity flow through the grid at peak load. The electricity flow is limited by the capacity of the gird. In areas where the capacity of the grid is limiting the electricity flow on a long term basis, the grid has to be expanded or improved [15].

Short term peak load though also limits the electricity flow. However, it is not always economically feasible to expand or improve the electricity grid when the peak loads do not occur often. In this case flexible congestion management alternatives could be more economical. V2G is such a flexible congestion management alternative, and in this scenario the objectives of the TSO and the aggregator are in line. The prevented investment costs could be shared with an aggregator as they are preventing the investments. If the benefits are shared this could result in slightly higher profits for EV owners and aggregators. In this work however, destressing the loads of the electricity grid by using V2G was not explicitly considered or an objective. A charging scheme should be implemented that not only generates profits, but also avoids grid overcharging[17, 46].

In [17] the effect of RRP provision by EVs was analyzed for an average urban area. This analysis focused on the effect on substations. The limiting factor in substations was assumed to be the transformers. Under the baseline scenario, i.e. no V2G, overcharging would occur when 20 EVs were charging. In the V2G scenario, overcharging would occur with a fleet of 16 EVs. This implies that providing RRP contributes to the peak load in urban distribution grids. However, under the baseline scenario overcharging occurred at a fleet of 20 EVs, justifying the general concern about overcharging caused by a future large-scale integration of EVs [9, 17].

There are several synergy advantages possible for this scenario. First, production costs of electricity could be decreased. The electricity costs of interest arise in four categories: reduce costs in fluctuations of demand that traditionally have to be mitigated by conventional coal- and/or gasplants; preventing temporary stops of renewable energy sources; preventing or delaying investments in peakload capacity; control discrepancies in supply and demand of electricity. Second, cost savings could be generated by preventing investments in grid reinforcement. Lastly, an increase in the number of EVs and solar-PV could be achieved due to mutual benefits [15].

8.2 Limitations Dutch Electricity Market on Benefits

The costs of charging an EV at home consist of roughly two components. The raw electricity price and the taxes. The raw electricity price is between €0,05/kWh and €0,10/kWh. The taxes on electricity for charging are over 100% of the raw electricity price. Charging an EV thus results in a price of around €0,23/kWh. If the EV discharges for V2G, the electricity taxes are not restituted. When the vehicle then has to charge again, the electricity taxes have to be paid again as well. Take for example this scenario: During the night a vehicle with a battery capacity of 10 kWh charges for a price of €0,04/kWh and has to pay taxes accounting for €0,12/kWh. Including the general BTW taxes, the EV owner charges for a total amount of €1,94. During the day the EV owner sells 10 kWh for a price of €0,10/kWh. The EV owner receives €1,00. Even though the EV owner sells the electricity for 250% of the original acquisition price, the EV owner does not make a profit due to the taxes. Only when the taxes on electricity are restituted by selling electricity to grid using e.g. V2G, this form of flexibility is economically interesting. In short, when the normal raw electricity price €0,06/kWh drops to €0,03/kWh, a decrease of 100%, the total electricity price including taxes only drops by 17% [15].

In the analysis a price of €0,10/kWh was assumed in accordance with Hoogvliet, et al. (2017). Even though by using the upper bound of the raw electricity price, benefits of providing RRP down are higher, the benefits of using the lower bound of the electricity price results in higher estimates of the potential benefits that could be made with V2G. The benefits for the V2G scenario when the lower bound, €0,05/kWh, is used for the normal electricity price can be found in Table 12. The reason for the increase in benefits for a lower electricity price is that more RRP up can be provided. The bid price of RRP up depends partly on the normal electricity price. For SC on the other hand, the benefits decrease, as the benefits that could be made using RRP down is smaller.

	Tesla	ZOE	Leaf	Outlander	V60	Golf
Profits baseline	-€0,77	-€1,17	-€1,14	-€0,34	-€0,32	-€0,25
Benefits V2G	€2.74	€2,59	€0,92	€0,16	€0,11	-€0,03
Times RRP down provided	16	19	21	20	20	20
Times RRP up provided	8	8	8	8	8	8
Benefits SC	-€0,08	-€0,18	-€0,07	-€0,44	-€0,46	-€0,48
Times RRP down	14	20	19	18	16	17

Table 12: Overview of benefits for the first weekday of autumn 2017 (25/26-09) using a normal electricity price of €0,05/kWh

Moreover, the RRP market has a limited amount of RRP available at settlement prices that comply with the profitability requirements. The economically interesting RRP up and down settlement prices in 2014 coincide with RRP up and down capacities of 45,8 GW and 167,7 GW respectively. In 2015 this was 67 GW and 182 GW. About 30.000 EVs or 60.000 PHEVs are enough to saturate the market [17]. Considering that there are about 25.000 EVs and 100.000 PHEVs [30] the RRP can already be saturated if every EV and PHEV participates in SC or V2G.

Another limitation of the Dutch electricity market also discussed in Section 4.2 is the requirement of symmetrical bids in the RRP market. If SC is also adopted by an aggregator, it has significantly more capacity for RRP down bids than for RRP up bids. The capacity of RRP down bids is limited by the capacity of RRP up bids though. In the IDM this requirement does not hold. Therefore, the intraday market has great potential for aggregators in the Netherlands. The IDM is also expected to grow in capacity as a result of the increase of renewable energy sources, See section 4.1.6.

8.3 Centralized Controller

The use of a centralized controller was required in order to oblige to several market constraints. The market constraints could not be met by one single EV, instead a large number of EVs should be aggregated in order to meet these requirements. However, the computing time also increases as the problem is growing. The problem is growing when the number of vehicles increases. In this research the simulation is performed for 6 different vehicles, i.e. a problem set of 6 vehicles. However, as discussed previously, 6 vehicles is not a realistic number for an aggregator. An aggregator should have around 10.000 vehicles to oblige by market constraints. In order to give an estimation about the computing times for such a problem set, a relation between the computing time and number of vehicles is desired. This relation turns out to be linear, as can be seen in Figure 53. For 10.000 vehicles the computation time would then be 15.000 minutes. It should be noted that this calculation time is based on the simulation of one complete day, and not one singular bid. As the relation turns out to be linear, it is also expected that the computation time required for each bid is equal. Therefore, the time it takes to make one bid is roughly 150 minutes, as there are 96 bidding periods in a day.

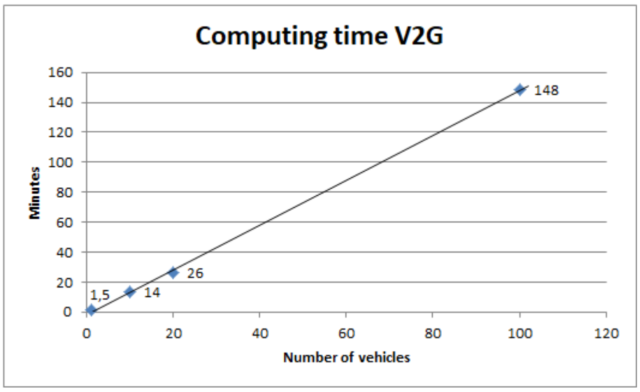

Figure 53: Relation between the number of vehicles and the computing time for a day

A computation time of 150 minutes per bid is undesirable considering the bidding horizon of 15 minutes. Several solutions could be implemented in order to reduce to computing time. First of all, a faster computer could be used. Second, the simulation was not designed for speed but for accuracy. In practice, speed is also an important consideration for the design of the optimization problem. Another solution could be a distributed controller. A distributed controller is able to run the simulation for a single EV disregarding the market constraints likewise the subproblems in Section 7.2.1. If per EV an optimal bid is made, the market constraints could be met by simply making the bids for RRP up and down equal and integer. This would however, require a more complicated dispatching algorithm, as not all spare capacity is bid. A weighted dispatching algorithm could be used, taking into account the costs of degradation, incitement, and also the freedom of the EV to provide RRP. The freedom of an EV is related to the difference between the SOC and the battery capacity as well as the SOC and the required SOC. The higher the differences between these two factors, the more freedom an EV has regarding RRP provision. The design of such a weighted dispatching algorithm was outside the scope of this research though.

8.4 EV Owner Preferences

EV owners are of major importance for the implementation of SC and V2G. Therefore, the EV owners' preferences and characteristics should be respected. The characteristics are mostly related to the EV itself, e.g. battery capacity and connection power, where the EV owner's preference is associated to for instance required SOC and type of charging. The differences of these characteristics and preferences have been tested. However, many other situations than tested in the sensitivity analysis with varying preferences and characteristics exist. In [17] and [29] for instance, the effect of different driving patterns is simulated. In these studies also weekends are simulated. This research only tested regular weekdays, with weekday commuting characteristics.

The survey analysis indicated that EV owners require incitement compensation for their extra efforts and longer charging times. For EV owners it is important that the benefits they receive from providing SC or V2G services outweigh the perceived barriers [38] [16]. The monetary benefits showed that for V2G profits can be made for EVs, but barely for PHEVs. For SC the profits for EVs decrease by more than 50%. The decrease of more than 50% for SC can be assigned to the insights from the survey that EV owners required more than 50% of the incitement compensation whereas it was explicitly stated that only 50% of the benefits could be attained by SC in comparison to V2G. This could indicate that the incitement compensation required by the EV owners is higher than the amount an aggregator could economically provide.

In order to make EVs in SC and PHEVs in both SC and V2G profitable, the incitement compensation should be reduced. One option could be to improve the perceived extra efforts by an EV owner. As the incitement compensation is related to the perceived extra efforts, the extra effort should be decreased. Another option is to improve the awareness about the extra efforts, perhaps the perceived extra efforts is higher than the actual extra efforts.

The incitement compensation however, does decrease the driving costs of an EV per km. The results of the survey indicated that for consumers looking to buy a new vehicle, whether it is gasoline or EV, the acquisition price is a major consideration. As the incitement compensation provides some cash back to the consumer, an EV might become more financially attractive. However, the questions of the survey were not aimed to see whether SC or V2G could help sell EVs, therefore this conclusion cannot be drawn. The questions in this survey were aimed at getting insights about whether people who already own an EV are willing to participate in SC or V2G. However, it provides some insight into why there are only few respondents who own an EV. If the investment price per km of an EV could decrease due to SC or V2G profits, an EV might become more interesting for consumers who are considering to buy a new vehicle. In [28] they also evaluated whether V2G could help sell EVs using the data from a survey aimed at people who already own an EV and whether they are willing to participate in SC or V2G. This survey had a contractual V2G agreement, and concluded that the V2G could not help EVs to enter the market, as the perceived inconvenience costs associated to V2G-contractual outnumbered the potential benefits of V2G.

Privacy concerns for the EV owner could arise as an aggregator is continuously monitoring the EV's identity or characteristics and location. The privacy concerns regard leakage of this information. Using this data personal the activities of the EV owner can be easily deduced [48]. In this same article, a secure and privacy-preserving communication and precise reward architecture for V2G networks is proposed, the P^2 framework. This should decrease EV owner reluctance to participate in SC or V2G due to privacy concerns.

8.5 Business EV fleet

The before discussed EV owners related to consumer who privately owned an EV. Focusing solely on EV owners who privately own an EV disregards the potential of the business EV fleet. There are two types of business EV fleet distinguished, the normal EVs such as the Tesla and ZOE under lease contract, and electric delivery trucks and vans that are used for businesses. Normal EVs under lease contract could be used under V2G-contractual. In the lease contract an aggregator could also discuss contractual commitment to SC or V2G. V2G-contractual has the advantage over V2G-flexible that an aggregator has a more reliable EV fleet battery capacity.

For the heavy duty electric delivery trucks and vans it is often desired to come with bi-directional equipment to use as a backup power source at warehouses and businesses regardless of V2G. This eliminates the requirement of high investment costs in order to enable V2G. From a business prospective, if it is more profitable to replace the battery more frequently due to V2G operation, therefore it will not be an inconvenience, but a welcome opportunity [35].

8.6 Practical Considerations Regarding Implementation

In this study multiple costs for the aggregator were taken into account, including the incitement costs, degradation costs and regular charging costs. Despite efforts to make the benefits as realistic as possible, one cost function was left out, the investment costs. In Chapter 5 the importance of investment costs were discussed. Currently, the precise height of the investment costs are unknown, and is therefore left out. The investment costs are required to ensure bi-directional electricity flow. For this instance, both the battery [35] and the charging facilities [17] have to be replaced or updated. The investment costs are a form of fixed costs, and could be depreciated over the years. As the investment costs are fixed, benefits obtained in the simulation are indifferent whether or not these costs are considered. The height of the investment costs should not be higher than the monetary benefits accumulated for the number of years the investment is functional.

Moreover, even though the EV owners are compensated for the cost of degradation, they will have to replace their batteries more frequently as a consequence of V2G. This is an inconvenience the EV owners may not want to deal with [35, 36].

9 Conclusion

In short, this study contributed to the research on maximizing profits for an aggregator in the Netherlands providing SC and V2G services taking into account several practical limitations. This study provides an exploration of potential benefits EVs could generate by providing RRP. The practical limitations were among others: realistic degradation costs, EV owner preferences, physical limitations, incitement compensation and bidding horizon. The incitement compensation was examined using a survey as the height and details of an incitement compensation were unknown. The bidding horizon, required to oblige by market constraints, was also not researched for the Dutch electricity market yet. The advantages and disadvantages of this study are:

Advantages:
- Usage of a bidding horizon
- Consideration of realistic degradation costs
- Consideration and first exploration of realistic incitement compensations
- Explicit distinction between SC and V2G
- Usage of MPC

Disadvantages:
- No consideration of investment costs
- No simulation for a realistic scenario with thousands of EVs
- Small respondents group in the survey
- No consideration for the goal of the TSO
- No consideration of the IDM

Finally, a short description of the answer for the main research question is provided.

- RQ: *How can profits for an aggregator in the Netherlands, using the V2G and SC concepts, be maximized considering practical limitations?*

For an aggregator in the Netherlands, the profits could be maximized using a profit maximization algorithm that evaluates the potential bid size of each EV in order to make optimal bids in the electricity markets of RRP and IDM. The profit of an aggregator is limited by the degradation costs, investment costs, and incitement costs, which encompass the practical consideration. The potential bid size of each EV also depends on several physical limitations. The range of benefits for an aggregator in the Netherlands under normal circumstances for V2G are between -€14,60 and €773,80; and for SC between -€120,45 and €244,55.

9.1 V2G versus SC

Benefits depend greatly on the type of EV and type of charging. It can be verified that EVs are profitable, PHEVs on the other hand are barely, if at all, profitable. The type of charging, i.e. SC or V2G, has a great impact on the profits as well. SC generates a significantly lower benefit than V2G. Moreover, the RRP market requires symmetrical bidding, which makes the SC type of charging even more undesirable for an aggregator. Concluding, in the Netherlands when only bidding in the RRP market, in order to maximize profits an aggregator could best use only V2G, as the bids are limited by the capacity available for a RRP up bid. If SC and V2G are combined, the charging times per EV will increase as not all capacity for RRP down can be bid. It should be noted that the investments costs for V2G are not considered in this comparison. If investment costs are lower than €200,- per year than each EV remains more profitable in the V2G scenario than in the SC scenario. If investment costs exceed €200,- per year than it depends on the type of EV whether the investments are sound.

9.2 Future Work

This research focused on the RRP market. The intraday market is suitable for SC and V2G as well though. Due to time considerations, this work could not implement both the RRP market and IDM in a simulation. The profit maximization algorithm for IDM has been developed. Future work could focus on simulating RRP and IDM simultaneously. The IDM will become more important in the future as the unpredictability of supply increases by the increase of renewable energy sources. Moreover, the IDM could be important for the profit of an aggregator since the IDM does not require a symmetric bid. In this way, SC is still a sound charging strategy for EV owners and aggregators. Besides, the IDM has a lower minimum bid constraint. The remaining excess capacity an aggregator that could not be bid in the RRP market due to SC and the integer constraint could be used for a bid in the IDM. For aggregators the OTC market might be interesting as well. Details of this market are unknown for outsiders, but real-life aggregators could perhaps get access to this information.

In this research a centralized controller was adopted, due to the market constraints for RRP. Nevertheless, a decentralized controller could be more useful in practice as the computational times for a centralized controller increases significantly if the problem grows. By adopting a decentralized controlling this increase in computing time could be prevented or at least mitigated. Implementation of a decentralized controller would require a more complicated dispatching algorithm though. The weighted dispatching algorithm should take into consideration the freedom an EV has (the difference between battery capacity and SOC, and the difference between SOC and the required SOC), the degradation costs, and the incitement costs.

The final suggestion for future work is related to the survey. In this thesis, the purpose of the survey was a first exploration to obtain a rough estimation of the height of the incitement compensations. The survey however, was not designed to provide a definitive value for the height of the incitement compensation. Moreover, the respondents group does not fully reflect the complete Netherlands, as only 83 people participated. Additional attempts should be made in order to overcome the social barriers associated to the socio-technical system of V2G and SC to achieve a widespread public acceptance.

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A Bidding Procedure RRP

The procedure an aggregator in the Netherlands should follow in order to make a valid bid.

The diagram below shows the structure of the messages of RRP submitted by the suppliers:

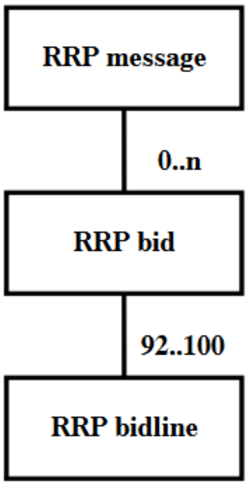

Figure 54: Bidding messages sequence

The RRP bidder is required to confer values upon the following attributes in its RRP message:

Attribute	*Unit*	*Description*	*Permissible values*
Supplier	N/A	Identification of the RRP supplier	EAN code
PRP	N/A	Identification of the PRP (Programme Responsible Party) whose imbalance will be adjusted on activation.	EAN code
Request	N/A	If the message is submitted at TenneT's request, the TenneT-issued request number must be included	TenneT-issued request number
Date of delivery	N/A	The date for which the bids relate	Date in the range[1] current and current + 7 days

Figure 55: Attributes of RRP message

Each bid in the RRP message is specified through the following attributes:

Attribute	***Unit***	***Description***	***Permissible values***
Contract	N/A	Identification of the contract between the supplier and TenneT	TenneT-issued contract number comprising 10 alphanumerical characters
Reference	N/A	Bidder-issued unique identification of the bid as part of the message	bidder's choice
Object	N/A	An object enables a bidder to couple two bids. From an Object only one bid can be activated.	bidder's choice
Activation time	PTU	Minimum PTU interval relative to current for which Bid is available to be activated by TenneT; distinguishes Regulating Power, Reserve Power Balancing, Reserve Power Other purposes	Integer value in the 0 to 672 range[1] (7 days) Regulation Power (contracted/not contracted Activation Time = 0 Reserve Power Balancing Activation Time = 1, 2, 3, 4 Reserve Power Other purposes Activation Time ≥ 5
Activation Duration	PTU	Minimum number of consecutive PTU's for admissible activation by TenneT	Integer value 1 or in the range 0 to 672 range[1] (7 days) Regulation Power (contracted/not contracted Reserve Power Balancing Activation Duration = 1 Reserve Power Other purposes Activation duration ≥ 4
Power	MW	Bidsize + upward - downward	Upward: Integer in range[1] 4 to 200 Downward: Integer in range[1] -4 to -200
Regulation rate	% per minute	Regulation rate, as percentage of bidsize per minute	One decimal place, value in the range[1] 7.0 to 100.0
Location/Grid object	N/A	A connection, or set of connections, within the Dutch high-voltage grid, from which bidder will dispatch on activation. This connection or set of connections belongs to one owner or administrator.	EAN code

Figure 56: Attributes of RRP bid

Each PTU on the date of delivery for which the bid is available must be specified.

Attribute	***Unit***	***Description***	***Permissible values***
Availability	PTU	PTU number for which bid applies	Unique Integer value in range[1] 1 to 100, ascending
Bid price	€/MWh	Energy price	Two decimal places Value in the range[1] –100,000.00 to +100,000.00

Figure 57: Attributes of RRP bidline

B Survey

B.1 Survey Design

In the Section the survey conducted among 83 respondents is provided. This survey is in Dutch. The survey is used to obtain a realistic estimation of the incitement compensation. The results of the survey are discussed in Chapter 7.

Intro

Dankuwel dat u mee wilt doen aan dit onderzoek.

Dit onderzoek is bedoeld om inzicht te krijgen in waarom mensen voor een elektrische auto kiezen, en om te kijken of de batterij in de elektrische auto ook gebruikt kan worden voor de opslag en levering van elektriciteit.

Populatie

Question 1 Geslacht

- Man
- Vrouw

Question 2 Leeftijd

Waarden

Question 3

Hieronder beschrijven wij verschillende personen. Voor elke persoon beschrijven wij wat er erg belangrijk voor ${e://Field/G2} is in het leven. Wij willen u vragen elke beschrijving te lezen en aan te geven in welke mate deze persoon op u lijkt. De betekenis van de scores is als volgt:

1 betekent dat de persoon **helemaal niet** op u lijkt; en
7 betekent dat de persoon **heel sterk** op u lijkt.
Hoe hoger het cijfer, **hoe meer** de beschreven persoon op u lijkt.

Probeer zoveel mogelijk **onderscheid** te maken in uw antwoorden door zoveel mogelijk **verschillende cijfers** te gebruiken. De beschrijving van de persoon die het meest op u lijkt, zou dus het hoogste cijfer moeten krijgen. De beschrijving van de persoon die het minst op u lijkt, het laagste.

	Lijkt helemaal niet op mij 1	2	3	4	5	6	Lijkt heel sterk op mij 7
Het is belangrijk voor ${e://Field/G2} om te genieten van de mooie dingen in het leven.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om controle te hebben over wat andere mensen doen.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om gezag te hebben over anderen.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om invloedrijk te zijn.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om geld en bezittingen te hebben.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om dingen te doen die ${e://Field/G1} fijn vindt.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om milieuvervuiling te voorkomen.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} dat iedereen dezelfde kansen krijgt.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om het milieu te beschermen.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om zorg te dragen voor mensen die minder goed af zijn.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om plezier te hebben.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om zich verbonden te voelen met de natuur.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om behulpzaam te zijn en het welzijn van anderen te verbeteren.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om respect te hebben voor de natuur.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} om hard te werken en ambitieus te zijn.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} dat iedereen rechtvaardig behandeld wordt.	○	○	○	○	○	○	○
Het is belangrijk voor ${e://Field/G2} dat er geen oorlog en conflict is.	○	○	○	○	○	○	○

Motivatoren voor auto

Question 4

Hoe zou u een auto met benzine motor omschrijven?

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Duur	○	○	○	○	○	○	○
Goed voor het milieu	○	○	○	○	○	○	○
Lange levensduur	○	○	○	○	○	○	○
Hoge actieradius	○	○	○	○	○	○	○
Hoge topsnelheid en acceleratie	○	○	○	○	○	○	○
Hoog rijgemak	○	○	○	○	○	○	○
Statusgevend	○	○	○	○	○	○	○

Question 5

Hoe zou u een elektrische auto omschrijven?

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Duur	○	○	○	○	○	○	○
Goed voor het milieu	○	○	○	○	○	○	○
Lange levensduur	○	○	○	○	○	○	○
Hoge actieradius	○	○	○	○	○	○	○
Hoge topsnelheid en acceleratie	○	○	○	○	○	○	○
Hoog rijgemak	○	○	○	○	○	○	○
Statusgevend	○	○	○	○	○	○	○

Elektrische auto ja of nee

Question 6

Bent u in het bezit van een auto?

○ Ja
○ Nee

Question 7

Bent u in het bezit van een elektrische auto of plug-in hybrid?

○ Ja
○ Nee

Question 8

Waar let u op bij het aanschaffen van een auto?

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Prijs	○	○	○	○	○	○	○
Milieu overwegingen	○	○	○	○	○	○	○
Levensduur	○	○	○	○	○	○	○
Actieradius	○	○	○	○	○	○	○
Topsnelheid en acceleratie	○	○	○	○	○	○	○
Rij gemak	○	○	○	○	○	○	○
Status	○	○	○	○	○	○	○

Question 9

Ik leg mijn auto normaliter enkel aan de oplader om de auto volledig op te laden en dus niet voor een langere tijd of wanneer dit niet nodig is (bijv. als de batterij al vol genoeg is).

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

V2G concept

Stel u bent in het bezit van een elektrische auto.

Elektrische auto's hebben batterijen om elektrisch rijden mogelijk te maken. Maar een auto wordt gemiddeld maar 1 uur per dag gebruikt. In de 23 uur dat de auto niks doet of stil staat kan de auto gebruikt worden om het elektriciteitsnet te stabiliseren. De batterijen van een elektrische auto kunnen gebruikt worden om elektriciteit op te slaan EN terug te geven aan het net om zo de productie en vraag gelijk te maken. Dit is het V2G-concept (Vehicle-to-Grid). Met SO (Slim Opladen) wordt de batterij alleen gebruikt om elektriciteit op te slaan en dus NIET om terug te geven.

Omdat één auto maar een beperkte capaciteit heeft, zullen er veel auto's gekoppeld moeten worden om een grote opslag te vormen. Dit is de taak van aggregator.

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V2G vragen

Question 10

Ik ben bereid deel te nemen aan V2G (Vehicle-to-Grid) zoals hiervoor uitgelegd.

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Question 11

Ik ben bereid deel te nemen aan SO (Slim Opladen) zoals hiervoor uitgelegd.

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Question 12

Ik ben bereid om mijn auto zo lang als mogelijk aan de oplader te leggen om deze op te laden en om V2G of SO mogelijk te maken.

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Compensatie concept

Er wordt nagedacht over een compensatie voor de deelnemers aan V2G (Vehicle-to-Grid) en SO (Slim Opladen). De hoogte van de compensatie en de voorwaarden hiervoor moeten nog bepaald worden.

Er zijn 2 verschillende compensaties, afschrijvingscompensatie en motivatiecompensatie.

De afschrijvingscompensatie is bedoeld om de afschrijvingskosten van de batterij te vergoeden. Afschrijvingskosten van de batterij worden veroorzaakt op het moment dat de batterij van de auto extra belast wordt door het gebruik van V2G. SO heeft geen afschrijvingscompensatie omdat de batterij niet extra belast wordt.

De motivatiecompensatie is bedoeld om u te motiveren de auto zo lang als mogelijk aan de oplader te leggen. Hoe langer de auto aan de oplader ligt hoe langer een aggregator de batterij kan gebruiken om het elektriciteitsnetwerk te stabiliseren. De motivatiecompensatie geldt voor zowel V2G als SO.

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Compensatie vragen

Question 13

Als V2G (Vehicle-to-Grid) de batterij extra belast verwacht ik afschrijvingscompensatie voor de afschrijvingskosten.

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Question 14

Ik verwacht een afschrijvingscompensatie aan de hand van het aantal uur dat:

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Ik mijn auto beschikbaar stel	○	○	○	○	○	○	○
Mijn auto daadwerkelijk wordt gebruikt	○	○	○	○	○	○	○
Beide	○	○	○	○	○	○	○

Question 15

Ik ben bereid om mijn auto zo lang als mogelijk aan de oplader te leggen om deze op te laden en om V2G of SO (Slim Opladen) mogelijk te maken, als ik hiervoor een motivatiecompensatie ontvang

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Question 16

Ik verwacht een motivatiecompensatie aan de hand van het aantal uur dat:

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Ik mijn auto beschikbaar stel	○	○	○	○	○	○	○
Mijn auto daadwerkelijk wordt gebruikt	○	○	○	○	○	○	○
Beide	○	○	○	○	○	○	○

Beschikbaarheid

Om de elektriciteitsmarkt te stabiliseren moet een aggregator (de instantie die vele auto's koppelt om één grote opslag te creëren) van tevoren aangeven hoeveel capaciteit hij tot zijn beschikking heeft. Omdat het gebruik van een auto moeilijk te voorspellen is, is het in het belang van een aggregator nodig om te weten of een auto beschikbaar is of niet. Om te weten of en hoe lang een aggregator gebruik kan maken van uw batterij zijn er 3 mogelijkheden.

1. Flexibel Opladen - De auto wordt minstens 24 uur niet gebruikt, de batterij kan lang gebruikt worden voor V2G of SO en dit resulteert in hogere compensaties dan Normaal Opladen. De batterij is opgeladen voor de volgende trip.

2. Normaal Opladen - De auto wordt normaal gebruikt, de batterij kan gebruikt worden voor V2G of SO en resulteert in compensaties. De batterij is opgeladen voor de volgende trip.

3. Prioriteit Opladen - De auto wordt zo snel mogelijk gebruikt, en de batterij kan niet gebruikt worden voor V2G of SO en resulteert in geen compensaties. De batterij wordt zo snel mogelijk opgeladen.

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Beschikbaarheid vragen

Question 17

Hoe lang bent u bereid van tevoren aan te geven wanneer u zult vertrekken?

90 minuten	75 minuten	60 minuten	45 minuten	30 minuten	15 minuten	Niet
○	○	○	○	○	○	○

Question 18

Ik ben bereid aan te geven of ik Flexibel, Normaal of Prioriteit wil opladen

Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
○	○	○	○	○	○	○

Question 19

Tot hoe ver zou uw auto opgeladen moeten zijn als u begint aan een normale trip?

40-50%	50-60%	60-70%	70-80%	80-90%	90-100%	100%
○	○	○	○	○	○	○

Question 20

In welke mate zijn de onderstaande redenen om niet deel te nemen op u van toepassing?

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Privacy overwegingen	○	○	○	○	○	○	○
Extra moeite	○	○	○	○	○	○	○
Geen behoefte aan	○	○	○	○	○	○	○
Kan ik niet aangeven omdat ik dit niet weet	○	○	○	○	○	○	○

V2G compensatie

Question 21

Met V2G-flexibel (Vehicle-to-Grid) wordt uw auto gebruikt om het elektriciteitsnet te stabiliseren door energie af te nemen en aan te leveren. Het zal dus langer duren voordat uw auto volledig opgeladen is, maar de auto zal voor de volgende trip opgeladen zijn. De auto kunt u naar eigen voorkeur blijven gebruiken.

Omdat de hoogte van de motivatiecompensatie af hangt van het aantal uur dat de auto gebruikt wordt/beschikbaar is, zal deze motivatiecompensatie van toepassing zijn als gedurende een jaar de auto gemiddeld 20 uur per dag aan de oplader ligt. Dit bedrag krijgt u naast de afschrijvingscompensatie. Hoe hoog zou de motivatiecompensatie minstens moeten zijn zodat u gebruik zult maken van V2G-flexibel? Dit bedrag is de motivatiecompensatie voor een heel jaar.

0 50 100 150 200 250 300 350 400 450 500

€/jaar

Question 22

Bij V2G-contractueel geldt hetzelfde als voor V2G-flexibel behalve voor het gebruik van de auto. Bij V2G-contractueel bent u verplicht uw auto elke dag 20 uur per dag aan de oplader te leggen.

Hoe hoog zou de motivatiecompensatie minstens moeten zijn zodat u gebruik zult maken van V2G-contractueel? Dit bedrag is de motivatiecompensatie voor een heel jaar.

0 50 100 150 200 250 300 350 400 450 500

€/jaar

Question 23

Bij SO (Slim Opladen) geldt hetzelfde als voor V2G-flexibel behalve dat de auto alleen wordt opgeladen en dus niet wordt afgeladen. Hierdoor kan er maar de helft van het voordeel behaald worden als bij V2G.

Hoe hoog zou de motivatiecompensatie minstens moeten zijn zodat u gebruik zult maken van SO? Dit bedrag is de motivatiecompensatie voor een heel jaar.

	0	50	100	150	200	250	300	350	400	450	500
€/jaar											

Question 24

Waarvoor zou u de motivatiecompensatie willen krijgen?

	Helemaal mee oneens 1	2	3	4	5	6	Helemaal mee eens 7
Lagere flexibiliteit	○	○	○	○	○	○	○
Langere oplaadtijd	○	○	○	○	○	○	○
De extra moeite	○	○	○	○	○	○	○
Extra inkomsten	○	○	○	○	○	○	○

Afsluiting

Bedankt voor het invullen van mijn vragenlijst en hierbij deel te nemen aan mijn onderzoek!

B.2 Survey Results

In this Section the SPSS outputs of the different statistical test are presented. The interpretation is discussed in Chapter 7.

Bivariate Correlation - Hypothesis 1 and 3

Correlations

		Willingness to participate in V2G -Q10	Willingness to participate in SC - Q11	Willingness to participate in V2G or SC if an incitement compensation is received - Q15	I expect a degradation compensation for V2G - Q13	I expect a degradation compensation for the availability - Q14a	I expect a degradation compensation for the usage - Q14b	I expect a degradation compensation for both - Q14c
Willingness to participate in V2G -Q10	Pearson Correlation	1	,754**	,440**	,244*	0,063	0,208	0,135
	Sig. (2-tailed)		0,000	0,000	0,027	0,576	0,063	0,229
	N	83	83	82	82	81	81	81
Willingness to participate in SC - Q11	Pearson Correlation	,754**	1	,434**	,353**	0,136	,295**	0,133
	Sig. (2-tailed)	0,000		0,000	0,001	0,225	0,007	0,236
	N	83	83	82	82	81	81	81
Willingness to participate in V2G or SC if an incitement compensation is received - Q15	Pearson Correlation	,440**	,434**	1	,465**	,296**	,368**	,222*
	Sig. (2-tailed)	0,000	0,000		0,000	0,007	0,001	0,046
	N	82	82	82	82	81	81	81
I expect a degradation compensation for V2G - Q13	Pearson Correlation	,244*	,353**	,465**	1	,306**	,473**	,263*
	Sig. (2-tailed)	0,027	0,001	0,000		0,006	0,000	0,018
	N	82	82	82	82	81	81	81
I expect a degradation compensation for the availability -	Pearson Correlation	0,063	0,136	,296**	,306**	1	-0,039	,482**
	Sig. (2-tailed)	0,576	0,225	0,007	0,006		0,728	0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for the usage - Q14b	Pearson Correlation	0,208	,295**	,368**	,473**	-0,039	1	,590**
	Sig. (2-tailed)	0,063	0,007	0,001	0,000	0,728		0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for both - Q14c	Pearson Correlation	0,135	0,133	,222*	,263*	,482**	,590**	1
	Sig. (2-tailed)	0,229	0,236	0,046	0,018	0,000	0,000	
	N	81	81	81	81	81	81	81

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 58: SPSS output bivariate correlation between willingness to participate in V2G or SC and incitement compensation

Correlations								
		Willingness to participate in V2G -Q10	Willingness to participate in SC - Q11	Willingness to participate in V2G or SC if an incitement compensation is received - Q15	I expect a degradation compensation for V2G - Q13	I expect a degradation compensation for the availability - Q14a	I expect a degradation compensation for the usage - Q14b	I expect a degradation compensation for both - Q14c
Willingness to participate in V2G -Q10	Pearson Correlation	1	,754**	,440**	,244*	0,063	0,208	0,135
	Sig. (2-tailed)		0,000	0,000	0,027	0,576	0,063	0,229
	N	83	83	82	82	81	81	81
Willingness to participate in SC - Q11	Pearson Correlation	,754**	1	,434**	,353**	0,136	,295**	0,133
	Sig. (2-tailed)	0,000		0,000	0,001	0,225	0,007	0,236
	N	83	83	82	82	81	81	81
Willingness to participate in V2G or SC if an incitement compensation is received - Q15	Pearson Correlation	,440**	,434**	1	,465**	,296**	,368**	,222*
	Sig. (2-tailed)	0,000	0,000		0,000	0,007	0,001	0,046
	N	82	82	82	82	81	81	81
I expect a degradation compensation for V2G - Q13	Pearson Correlation	,244*	,353**	,465**	1	,306**	,473**	,263*
	Sig. (2-tailed)	0,027	0,001	0,000		0,006	0,000	0,018
	N	82	82	82	82	81	81	81
I expect a degradation compensation for the availability - Q14a	Pearson Correlation	0,063	0,136	,296**	,306**	1	-0,039	,482**
	Sig. (2-tailed)	0,576	0,225	0,007	0,006		0,728	0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for the usage - Q14b	Pearson Correlation	0,208	,295**	,368**	,473**	-0,039	1	,590**
	Sig. (2-tailed)	0,063	0,007	0,001	0,000	0,728		0,000
	N	81	81	81	81	81	81	81
I expect a degradation compensation for both - Q14c	Pearson Correlation	0,135	0,133	,222*	,263*	,482**	,590**	1
	Sig. (2-tailed)	0,229	0,236	0,046	0,018	0,000	0,000	
	N	81	81	81	81	81	81	81

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 59: SPSS output bivariate correlation between willingness to participate in V2G or SC and degradation compensation

Correlations

		Willingness to participate in V2G -Q10	Willingness to participate in SC - Q11	Willingness to participate in V2G or SC if an incitement compensation is received - Q15	I am willing to indicate charging type - Q18
Willingness to participate in V2G -Q10	Pearson Correlation	1	,754**	,440**	,277*
	Sig. (2-tailed)		0,000	0,000	0,013
	N	83	83	82	80
Willingness to participate in SC - Q11	Pearson Correlation	,754**	1	,434**	,310**
	Sig. (2-tailed)	0,000		0,000	0,005
	N	83	83	82	80
Willingness to participate in V2G or SC if an incitement compensation is received - Q15	Pearson Correlation	,440**	,434**	1	,485**
	Sig. (2-tailed)	0,000	0,000		0,000
	N	82	82	82	80
I am willing to indicate charging type - Q18	Pearson Correlation	,277*	,310**	,485**	1
	Sig. (2-tailed)	0,013	0,005	0,000	
	N	80	80	80	80

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 60: SPSS output bivariate correlation between willingness to participate in V2G or SC and willingness to indicate charging type

Bivariate Correlation - Hypothesis 2

Correlations								
		Hed	Ego	Alt	Bio	Willingness to participate in V2G -Q10	Willingness to participate in SC - Q11	Willingness to participate in V2G or SC if an incitement compensation is received - Q15
Hed	Pearson Correlation	1	,354**	,230*	0,130	0,100	0,209	,283*
	Sig. (2-tailed)		0,001	0,037	0,243	0,368	0,058	0,010
	N	83	83	83	83	83	83	82
Ego	Pearson Correlation	,354**	1	0,024	0,145	0,135	,273*	0,086
	Sig. (2-tailed)	0,001		0,829	0,192	0,225	0,013	0,443
	N	83	83	83	83	83	83	82
Alt	Pearson Correlation	,230*	0,024	1	,332**	,227*	,276*	0,157
	Sig. (2-tailed)	0,037	0,829		0,002	0,039	0,012	0,158
	N	83	83	83	83	83	83	82
Bio	Pearson Correlation	0,130	0,145	,332**	1	0,157	,290**	0,074
	Sig. (2-tailed)	0,243	0,192	0,002		0,156	0,008	0,510
	N	83	83	83	83	83	83	82
Willingness to participate in V2G -Q10	Pearson Correlation	0,100	0,135	,227*	0,157	1	,754**	,440**
	Sig. (2-tailed)	0,368	0,225	0,039	0,156		0,000	0,000
	N	83	83	83	83	83	83	82
Willingness to participate in SC - Q11	Pearson Correlation	0,209	,273*	,276*	,290**	,754**	1	,434**
	Sig. (2-tailed)	0,058	0,013	0,012	0,008	0,000		0,000
	N	83	83	83	83	83	83	82
Willingness to participate in V2G or SC if an incitement compensation is received - Q15	Pearson Correlation	,283*	0,086	0,157	0,074	,440**	,434**	1
	Sig. (2-tailed)	0,010	0,443	0,158	0,510	0,000	0,000	
	N	82	82	82	82	82	82	82

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 61: SPSS output bivariate correlation between willingness to participate in V2G or SC and the variables hedonic, egoistic, altruistic and biospheric values

Bivariate Correlation - Hypothesis 4

Correlations

		Lower flexibility - Q24a	Longer charging time - Q24b	Extra efforts - Q24c	Additional income - Q24d	Height of incitement compensation V2G-flexible - Q21	Height of incitement compensation V2G-contractual - Q22	Height of incitement compensation SC - Q23
Lower lexibility - Q24a	Pearson Correlation	1	0,071	0,019	-0,177	0,084	0,114	0,132
	Sig. (2-tailed)		0,550	0,874	0,134	0,482	0,338	0,265
	N	73	73	73	73	73	73	73
Longer charging time - Q24b	Pearson Correlation	0,071	1	,376**	-0,025	,390**	,459**	,330**
	Sig. (2-tailed)	0,550		0,001	0,831	0,001	0,000	0,004
	N	73	73	73	73	73	73	73
Extra efforts - Q24c	Pearson Correlation	0,019	,376**	1	0,188	,569**	,476**	,382**
	Sig. (2-tailed)	0,874	0,001		0,111	0,000	0,000	0,001
	N	73	73	73	73	73	73	73
Additional income - Q24d	Pearson Correlation	-0,177	-0,025	0,188	1	0,191	0,076	0,185
	Sig. (2-tailed)	0,134	0,831	0,111		0,106	0,524	0,116
	N	73	73	73	73	73	73	73
Height of incitement compensation V2G-flexible - Q21	Pearson Correlation	0,084	,390**	,569**	0,191	1	,699**	,589**
	Sig. (2-tailed)	0,482	0,001	0,000	0,106		0,000	0,000
	N	73	73	73	73	73	73	73
Height of incitement compensation V2G-contractual - Q22	Pearson Correlation	0,114	,459**	,476**	0,076	,699**	1	,358**
	Sig. (2-tailed)	0,338	0,000	0,000	0,524	0,000		0,002
	N	73	73	73	73	73	73	73
Height of incitement compensation SC - Q23	Pearson Correlation	0,132	,330**	,382**	0,185	,589**	,358**	1
	Sig. (2-tailed)	0,265	0,004	0,001	0,116	0,000	0,002	
	N	73	73	73	73	73	73	73

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 62: SPSS output bivariate correlation between height of incitement compensation and the variables lower flexibility, longer charging time, extra efforts, and additional income

Bivariate Correlation - Hypothesis 5

Correlations								
		Hed	Ego	Alt	Bio	Height of incitement compensation V2G-flexible - Q21	Height of incitement compensation V2G-contractual - Q22	Height of incitement compensation SC - Q23
Hed	Pearson Correlation	1	,354**	,230*	0,130	,302**	0,204	,235*
	Sig. (2-tailed)		0,001	0,037	0,243	0,009	0,083	0,045
	N	83	83	83	83	73	73	73
Ego	Pearson Correlation	,354**	1	0,024	0,145	-0,122	-0,138	-0,163
	Sig. (2-tailed)	0,001		0,829	0,192	0,302	0,243	0,167
	N	83	83	83	83	73	73	73
Alt	Pearson Correlation	,230*	0,024	1	,332**	0,112	0,091	-0,038
	Sig. (2-tailed)	0,037	0,829		0,002	0,344	0,445	0,750
	N	83	83	83	83	73	73	73
Bio	Pearson Correlation	0,130	0,145	,332**	1	0,112	0,046	-0,024
	Sig. (2-tailed)	0,243	0,192	0,002		0,346	0,700	0,842
	N	83	83	83	83	73	73	73
Height of incitement compensation V2G-flexible - Q21	Pearson Correlation	,302**	-0,122	0,112	0,112	1	,699**	,589**
	Sig. (2-tailed)	0,009	0,302	0,344	0,346		0,000	0,000
	N	73	73	73	73	73	73	73
Height of incitement compensation V2G-contractual - Q22	Pearson Correlation	0,204	-0,138	0,091	0,046	,699**	1	,358**
	Sig. (2-tailed)	0,083	0,243	0,445	0,700	0,000		0,002
	N	73	73	73	73	73	73	73
Height of incitement compensation SC - Q23	Pearson Correlation	,235*	-0,163	-0,038	-0,024	,589**	,358**	1
	Sig. (2-tailed)	0,045	0,167	0,750	0,842	0,000	0,002	
	N	73	73	73	73	73	73	73

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Figure 63: SPSS output bivariate correlation between height of incitement compensation and the variables hedonic, egoistic, altruistic and biospheric values

Linear Regression - Hypothesis 2

Coefficients[a]									
		Unstandardized Coefficients		Standardized Coefficients			Correlations		
Model		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part
1	(Constant)	1,778	1,613		1,102	0,274			
	Hed	0,006	0,243	0,003	0,023	0,981	0,100	0,003	0,003
	Ego	0,177	0,176	0,118	1,004	0,318	0,135	0,113	0,109
	Alt	0,376	0,223	0,200	1,683	0,096	0,227	0,187	0,184
	Bio	0,101	0,160	0,073	0,629	0,531	0,157	0,071	0,069

a. Dependent Variable: Willingness to participate in V2G

Figure 64: SPSS output linear regression method with the dependent variable Q10 - Willingness to participate in V2G versus the variables hedonic, egoistic, altruistic and biospheric values

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part
1	(Constant)	0,039	1,459		0,027	0,978			
	Hed	0,123	0,220	0,063	0,561	0,576	0,209	0,063	0,058
	Ego	0,314	0,159	0,219	1,974	0,052	0,273	0,218	0,202
	Alt	0,352	0,202	0,194	1,742	0,085	0,276	0,194	0,179
	Bio	0,244	0,145	0,185	1,686	0,096	0,290	0,188	0,173

Coefficients[a]

a. Dependent Variable: Willingness to participate in SC

Figure 65: SPSS output linear regression method with the dependent variable Q11 -Willingness to participate in SC versus the variables hedonic, egoistic, altruistic and biospheric values

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part
1	(Constant)	0,840	1,634		0,514	0,609			
	Hed	0,544	0,247	0,264	2,205	0,030	0,283	0,244	0,240
	Ego	-0,017	0,178	-0,011	-0,096	0,924	0,086	-0,011	-0,010
	Alt	0,181	0,227	0,095	0,800	0,426	0,157	0,091	0,087
	Bio	0,010	0,165	0,007	0,060	0,952	0,074	0,007	0,007

Coefficients[a]

a. Dependent Variable: Willingness to participate in V2G or SC if an incitement compensation is received

Figure 66: SPSS output linear regression method with the dependent variable Q15 - Willingness to participate in V2G or SC when an incitement compensation is received versus the variables hedonic, egoistic, altruistic and biospheric values

Linear Regression - Hypothesis 4

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part
1	(Constant)	-16,336	68,964		-0,237	0,813			
	Lower lexibility - Q24a	6,423	7,678	0,082	0,837	0,406	0,084	0,101	0,080
	Longer charging time - Q24b	17,566	8,603	0,212	2,042	0,045	0,390	0,240	0,195
	Extra efforts - Q24c	34,971	7,964	0,464	4,391	0,000	0,569	0,470	0,420
	Additional income - Q24d	9,435	7,633	0,123	1,236	0,221	0,191	0,148	0,118

a. Dependent Variable: Height of incitement compensation V2G-flexible - Q21

Figure 67: SPSS output linear regression method with the dependent variable Q21 - Height of incitement compensation V2G-flexible versus the variables lower flexibility, longer charging time, extra efforts, and additional income

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part
1	(Constant)	93,480	66,707		1,401	0,166			
	Lower lexibility - Q24a	6,627	7,426	0,091	0,892	0,375	0,114	0,108	0,089
	Longer charging time - Q24b	24,865	8,321	0,323	2,988	0,004	0,459	0,341	0,297
	Extra efforts - Q24c	24,228	7,703	0,346	3,145	0,002	0,476	0,356	0,313
	Additional income - Q24d	2,489	7,383	0,035	0,337	0,737	0,076	0,041	0,034

a. Dependent Variable: Height of incitement compensation V2G-contractual - Q22

Figure 68: SPSS output linear regression method with the dependent variable Q22 - Height of incitement compensation V2G-contractual versus the variables lower flexibility, longer charging time, extra efforts, and additional income

Coefficients[a]									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
		B	Std. Error	Beta			Zero-order	Partial	Part
1	(Constant)	-104,158	88,333		-1,179	0,242			
	Lower lexibility - Q24a	12,724	9,834	0,141	1,294	0,200	0,132	0,155	0,138
	Longer charging time - Q24b	21,422	11,019	0,226	1,944	0,056	0,330	0,229	0,208
	Extra efforts - Q24c	22,733	10,200	0,263	2,229	0,029	0,382	0,261	0,238
	Additional income - Q24d	14,664	9,777	0,167	1,500	0,138	0,185	0,179	0,160

a. Dependent Variable: Height of incitement compensation SC - Q23

Figure 69: SPSS output linear regression method with the dependent variable Q23 - Height of incitement compensation SC versus the variables lower flexibility, longer charging time, extra efforts, and additional income

Linear Regression - Hypothesis 5

Coefficients[a]									
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
		B	Std. Error	Beta			Zero-order	Partial	Part
1	(Constant)	-26,729	153,827		-0,174	0,863			
	Hed	62,244	21,245	0,342	2,930	0,005	0,302	0,335	0,329
	Ego	-27,114	14,754	-0,214	-1,838	0,070	-0,122	-0,218	-0,206
	Alt	4,302	19,278	0,027	0,223	0,824	0,112	0,027	0,025
	Bio	11,568	13,610	0,102	0,850	0,398	0,112	0,103	0,095

a. Dependent Variable: Height of incitement compensation V2G-flexible - Q21

Figure 70: SPSS output linear regression method with the dependent variable Q21 - Height of incitement compensation V2G-flexible versus the variables hedonic, egoistic, altruistic and biospheric values

Coefficients[a]										
		Unstandardized Coefficients		Standardized Coefficients			Correlations		
Model		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part
1	(Constant)	181,620	148,060		1,227	0,224			
	Hed	41,182	20,449	0,243	2,014	0,048	0,204	0,237	0,234
	Ego	-23,412	14,201	-0,199	-1,649	0,104	-0,138	-0,196	-0,191
	Alt	6,095	18,555	0,041	0,328	0,744	0,091	0,040	0,038
	Bio	3,889	13,100	0,037	0,297	0,767	0,046	0,036	0,034

a. Dependent Variable: Height of incitement compensation V2G-contractual - Q22

Figure 71: SPSS output linear regression method with the dependent variable Q22 - Height of incitement compensation V2G-contractual versus the variables hedonic, egoistic, altruistic and biospheric values

Coefficients[a]									
		Unstandardized Coefficients		Standardized Coefficients			Correlations		
Model		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part
1	(Constant)	75,717	179,702		0,421	0,675			
	Hed	63,214	24,819	0,302	2,547	0,013	0,235	0,295	0,291
	Ego	-34,659	17,236	-0,239	-2,011	0,048	-0,163	-0,237	-0,230
	Alt	-16,102	22,520	-0,088	-0,715	0,477	-0,038	-0,086	-0,082
	Bio	1,471	15,899	0,011	0,093	0,927	-0,024	0,011	0,011

a. Dependent Variable: Height of incitement compensation SC - Q23

Figure 72: SPSS output linear regression method with the dependent variable Q23 - Height of incitement compensation SC versus the variables hedonic, egoistic, altruistic and biospheric values