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Thesis Energy Science

Assessing the monetary value and impacts of regulating- and reserve power provision by electric vehicles in Dutch urban areas.

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Abstract

Recent years have shown a significant increase in electric vehicles (EVs), which could make a significant contribution to meeting European, national and municipal energy and climate goals. However, EVs are reported to be parked for roughly 90% of the time, which makes them available for other purposes. One of these purposes is the provision of regulating- and reserve power (RRP) to the transmission system operator, a concept that can be ranked under vehicle-to-grid (V2G). The aim of this research is to determine the potential value that EVs could generate by providing RRP and identify important factors surrounding the provision of RRP. Since several large cities within the Netherlands have ambitious implementation plans for EVs the focus lies on urban areas. This research consists of three parts. Firstly, a survey was conducted on the regulation and operation surrounding the Dutch electricity infrastructure in relation to RRP provision. It was found that these were generally favorable for RRP provision by EVs. Secondly, the characteristics of the Dutch EV fleet and its users were assessed to indicate the potential for RRP provision, which led to the identification of the resident-commuter (RC)-, resident and commuter user type. Thirdly, a model was developed to simulate four commonly sold EVs in an urban area in the Netherlands under a baseline charging- and RRP dispatch scheme for one year. The results identified profit, battery throughput and state-of-charge distribution as important indicators for the performance of RRP provision. While loads on the infrastructure are impacted as well, these experience little effect under the modeled EV fleet. Depending on EV- and user type the provision of RRP resulted in net benefits in the range between €118 and €632. This is accompanied by increased battery throughput, deeper discharging of the battery and lower SOC distributions. However, the latter has little effect on the assumed trip requirements of the EV user. Subsequently, an assessment was made on the sensitivity of the results for changes in user characteristics and fleet sizes, which offered both favorable prospects and limitations. In conclusion it can be stated that the provision of RRP by EVs in the Netherlands shows promising potential and further research should be pursued.

Acknowledgements

The completion of this thesis concludes an extraordinary time of my studies, filled with peaks and valleys. Here I would like to thank some of the people who played an important role during this time.

Firstly I want to thank Hugo Niesing. Hugo heads Resourcefully, a consultancy firm aimed at innovative projects surrounding smart water and –energy use. With Hugo the first ideas regarding my graduation project took shape. Our initial aim was to assess the potential of energy storage in EVs in residential areas. Even though this project did not become my final thesis, our collaboration turned out to be more than fruitful. Over the course of the next few months we embarked on the organization of the first vehicle-to-grid conference held in the Netherlands, in collaboration with Mirjam and the University of Applied Sciences in Amsterdam. This took place in March 2014 where the idea emerged that ended up to be the thesis that lies before you. I've experienced working with Huge as a fun and inspiring experience for which I owe him much gratitude.

I found Geert Litjens willing to supervise this thesis. Geert took ample time to guide me through the process and introduced me to programming in Python, a skill I found challenging and fun to learn and of which I'm sure I will benefit from in the future. Thank you for providing me with useful feedback and motivation when I needed it and best of luck in obtaining your PhD degree!

Outside the university there were a few people who provided me with input for my research. Hannah Kamphuijs of "De Groene Bocht" allowed me to read the smart meter data that I used to construct the commercial load profiles. Frank Nobel of Tennet provided me with documentation and elaboration on the Dutch market for regulating- and reserve power. Thijs Turel from Liander supplied key figures that I could use to make assumptions regarding the distribution grid characteristics. Jop Spoelstra, Rudy van der Kolk, Bart Sloep and Matteo van der Molen provided me with important considerations regarding EVs in urban areas. Paul Codani was willing to review one of my chapters regarding the suitability of TSO rules for the provision of RRP. Thanks to all for your contribution!

I would also like to thank my family and friends for their involvement and providing the much-needed distraction. Doing fun stuff during the weekend provided plenty of energy to start again on Monday. In particular I thank Tessa, who way to often had to suffer through my complaints and nightly mulling, but nevertheless stayed supportive and motivated me to keep going.

A common practice states that one should save the best for last. It therefore obvious that here I mention my parents, who have supported my studies in all ways possible. Mom, Dad, thank you for the endless counsel and encouragement, especially during this final part of my studies (but this time: really).

Abbreviations

CF	Charging Facility
DSO	Distribution System Operator
DoD	Depth of discharge
EV (s)	Electric Vehicle(s)
FEV	Full Electric Vehicle
KPI	Key Performance Indicators
LV	Low Voltage
MV	Medium Voltage
PHEV	Plug-in Hybrid Electric Vehicle
BRP	Balance Responsible Party
REV	Range extended Electric Vehicle
RRP	Regulating- and reserve power
SOC	State Of Charge
TSO	Transmission System Operator
V2G	Vehicle-to-grid

Symbols and units

Symbol	Unit	Explanation
$E_{charged}$	kWh	Volume of electricity charged to the battery
E_{RRP}	kWh	Volume of RRP delivered
L_{aggr}	kW	Load created by households and businesses
L_{sub}	kW	Load on the substation
P_{cf}	kW	Charging facility's power output
P_{drive}	kW	EV power consumption during trips
p_{el}	€/kWh	Electricity price
p_{settle}	€/kWh	Settlement price
SOC	%	State of charge
SOC_{max}	%	EV battery's maximum state of charge
SOC_{min}	%	EV battery's minimum state of charge
SOC_{req}	%	Required state of charge at time of a trip
t_{trip}	Hours	Time until departure
Δt	Hours	Duration of time step
η_{cf}	%	Efficiency of the charging facility
η_{sub}	%	Efficiency of the substation
π	€	Profit

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1 Introduction

Supported by policy schemes, the number of electric vehicles (EVs) registered in the Netherlands increased from 6258 in 2012 to 42241 in 2014. This fleet consisted of full electric- (FEV), plug-in hybrid electric- (PHEV) and range extended electric vehicles (REV) (RVO, 2014). In combination with a renewable electricity supply these vehicles could be a promising option for a low-carbon transport sector(Liu, Hu, Lund, & Chen, 2013). However, the increase of EVs also has an impact on the grid as users currently recharge during the existing demand peaks. Eising et al (2014) assessed this problem for the coverage area of Liander in the Netherlands and concluded that the grid can face capacity problems as soon as 2015.
Additionally, stimulated by European- and national policies, the share of renewable energy in the electricity mix has risen and this trend is expected to continue for the coming years (ECN, 2014). In general, the growth of renewable energy sources is a desirable development. However, due to its intermittent nature it also creates challenges with regard to grid balancing (Hammons, 2008).

The above-described developments indicate that the grid faces challenges with respect to capacity- and balance problems due to an increasing number of EVs and renewable energy. This requires new investments to be made into the grid(BSW Solar, 2013; Verbong, Beemsterboer, & Sengers, 2013) or the provision of more ancillary services, respectively. However, the combination of these developments shows a potential solution. EVs are currently used solely for the purpose of transportation, even though they are parked for more then 90% of the time(Bates & Leibling, 2012; Kempton & Tomić, 2005a). During this time the batteries inside the EVs are available for services other than transport. In combination with smart-grid technology and depending on use and time of use, EVs could be used for ancillary services or power supply. This technology is known as vehicle-to-grid (V2G).

1.1 Previous research

The concept of using electric vehicles for power supply was first explored by Kempton & Letendre (1997). In this paper the authors outlined the potential use of electric vehicles in light of oncoming deregulation of the electricity market and the rise of intermittent, distributed electricity sources and the effects they have on the grid. EV was mostly considered to act as dedicated storage/supply technology. However, in a later article Kempton & Tomić (2005b) assessed that V2G would primarily be profitable in markets for voltage- and frequency control and spinning reserves, also referred to as “ancillary services” (Hirst & Kirby, 1996). Here relatively short charging/discharging is required, which has less adverse impacts on the battery in comparison to the earlier mentioned storage. If the number of EVs would rise and V2G markets start to saturate, then V2G would be suitable to facilitate the integration of large-scale renewable energy (see also: Fattori, Anglani, & Muliere, 2014; Knezovic et al., 2014; Liu et al., 2013).
The potential of V2G is determined by numerous factors such as, driver preferences with regards to travel patterns and associated batteries state-of-charge (SOC), charging facilities and communication between grid operator and EV owner. In Mwasilu et al. (2014) a review is provided on both the latest advancements in V2G research and on possible communication and control network designs, indicating that that V2G could be a promising solution for potential grid stability problems.
The research described above indicates that V2G is technically possible and makes economic sense in several cases. However, rules and regulations seem to be a bottleneck for large-scale deployment. Codani & Petit (2014) analysed the rules and regulations in France and concluded that EV drivers are now incapable of providing ancillary services due to the current regulatory system and are therefore missing between €193 and €593 euro per year. These values are derived by creating an simulation model inspired by the work of Kempton & Tomić (2005a).

1.2 Scope

Municipalities are making policies to stimulate a clean urban environment. For example, Amsterdam and Utrecht are prohibiting polluting vehicles in certain areas of the city (based on age, type of fuel used and function) and are promoting electric transport. In addition, the mix of residential and commercial activities in urban areas leads to distinctive patterns in both electricity demand and presence of electric vehicles. As a result, urban areas are likely to have a significant number of electric vehicles and therefore form the geographical scope of this study.

Ancillary services are considered to be the most suitable V2G service that can be provided, followed by the integration of renewable energy by storing/dispatching overproduction (Kempton & Tomić, 2005b). The definition of ancillary services differs slightly in literature. Generally, ancillary services could be defined as "services provided by the generation, transmission and control equipment that are necessary to support the transmission of electric power from the producer to the consumer"(Raineri, Ríos, & Schiele, 2006). These services include frequency control, voltage control and system backup and are provided by dispatching different forms of power. To comply with definitions used in the Dutch regulatory context this research considers ancillary services to be services that are delivered by providing regulating-, reserve- and emergency power. In practice, the latter is called infrequently, while regulating- and reserve power (RRP) is dispatched very often. Therefore this research will focus on the provision of RRP by EVs.

Although V2G could be applicable for other services, such as renewable energy integration(Castillo-Cagigal et al., 2011; Liu et al., 2013), the fact that RRP provision is already provided through a operational market system makes to the most feasible V2G service to assess. Therefore these other services are considered to lie outside the scope of this research.

1.3 Aim & Research question

Previous research shows that V2G has the potential to generate revenue for EV owners by providing ancillary services. Research thus far has been conducted with regard to U.S., Danish and French circumstances (Codani & Petit, 2014; Knezovic et al., 2014; Vandael et al.(2013)), but not yet for the Netherlands.

Therefore the aim of this research is to provide insight in the feasibility of V2G services in the Dutch urban areas in the form of RRP provision, thereby posing the following research question:

Which factors influence the potential value created for EV owners who provide regulating- and reserve power through their EVs in a Dutch urban area?

1. Is RRP provision by EVs applicable in the Netherlands?
    a. Is RRP provision by EVs facilitated by current rules and regulations?
    b. Is the current infrastructure and it's characteristics suitable for RRP provision?
    c. Do the Dutch EV fleet and the use patterns of EV drivers hold potential for RRP provision by EVs?
2. Which consequences and mechanisms can be identified for EVs providing RRP?
    a. What is the monetary value that can be created by different EV types?
    b. What is the monetary value that can be created by different user types?
    c. What are other important indicators surrounding the provision of RRP by EVs?
    d. Which mechanisms are decisive for the provision of RRP by EVs?
3. How sensitive are the identified indicators for changes in EV characteristics, -use and -number?
    a. How do user-related characteristics influence RRP provision by EVs?
    b. What is the consequence of an increased fleet size for the provision of RRP by EVs?

1.4 Relevance

This research holds relevance in several ways. Firstly, it will provide a first scientific estimation of the value of RRP provision by EVs in the Netherlands. It will show which components of the system are determining for the

possibility of EVs to provide RRP and provide recommendations for further research, such as the distribution of revenues over different actors and system boundaries.
From a more societal point of view, RRP provision by EVs can contribute to more sustainable areas in different ways. It can lower the cost of owning an EV, which makes EV a more interesting option for people and thereby resulting in less emissions from the transport sector.

1.5 Outline of the document

This research takes on the following approach. Chapter 2.2 assesses the Dutch electricity system in order to comprehend the regulatory- and technical context where RRP provision by EVs has to be placed in and identify suitable applications. Chapter 2.3 shows the composition of the Dutch EV fleet and user characteristics of Dutch EV drivers. This 2 chapter indicates the potential for RRP provision by EVs and therefore contributes to answering research question 1. Chapter 3 combines the findings presented in chapter 2 into a methodology that is used to quantify the potential monetary value of RRP provision by EVs. Additionally, the input data used to generate the results are introduced in this chapter. Chapter 4 presents simulation results, and identifies important indicators. Chapter 3 and 4 combined thus contribute to answering research question 2. Chapter 5 assesses to which extent these indicators are sensitive for changes in user characteristics and increasing fleet sizes, thereby answering research question 3. Chapter 6 will discuss these outcomes and their limitations. Chapter 7 will conclude this research.

2 Theoretical background

This chapter will discuss the technical- and regulatory context in which RRP provision by EVs has to be placed. Section 2.1 focuses on the power transmission- and distribution system and it's operation. Herein several topics are discussed. Firstly, the role of the transmission system operator (TSO) in maintaining a balanced grid is explained. Instruments used by the TSO are introduced as well as the regulatory environment that surrounds these instruments. Secondly the implications this has for the potential of RRP provision by EVs is presented. Section 2.2 will discuss the composition of the Dutch EV market, charging patterns and how this holds potential for RRP provision by EVs.

2.1 Electricity transmission and distribution in the Netherlands

The Dutch electricity system consists of a single transmission network and multiple distribution networks which operate under voltages ranging from 0,4 to 380 kV (Van Oirsouw, 2012). The transmission network is operated by the publicly held transmission system operator (TSO) Tennet and transports electricity from generation facilities to areas of demand under high voltages. There it is subsequently transformed to lower voltages and distributed to consumers through a series of substations and distribution networks that are owned and operated by various distribution service operators (DSOs) (figure 2.1.1).

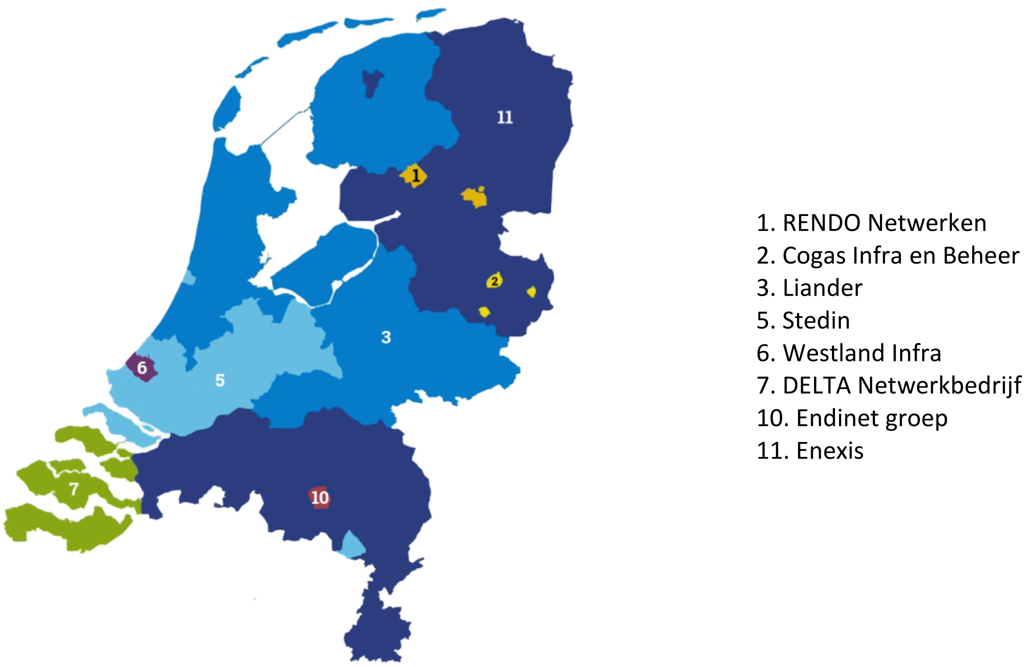

Figure 2.1.1: Overview of DSO service areas in the Netherlands (Energieleveranciers.nl, n.d.)

2.1.1 Operation of the Dutch electricity system

An electricity system must always be in balance, meaning that production and consumption must always be equal. The Dutch transmission system is part of a larger network of transmission systems in Western Europe who all operate at a frequency of 50 Hz. A frequency higher than 50 Hz is the result of production exceeding consumption. At a frequency of less than 50 Hz the opposite is the case. In both cases the system is in unbalance and needs to be restored. To achieve this it is necessary to continuously calibrate production and consumption. As TSO, Tennet holds responsibility for this process and uses several instruments to control it. First instrument deployed is the primary reserve, which is aimed at containing the frequency deviation. The primary reserve is locally installed on production units and automatically controlled. In order to restore the

frequency to 50 Hz Tennet uses further instruments, but before these are discussed it is important to explain the concept of a balance responsible party and the role it plays in the electricity system.
Preceding the process of actual electricity delivery is a process of buying and selling electricity in both long- and short-term electricity markets. Each party who is participating in these activities has balance responsibility, meaning that is it responsible for its own energy balance. This implies that each unit of energy that is added to the system by the BRP must have a customer. The BRP is obliged to communicate all these transactions on a 15-minute basis to Tennet in so-called e-programs one day in advance. These 15-minute intervals are called program time units (PTU) and are the same for each balance responsible party (BRP), yielding on uniform overview of production and consumption throughout the day. In reality production or consumption tends to deviate from the values stated in e-programs and results in a BRP being in unbalance and contributes to frequency deviation. If possible, the BRP can modify its production to correct for the deviation in its own e-program (Hummels, Hendriks, & Kling, 2007). In case the BRP is unable or unwilling to do this Tennet has regulating- and reserve power (RRP) at its disposal as instrument to restore balance.

RRP is dispatched either up, adding power to the system, or down, taking power from the system, depending on the direction of the unbalance. Although RRP separately have a similar impact on the unbalance, they differ in the way they are controlled and obtained (table 2.2.1). Key difference between the two lies in the way they are dispatched: Regulating power can be dispatched variably. Reserve power can only be called if full bid is dispatched (TenneT TSO B.V., 2012a). Therefore regulating power is controlled continuously by the national load frequency control to correct relatively small and short unbalances. Reserve power is only called when the TSO expects an unbalance to occur for at least one PTU so it can dispatch the full bid. In case of large outages Tennet can dispatch emergency power. Parties who are capable of significantly increasing production or cut-off load can supply this. Emergency power is contracted in large capacities exceeding 20 MW and called upon infrequently. This limits its potential as revenue source for EVs and is therefore not further assessed. In 2014 regulation power was by far the most used instrument to restore balance, with a roughly equal share between upwards (48%) and downwards (52%). The share of reserve power up, -down and emergency power is negligible small.

	Regulating power	Reserve power
Control	Continuously controlled by national load frequency control (FVR)	Fully dispatched when called
Volume calculation	Volume calculated based on control signal sent by FVR	Volume calculated per PTU
Obtainment	Obtained through both contractual agreements and market bids	Obtained through market bids only

Table 2.1.1: Characteristics of RRP

Regulating power is obtained in two ways. Firstly through contracts to ensure a certain minimum total capacity of 300MW in both directions. Contracted regulating power is currently only bought in capacities larger than 10MW and symmetric, meaning that the supplying party must be able to deliver power in both directions. This capacity is subsequently placed in the market for RRP where other parties can submit their bids. This market is discussed in more detail in the next section.

2.1.2 The market for regulating- and reserve power

The market for RRP, sometimes referred to as the unbalance market, is a single-buyer market where bids of RRP are offered to Tennet for each PTU. The market always contains the minimum contracted regulating capacity mentioned in the previous section. Parties who have access capacity in either direction can add this to the market in the form of marker bids. A bid is defined by TenneT as "an option, with the bidder setting a minimum condition (bid price) for acceptance of the risk of allowing some volume (up to the extend of the bid per PTU) in adjustment of its imbalance"(TenneT TSO B.V., 2012b). Bids can be placed until one hour in advance and can occur in two directions, up and down depending on the direction of the unbalance. For each PTU all bids and their associated prices are consolidated in a bid price ladder. Figure 2.1.2 shows an example of a bid price ladder. The right part of the graph shows bids for RRP up. If an upward correction is needed the bids for RRP up will be dispatched in order of increasing bid price. With respect to this example it entails that an upward dispatch of 600 MW yields a settlement price of 75 €/MWh. In case the full capacity of 800 MW is dispatched the price rises to 120 €/MWh. Tennet pays this price to the supplier of RRP. If a downward correction is needed the bids for RRP down are dispatched is order of decreasing bid price. In this case the supplier of RRP pays Tennet. Note that for RRP down negative prices can occur in which case Tennet pays the supplier. In figure 3 this is shown at a downward dispatch of 200 MW or more. The cost of restoring the unbalance is subsequently settled with the BRP that is responsible for the unbalance.

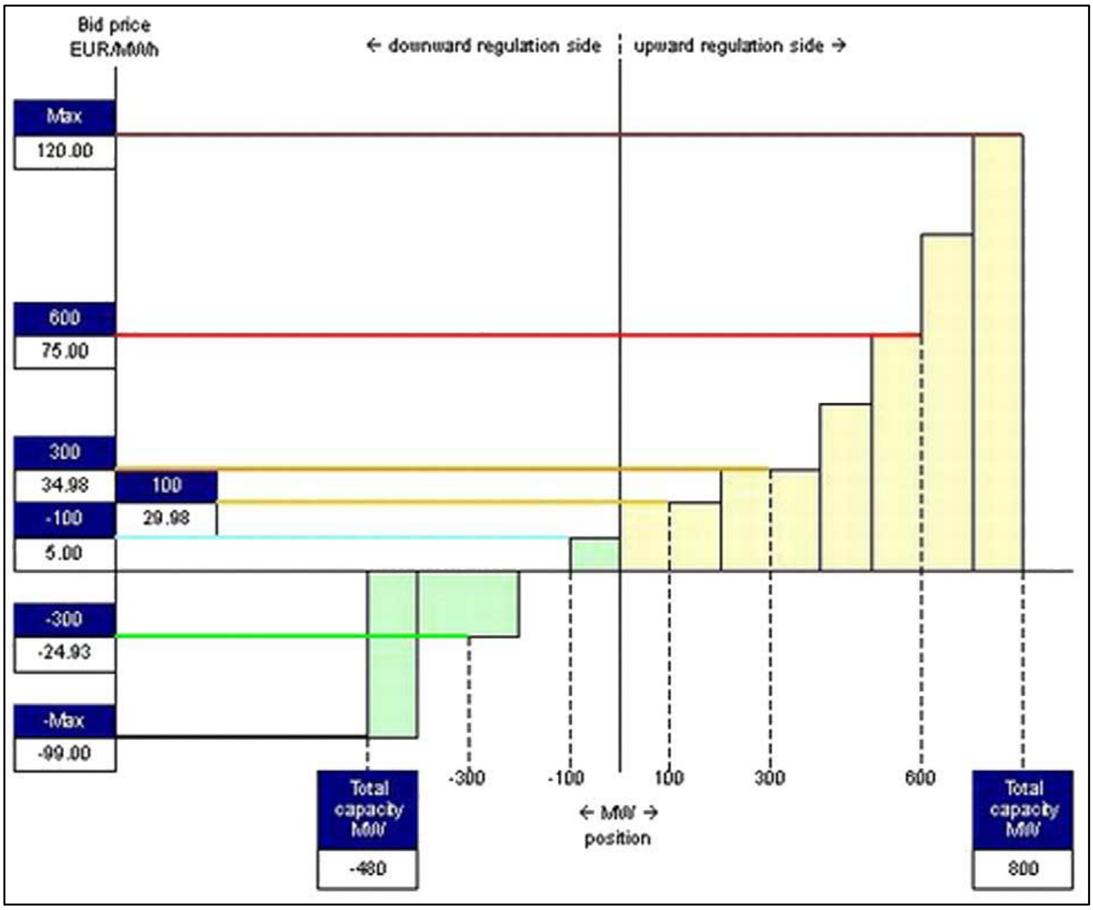

Figure 2.1.2: Illustration of a bid price ladder. Source: Boogert & Dupont (2005)

2.1.3 Suitability of TSO rules for RRP provision by EVs

The market for RRP could be interesting for EV owners, since participating in this market could lower their cost of ownership. TSOs set certain requirements with respect to the deployment of RRP and EVs supplying RRP should comply with these requirements. Additionally, the design of the market is not specifically designed for RRP provision by EVs and therefore it is desirable to assess if the current market design is suitable.

Before this is discussed it is important to introduce the concept of the aggregator, which plays a key role for all V2G applications. For the TSO individual EVs are too small and unreliable to control as power unit as TSOs are used to deal with a relatively small number of units providing MWs instead of a large amount of units providing KWs (Codani et al., 2014). Furthermore, EVs are not always available for RRP as their first priority is transport. An aggregator is an entity who controls a large number of EVs and, whilst taking into account their individual use patterns and technical specifications, and can provide a statistically reliable entity that meets a power level corresponding with the order of magnitude the TSO uses. More generally speaking, aggregators allow commercial consumers to gain access to energy markets. Currently, several aggregators are active on the day ahead-, intraday- and unbalance market among which are Powerhouse and Agro-Energy. These parties provide their costumers, for a large share active in horticulture, the opportunity to sell their flexibility by matching their consumption with low energy prices in the different energy markets. This is similar to what EVs providing RRP will be doing on the unbalance market and shows that in terms of regulations aggregation could potentially possible.

A survey conducted by Codani et al. (2014) identifies rules and market characteristics that are important for aggregation and the performance of RRP provision by EVs. By consulting bidding manuals (TenneT TSO B.V., 2012b, 2013, 2014) and Frank Nobel (personal communication, July 27th, 2015) the rules set by TenneT can be compared to the characteristics described in Codani et al.(2014). The results are summarized in table 2.1.2.

Minimum size of the power bid

In markets for RRP, bids have to exceed a minimum power level of power. To comply with this power level a certain amount of EVs has to be available and connected, depending on the power characteristics of the vehicle and charging facilities. For example, 100 EVs connected to 11kW charging facilities are needed to provide 1,1 MW of RRP. The minimum size of the power bid, power level of charging facilities and availability of EV determine the minimum amount of EVs an aggregator must have under his control to provide reliable RRP. Therefore a small minimum power bid is more favorable for RRP provision by EVs. Codani et al.'s (2014) survey reports a range of 0,1 to 10 MW in minimum bid sizes for RRP in TSO areas in Europe and the US.

In the Netherlands the minimum capacity for a bid placed in the market for RRP is 4 MW. This is not necessarily an unfavorable amount as Dutch public charging facilities have a combined power output of 28 MW.

Interoperability between DSOs

If TSO rules allow the provision of RRP from different DSO areas the minimum size of the power bid is more easily met, since the aggregator has a larger area under his disposal from which he can compose a fleet. This increases the odds for sufficient connected EV's.

This is not the case in the Netherlands. The TenneT bidding manual states that a (set of) connection(s) from which the bidder will dispatch has to belong to one owner or administrator. However, considering that there are only 8 DSOs active in the Netherlands and that 4 of these DSOs have a large service area, it is still likely that the minimum bid size can be achieved within one DSO service area (for reference see figure 2.1.1). This is not the case for a country like Denmark, who has 65 DSO's.

Type of aggregation: telemetry vs. financial aggregation

Using telemetry in aggregation entitles that the aggregator can control both bids and power flows from one or more central locations i.e. by implementing dispatch algorithms. This allows an aggregator to act as a single (virtual) connection node to the TSO and can therefore control the dispatch amongst the different units under its control. Financial aggregation on the other hand only allows for combining bids. This entitles that several RRP providers can act in a pool to reduce transaction costs, but that the aggregator has to dispatch the full bid of each provider when called upon. It that sense, it has no control over the power flow and is each providing unit in the same situation as if it's bidding separately in the market (Paul Codani, personal communication, August 10th, 2015).

In the Netherlands bids are bundled and dispatched using telemetry, allowing an aggregator to operate in different BRP areas. Telemetry is even required as Tennet wishes to receive real-time measurements on a 4-second basis and 5-minute accounting measurements for the purpose of quality control.

Nature of the payment scheme

The payment for RRP can occur in two ways, regulated and market-based. In regulated payment schemes RRP is delivered by entities that are appointed in advance through yearly-contracts. In the market-based situation entities can bid RRP on a daily- or even hourly basis. Given the dynamic nature of EVs a market-based payment scheme is preferable.

As explained in the section 2.1.1, the Dutch market for RRP obtains capacity through both contracts and market bids. It could therefore be characterized as semi-regulated. However, given the fact that contracted power is placed in the market where it competes with offered power it maintains market mechanism.

Incompleteness of payment scheme

There are cases where not all RRP remunerated by the TSO, because power delivery units are obliged to deliver. The resulting lack of incentive can lead to poor performance of RRP suppliers. An incomplete payment scheme is unfavorable for the implementation of RRP provision by EVs.

In the Netherlands all RRP is remunerated though an energy only fee and corrected on the unbalance of the BRP in question. Therefore the payment scheme in the Netherlands is assessed as complete.

Extra bonus for intense flexibility

RRP units can differ with respect to response speed. If RRP is only rewarded with a capacity price than it rewards slow-responding resources better than fast-responding resources, since fast-responding resources will exchange more energy with the system. EV's very quick response times, flexibility and accuracy call for payment schemes that reward this, for instance by paying a capacity price (€/MW), energy price (€/MWh) and a payment for response accuracy.

There is no explicit reward for response accuracy in the Dutch power system, but the fact that an energy only fee is paid favors fast ramping resources such as fleets of EV.

	Optimal based on Codani et al. (2014)	**TenneT**
Minimum bid size	100 kW	4 MW
Interoperability between DSO	Yes	No
Type of aggregation	Telemetry	Telemetry
Nature of payment scheme	Market-based	Market-based
Incompleteness of payment scheme	Complete	Complete
Bonus for intense flexibility	Yes	No

Table 2.1.2: Summary of TenneT rules and characteristics for RRP provision

If the rules and market characteristics of Tennet are compared to the ideal situation proposed by Codani et al. (2014) it can be concluded that the regulatory circumstances concerning the provision of RRP in the Netherlands are generally favorable.

2.1.3 Characteristics of the Low-Voltage grid

Electricity is supplied to consumers through substations and medium- and low-voltage distribution networks which are under the governance of the DSOs listed in figure 2.1.1. In urban areas these consumers are households and businesses, which differ in their electricity consumption patterns. Residential electricity consumption is characterized by an increase in the morning and peak in the evening, while commercial electricity consumption peaks during the day. Both these patterns are in line with a working day rhythm. As a result the distribution grid in urban areas faces an electricity demand throughout the day. Figure 2.1.3 shows an example of the electricity demand of different sectors throughout the day, namely commercial, residential, industrial and agricultural and other. For each sector it provides a clear representation of the relation between time-of-day and electricity consumption, which can be explained by the nature of its activities. The industrial- and agricultural sectors are characterized by a rather constant demand as both sectors are continuously in operation. The commercial- and residential sectors are both characterized by business day patterns, albeit in different ways. Commercial demand ramps up in the morning, peaks at mid-day and decreases towards the evening. This is in line with most office hours. Residential demand is characterized by a slight increase during the morning and a clear peak in the evening, consistent with people returning from work and starting domestic activities such as cooking, watching TV, etc. This research assumes that urban areas face demand from the commercial- and residential sector. Therefore it is expected that the load on the infrastructure in such areas is characterized by a steep increase during the morning, an extended peak throughout the afternoon and a decrease throughout the evening, similar to the "Total Demand" curve depicted in figure 2.1.3. Note however that this curve includes industrial and agricultural demand. Since the demand from these sectors is very constant it merely causes the "Total Demand' curve to shift upwards and doesn't alter the relative pattern, which is of importance for this research.

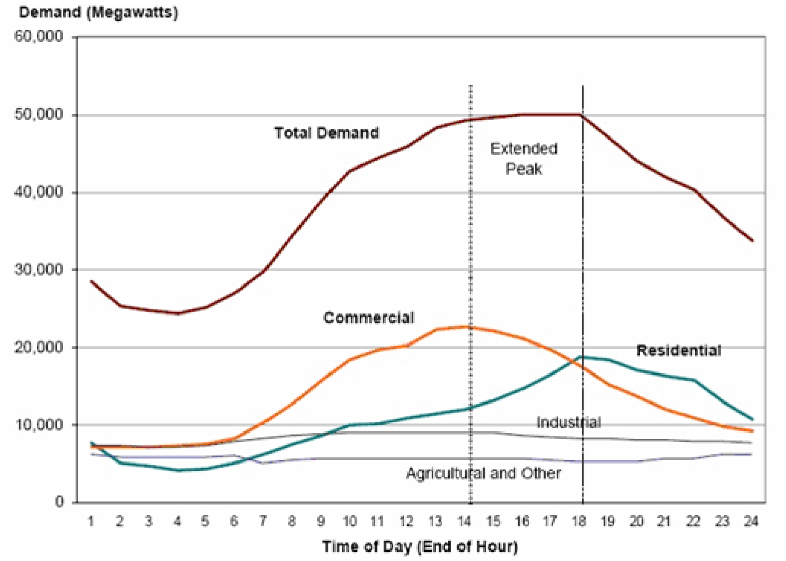

Figure 2.1.3: Electricity demand of different sectors throughout the day (source: Hruska, 2015)

The infrastructure that delivers electricity to the consumer has limited capacity with respect to the maximum loads that can be applied to the cables and the transformers in substations. In order to design a cost-efficient grid, DSOs take into account that it is unlikely that an entire area will exercise full demand at the exactly the same time. Although a safety margin is taken into account, placing an additional load, such as EVs, on the grid could cause overcharging in specific cases (Eising et al., 2014). Figure 2.1.4 shows a schematic overview of a distribution grid and possible bottlenecks, cable capacity and transformer capacity. While both could form a bottleneck, it must be stated the transformers are most likely to fail before maximum cable capacity is reached (Turel, 2015).

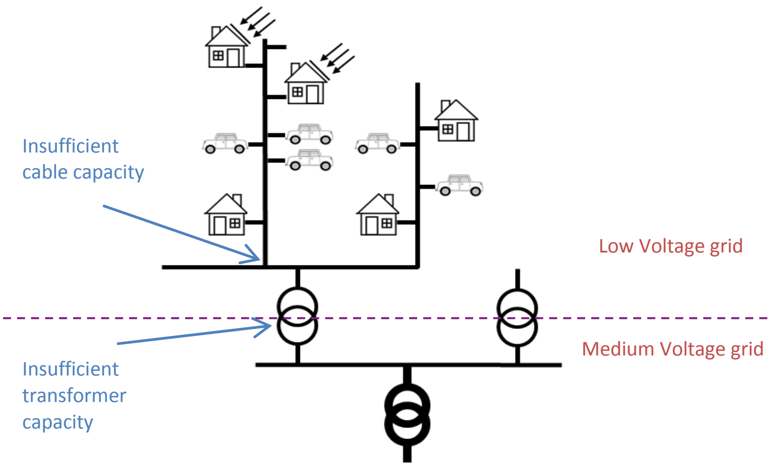

Figure 2.1.4: Schematic overview of a distribution grid and bottlenecks (Turel, 2015)

2.1.4 Impacts of RRP provision by EVs on the Low-Voltage grid

The consumption characteristics described above provide important considerations for the implementation of RRP provision by EVs, since it will determine the available capacity of the infrastructure. Table 2.1.3 describes the impacts of EV (dis)charging on the loads on different components of the distribution grid. When providing RRP down the EV will be charging and therefore the loads on the cables and transformer will increase. These increased loads lead to thermal effects that have an adverse affect on transformer aging and cable wear (Leemput et al., 2012). Additionally, the transformers and cables have a maximum capacity with regard to the load that can be placed on them.

When providing RRP up the load on the cables will stay equal and the load on the transformer will decrease, as the EV will provide electricity to the area instead of the substation.

EV action	Cable load	Transformer load
Charging i.e. RRP down	Increase	Increase
Discharging i.e. RRP up	None	Decrease

Table 2.1.3: Impact of EV (dis)charging on the loads on infrastructure components.

2.2 Electric vehicles in the Netherlands

2.2.1 Composition of the fleet

On 30th April 2015 there were 51.089 electric vehicles registered in the Netherlands, consisting of full electric- (FEV), plug-in hybrid electric- (PHEV) and range extended electric vehicles (REV). All these vehicles are capable of connecting to a charging facility (CF) and are therefore in theory suitable for RRP provision, although bidirectional charging is not yet possible. In this overview REVs are categorized under PHEV. Like a PHEV, a REV carries a both a combustion engine and an electric engine to provide propulsion. While the PHEV uses both engines to directly drive the power train, the REV only has an electric power train and uses it's combustion engine to drive an alternator that provides electric power. Table 2.2.1 shows registered EVs in the Netherlands and their associated battery capacities.

EV type	Model	Number	% of total EV fleet	Battery capacity (kWh)
PHEV	Mitsubishi Outlander	16.957	33%	12
	Volvo V60 Plug-in hybrid	10.631	21%	11,2
	Opel Ampera	4.969	10%	16
	Toyota Prius Plug-in	4.049	8%	4
	Volkswagen Golf	1.986	4%	8.8
	Other	4.610	9%	-
FEV	Tesla Model S	3.044	6%	70 or 85
	Nissan Leaf	1.286	3%	24
	Renault Zoe	920	2%	22
	Smart ForTwo Electric Drive	768	2%	17,6
	BMW I3	422	1%	22
	Other	1.447	3%	-
	Total PHEV	**43.202**		
	Total FEV	**7.887**		
	Grand total EV	**51.089**		

Table 2.2.1: Composition of Dutch EV fleet and associated batteries on 30th April 2015 (Hall, 2015; Mitsubishi Motors, 2015; Opel, 2014; RVO, 2015; The New Motion, 2015).

Throughout this thesis there will be several references to the Dutch fleet. Naturally, this fleet is continuously changing. Therefore, when a reference to the Dutch EV fleet is made this concerns the fleet that was registered in the Netherlands on 30th April 2015.

2.2.2 Characteristics of charging infrastructure and implications for the potential of RRP provision

The charging facility forms the connection between the EV and the grid. In Spoelstra (2014) an overview is presented of the types of charging facilities that are installed throughout the Netherlands. Currently, these are only capable of charging and therefore could only provide RRP down, but under the assumption that charging facilities will become bi-directional this gives a first rough estimation of the potential RRP that can be available. Figure 2.2.1 shows the potential RRP under the assumption that the entire Dutch fleet has a charging facility at its disposal. For reference, the minimum bid size is included in the figure, thereby showing that the current fleet can easily meet it. However, the number of public- and semi-public[1] charging facilities in the Netherlands is significantly smaller than the number of EVs. When the potential RRP is assessed based on the installed charging facilities figure 2.2.2 is obtained. The red bars refer to potential RRP, listed on the right axis. The blue bars refer to the number of installed charging facilities, listed on the left axis. Figure 2.2.2 shows that the

[1] As private charging data is difficult to obtain, only public- and semi-public charging facilities were assessed. Public charging facilities are defined as charging facilities that are located on public property. Semi-public charging facilities are charging facilities that are on private property such as offices and parking garages, but also available for visitors or external users. (Spoelstra, 2014)

assessed charging facilities are sufficient to meet the minimum bid size and therefore have potential for delivering RRP.

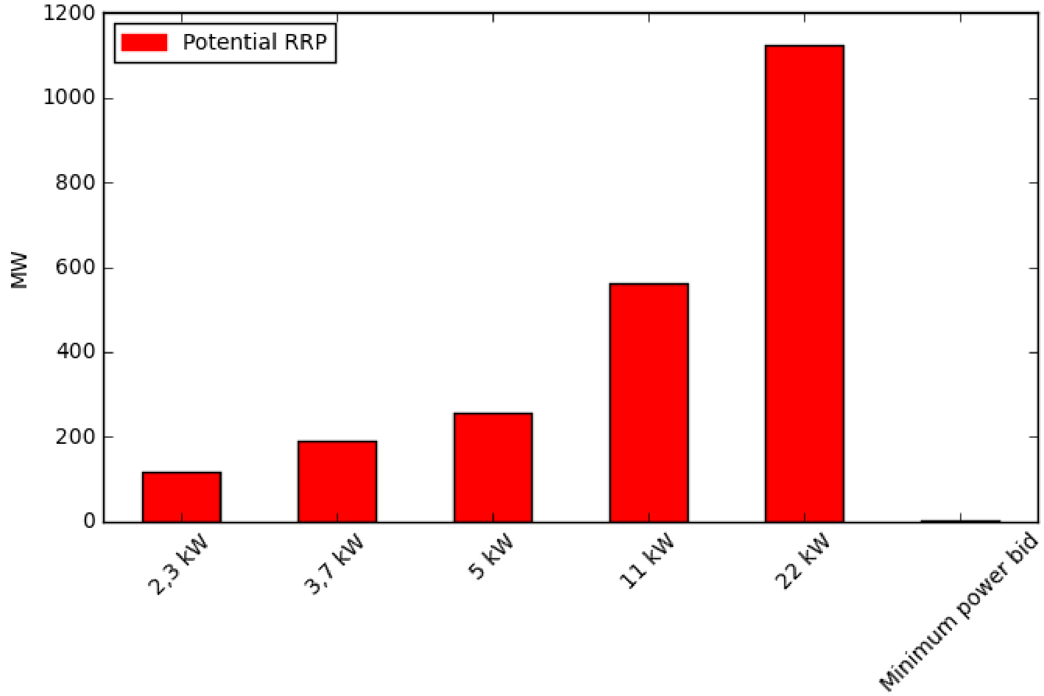

Figure 2.2.1: Potential RRP of the Dutch EV fleet (MW)

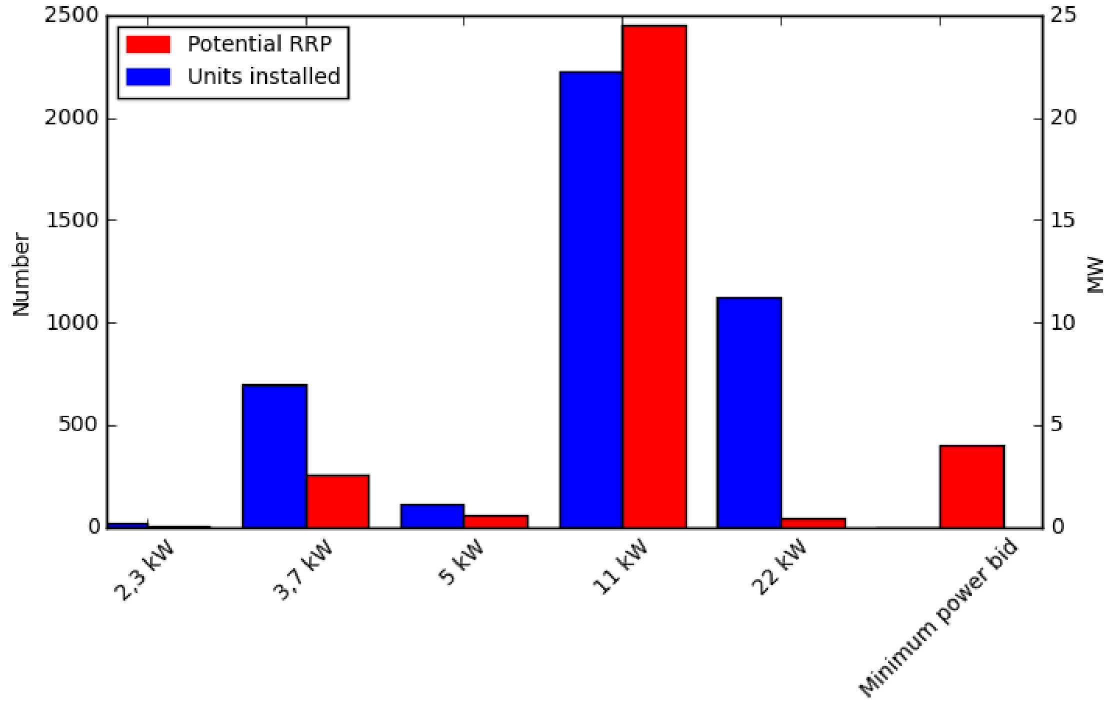

Figure 2.2.2: Potential RRP (MW) based on Dutch (semi-) public charging facilities in 2014.

2.2.4 Characteristics of charging patterns and implications for potential of RRP provision

Figures 2.2.1 and 2.2.2 show that there can be sufficient potential for RRP provision by EVs in terms of power. Whether this power can be delivered determines if the EV availability coincides with demand for RRP. Therefore a more detailed assessment of EV charging and connection times is required.

Studies have already been conducted on the charging preferences of Dutch EV drivers. Spoelstra (2014) assessed this based on a dataset that consisted of 965.413 transactions that took place at public- and semi-public CFs in the Netherlands between January 1st 2013 and April 30th 2014. The research shows that EV drivers are in general very routinized in the way they charge their vehicle. This is an important finding as this improves the predictability of EV availability for RRP provision. Table 2.2.2 shows key findings from Spoelstra (2014) that are in particular useful for this research.

Key findings		
	Public	**Semi-public**
Average charging time (hours)	0:45	0:43
Average connection time (hours)	6:40	6:15
Average energy transfer (kWh)	8,3	7,8
Average charging frequency (transactions/week)	3,23	

Table 2.2.2: Key findings from Spoelstra (2014)

Table 2.2.2 shows that the average connection time of Dutch EV drivers is nearly 9 times larger than the actual charging time. This implies that EVs have flexibility for charging or discharging and can therefore potentially offer RRP. In addition, EV drives complete on average 3,23 charging sessions per week, during which they could offer RRP. However, it has to be noted that the assessed data doesn't include private charging facilities. Assuming that a large share of Dutch EV drivers does charge at home the average amount of weekly charging sessions may exceed the stated average. According to The New Motion (personal communication, 2015), a large supplier of charging facilities, most drivers charge their vehicle each night at private facilities.

Now that the length of charging sessions is known, the next step is to establish at which time these sessions begin and end. Figure 2.8 shows at which times peaks occur in beginning and ending transactions.

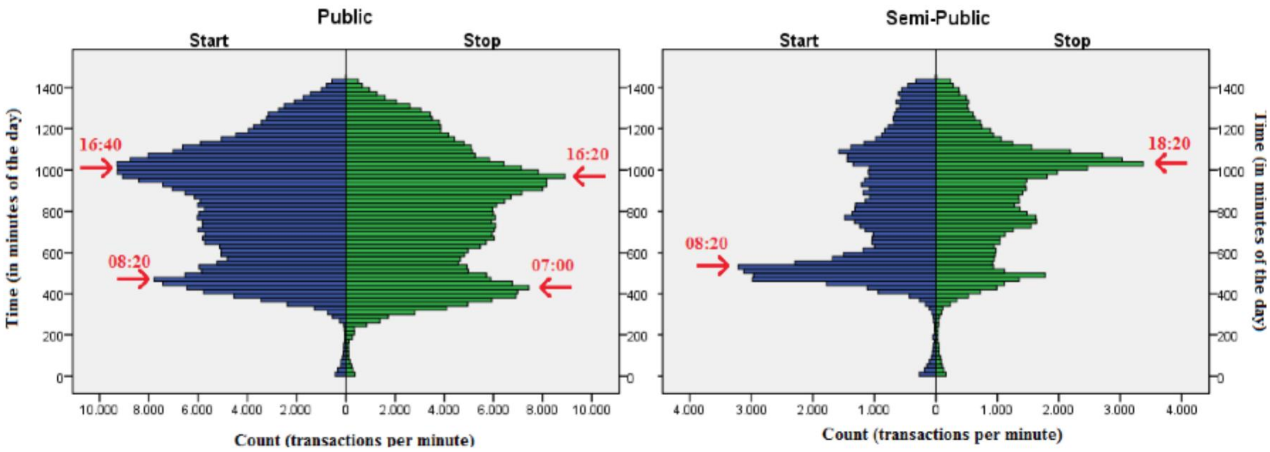

Figure 2.2.3: Start- and stop times of transactions for public- and semi-public charging facilities (Spoelstra, 2014)

A working day pattern becomes clearly visible as begin and end peaks coincide with general office hours. A remarkable observation is that the timespan between begin and end peaks are larger than the stated average connection time, which can be explained by the large share of short transactions found in the database. This is shown in figure 2.2.3 where a histogram is presented which compares the duration of the full charging transaction, i.e. the connection time, with the amount of occurrences in the database. This provides important considerations when developing the charging sessions that later will be used in the model. Short transactions will be less suitable for RRP provision by EVs than longer transactions, since during a short transaction it will be likely that the EV spends most of the connection time charging. In the database peaks are shown at 01:40, 08:20 and 10:40 hours. Even though there is a large peak of rather short transactions, the fact that the other peaks are considerably larger offer potential for RRP provision by EVs.

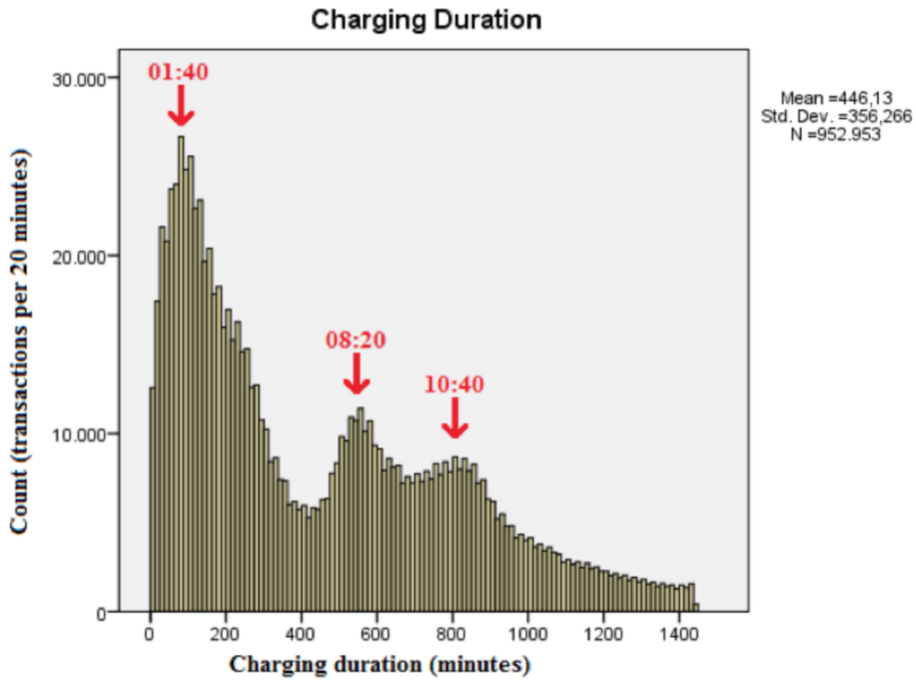

Figure 2.2.4: Duration of charging transactions vs. the count of these transactions (Spoelstra,

The potential for RRP provision by EVs can be further specified by assessing the ratio between charging time and actual connection time. This is ratio is called the time-ratio (equation 2.1) and is applied in Helmus & Van den Hoed (2015) on charging sessions in Amsterdam in 2014. For example, an EV who spends 8 hours connected to a charging facility and only needs 2 hours to fill up its battery has a TR of 25%.

$$Time\ ratio\ (TR) = \frac{Charging\ time}{Connection\ time} * 100\% \tag{2.1}$$

In their paper Helmus and Van der Hoed identify different user types based on characteristics found in charging behavior. Based on these characteristics the following user types were identified:

- Residents. Strong weekly pattern of ending charging transactions in the morning and starting charging transaction in the evening during weekdays. No patterns were identified for weekends.
- Commuters: Like residents, commuters have an explicit weekday pattern. This is the exact opposite of residents; starting charging transactions in the morning and ending them in the evening.
- Taxis. Short charging session with no clear distinction between weekdays and weekends.
- Visitors. Irregular arrival patterns. Furthermore visitors tend to charge during the weekends.
- Car sharing. This user type is characterized by a dip in charging times during peak traffic hours.
- RC-chargers. These users show a combination of both residential- and commuter behavior.

For this research it is important to have a consistent charging behavior with low time ratios. Therefore the user types residents, commuters and RC chargers will be assessed. The most important characteristics are selected and explained in table 2.2.3 and specified for the user types under investigation. In the first and second column the selected characteristic and the description of the characteristic are presented. The subsequent columns specify these characteristics for each user type.

Characteristic	Description of characteristics	User type		
		Residents	Commuters	RC chargers
Start time	*Mean and standard deviation of the start time of the charge session*	Weekdays between 17:00-19:00 with a low standard deviation	Weekdays between 7:30-9:00 with low to medium standard deviation	Combination of both
End time	*Mean and standard deviation of the end time of the charge session*	Next morning between 7:00 and 9:00 with a low standard deviation	Same day around 18:00 wit low standard deviation	
Duration	*Mean and standard deviation of the connection time*	Long, around 8 hours with a low standard deviation	Long, around 8 hours with a low standard deviation	
$TBS_{weekdays}$	*Mean and standard deviation of the time between two charging sessions during weekdays*	Medium, around 10 hours. Consistent per user with a low standard deviation	Medium, around 10 hours. Consistent per user with a low standard deviation	
$TBS_{weekend}$	*Mean and standard deviation of the time between two charging sessions during weekends*	Medium consistency per user. Medium standard deviation	Inconsistent per user. High standard deviation	
kWh	*Mean and standard deviation of kWh charged*	Mean 60% of max kWh of EV battery, medium standard deviation	Mean 80% of max kWh of EV battery, medium standard deviation	
Time ratio	*Mean and standard deviation of time-ratio*	Low, consistent around 20-30%	Medium, per user consistent around 20-30%	

Table 2.2.3: Characteristics of user types (Helmus and Van den Hoed (2015)

The results presented by Helmus and Van der Hoed are consistent with the findings of Spoelstra. In addition, the time-ratio's presented by Helmus and Van der Hoed support the claim that EVs have flexibility with regard to charging and therefore hold potential for RRP provision. Values of 20-30% are presented, which means that EVs are connected up to 5-times longer then necessary for charging alone. This is more than the 3-times reported in Spoelstra. Based on these characteristics connection times and -duration can be established for each user type. Additionally, the time between sessions indicate a daily pattern of connection for weekdays. The kWh charged can be used to determine the battery SOC at the time of connection. The implementation of these characteristics in this research will be further explained in chapter 3.4 where the input data is discussed.

2.2.5 Impact of charging and discharging on EV battery

RRP provision will alter the charging and discharging patterns of EVs in comparison to the conventional case where EVs are used for transportation only. It can be expected that the batteries will face a higher throughput of electricity, increased number of charge-discharge cycles and a lower depth of discharge (DoD). Although all these factors have an influence on battery wear and therefore cause costs, cycling and depth of discharge are considered to be the most important parameters in determining battery life (Han, Han, & Aki, 2014).

Battery cycle life can be defined as the amount of charge-discharge cycles a battery can complete before it fails to meet specific performance criteria (MIT Electric Vehicle Team, 2008). This cycle life is dependent on the depth of discharge (DoD), which is the opposite of the state of charge (SOC). For example, when a battery has a SOC of 20% the depth of discharge is 80%. In figure 2.2.5 the relation between depth of discharge and cycle life is presented for a lithium-ion battery. This figure is retrieved from Han et al. (2014) where they refer to cycle life as the achievable cycle count (ACC) at a specific DoD. What this figure shows is that deeper charge-discharge cycles lead to exponentially lower cycle life.

When considering the findings in table 2.2.3 it can be concluded that EV users in the category residents and commuters currently engage in medium to deep cycling of their EVs batteries as the DoD ranges between 60% and 80%. This puts the expected cycle life of EV batteries at the lower end of the scale.

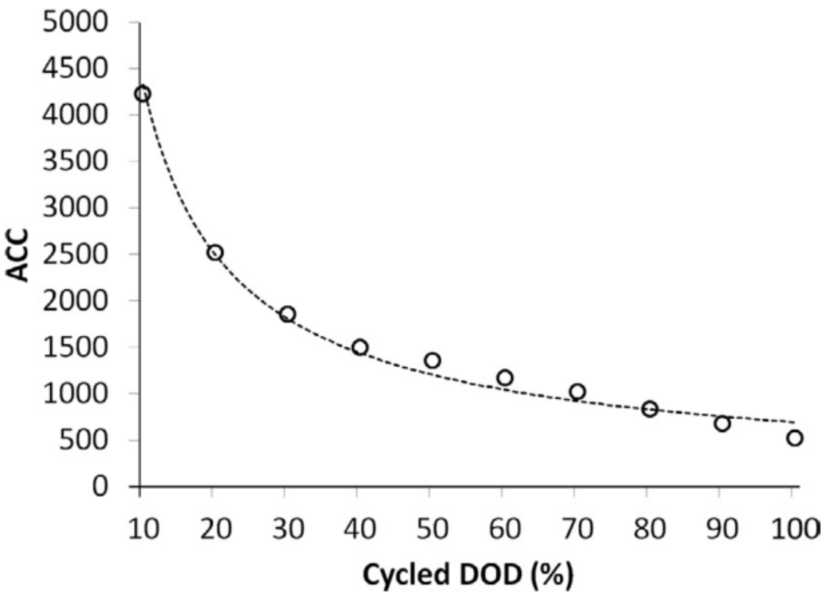

Figure 2.2.5: Relation between cycling and depth of discharge for a lithium-ion battery retrieved from Han et al (2014)

In this section important considerations are presented that are required to assess the impact of battery degradation on the economic performance of RRP provision by EVs. However, due to time constraints that applied to this research the exact quantification of this impact is considered to be out of scope. Instead, statements will be made regarding the battery throughput and cycle depth, which are shown to be important indicators for battery degradation.

3 Methodology

The previous chapter discussed the main considerations around the implementation of RRP provision by EVs in the Netherlands. This chapter presents the methodology that is used to identify and quantify the consequences of RRP provision by EVs. This methodology is divided into 4 parts. In section 3.1 a description is given of the model that is used to simulate EVs performing RRP. In section 3.2 the different dispatch schemes and associated calculations are presented. Section 3.3 explains the performance indicators that are used to determine the performance of EVs providing RRP. In section 3.4 the inputs that are used in the model are discussed. Section 3.5 presents the sensitivity analysis.

3.1 Model description

When assessing a distribution grid it is common practice to focus on the part that is to be designed or adapted. This entails that the grid model consists of only the components under study and simplifies the external grid by using assumptions (Van Oirsouw, 2012). This study focuses on the dispatch of EVs from an urban, low-voltage distribution grid and will therefore consider the overlying medium- and high-voltage networks to be the external grid. The grid model (figure 3.1.1) used in this study will consist of an unspecified number of lines that connects businesses and households to the external grid via one substation. In line with the findings in chapter 2, it is assumed that the capacity of all lines is significantly larger than substation capacity. Under the assumption that the charging facilities are evenly spread over the service area this means that substation capacity is the determining factor for the maximum load that can be exchanged with the external grid. In the model several charging facilities are placed that have an occupation similar to the charging characteristics found in chapter 2. The exact values that are used are further specified in section 2.4. For the sake of simplicity it is assumed that the EVs travel between identical areas with respect to loads and grid characteristics, thereby making it possible to execute simulations in one single model.

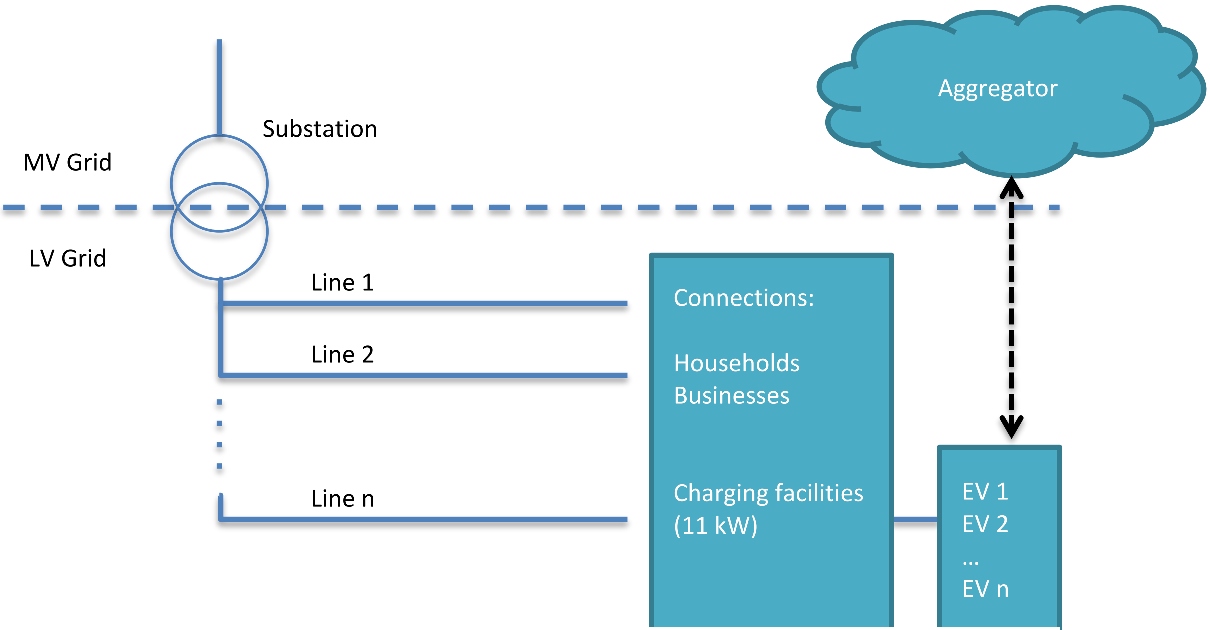

Figure 3.1.1: Overview of grid model

In order to the control the EVs an aggregator is necessary who receives information from the EVs regarding their travel plans. It is assumed that the aggregator has sufficient EVs under its disposal to meet the minimal bid size set by Tennet and that the aggregator possesses perfect information with regard to amount- and associated prices of RRP. This enables the aggregator to place bids in such a way that the most beneficial settlement price is received.

3.2 Dispatch schemes

The EVs placed in the model will be operated according to two dispatch schemes and based on the three user types describes in section 2.4.4. In order to automate the calculations a simulation model was written in Python. Firstly, a baseline will be established by simulating the EVs according to current charging characteristics without any RRP provision. Subsequently, the EVs will be controlled by a dispatch scheme aimed at providing RRP.

3.2.1 Baseline charging scheme

In the baseline situation EVs start charging immediately after connecting to the charging facility and continue charging until the battery is full or until they are disconnected for a trip. During the trip the EV consumes energy (E_{trip}) from the battery. After a trip an EV either reconnects or remains disconnected until the next trip. In the case of reconnection charging commences again. In case the EV stays disconnected the SOC remains equal until the next trip. These situations occur during the day for the resident user type and at night for the commuter user type. All user types are considered to be disconnected during weekends to account for the inconsistent travel behaviour that takes place during weekends.

In this research the costs of charging is based on the current electricity price (p_{el}). In reality the costs of charging are significantly higher, around €0,30/kWh[2], due to service fees, network costs and taxes. It is assumed that similar costs are made when electricity is exchanged with the market for RRP and therefore the energy-only price is considered when comparing both cases. This is further elaborated in chapter 3.4. Figure 3.2.1 shows a schematic overview of charging in the baseline scenario.

[2] Essent, 2015; Nuon, 2015

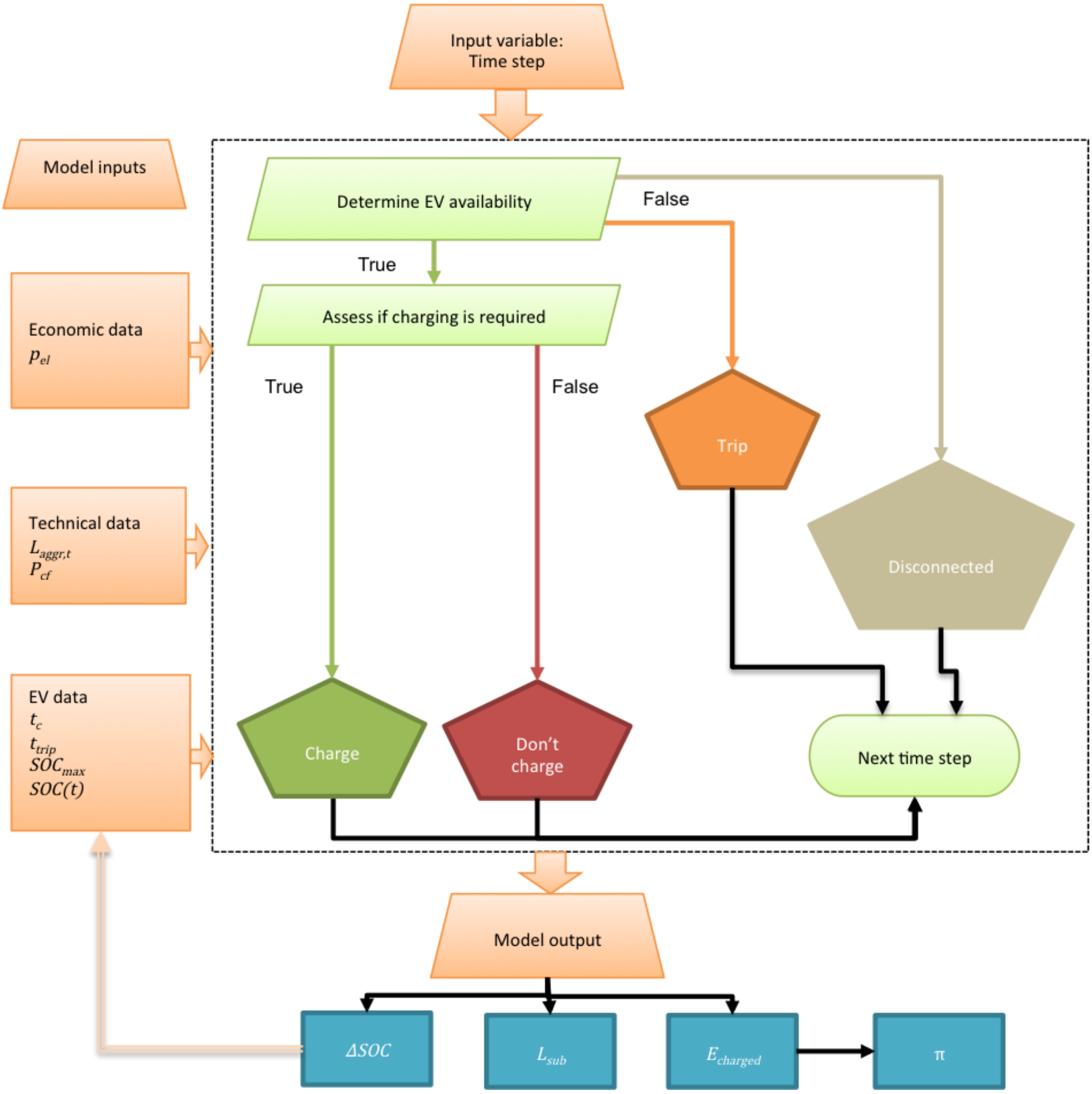

Figure 3.2.1: Schematic overview of the baseline charging scheme

The model inputs on the left show the different types of data that are used for calculating the eventual model outputs for each time step. The parallelograms represent assessments made during each time step. The assessments ultimately lead to a pentagonal block where calculations are made. Firstly, it is assessed whether an EV is connected to the charging facility (equation 3.1).

$$t \in t_c \qquad (3.1)$$

If the EV is not connected this yields a "False" signal, which means that the EV is on a trip or parked and nor connected. During a trip the trip the battery is depleted at the rate of the power consumption of the EV (equation 3.2). During disconnection the SOC remains equal.

$$SOC(t+1) = SOC(t) - P_{drive} * \Delta t \qquad (3.2)$$

If the EV is connected this yields a "True" signal that initiates the next assessment that assesses if charging is required. If the SOC at that time step ($SOC(t)$) is less than the maximum battery capacity (SOC_{max}), this will yield a "True" signal where after charging commences. If the battery is full a "False" signal is given and no charging will take place. This procedure mimics the way EVs are currently charged. Both outcomes result in calculations that lead to the model output for that time step:

- Change in SOC, described in equation 3.3. The change in SOC is dependent on the vehicle's charging power capacity (P_{cf}) , efficiency (η_{cf}) and duration of the time step (Δt). The resulting SOC ($SOC(t+1)$) is taken as input for the next time step.

$$SOC(t+1) = \begin{cases} SOC(t) + P_{cf} * \eta_{cf} * \Delta t & \text{if} \quad SOC(t) < SOC_{max} \\ 0 & \text{else} \end{cases} \quad (3.3)$$

- Volume of energy charged to the battery (equation 3.4).

$$E_{charged} = SOC(t+1) - SOC(t) \quad (3.4)$$

- Resulting load on the substation ($L_{sub,t}$), described in equation 3.5. Charging adds to the load that is placed on the substation by businesses and households ($L_{aggr,t}$) at that time step.

$$L_{sub,t} = \begin{cases} L_{aggr,t} + P_{cf} & \text{if} \quad SOC(t) < SOC_{max} \\ L_{aggr,t} & \text{else} \end{cases} \quad (3.5)$$

- Profit (equation 3.6). In this case profit (π) will be negative, as only costs for charging will occur or no costs at all.

$$\pi_{t,baseline} = \frac{E_{charged}}{\eta_{cf}} * p_{el} \quad (3.6)$$

3.2.2 Regulating- and reserve power dispatch scheme

In this situation the EVs provide RRP to Tennet in order to maintain grid balance. While in the baseline situation the EVs charge immediately after charging, this dispatch scheme determines charging and discharging based on profit generation. Therefore an EV will only be charging if the settlement price for downward RRP is favourable or if charging is required in order to ensure sufficient battery capacity for the next trip. An EV will be discharging if the settlement price for upwards RRP is favourable. A schematic overview of the dispatch scheme is depicted in figure 3.2.2.

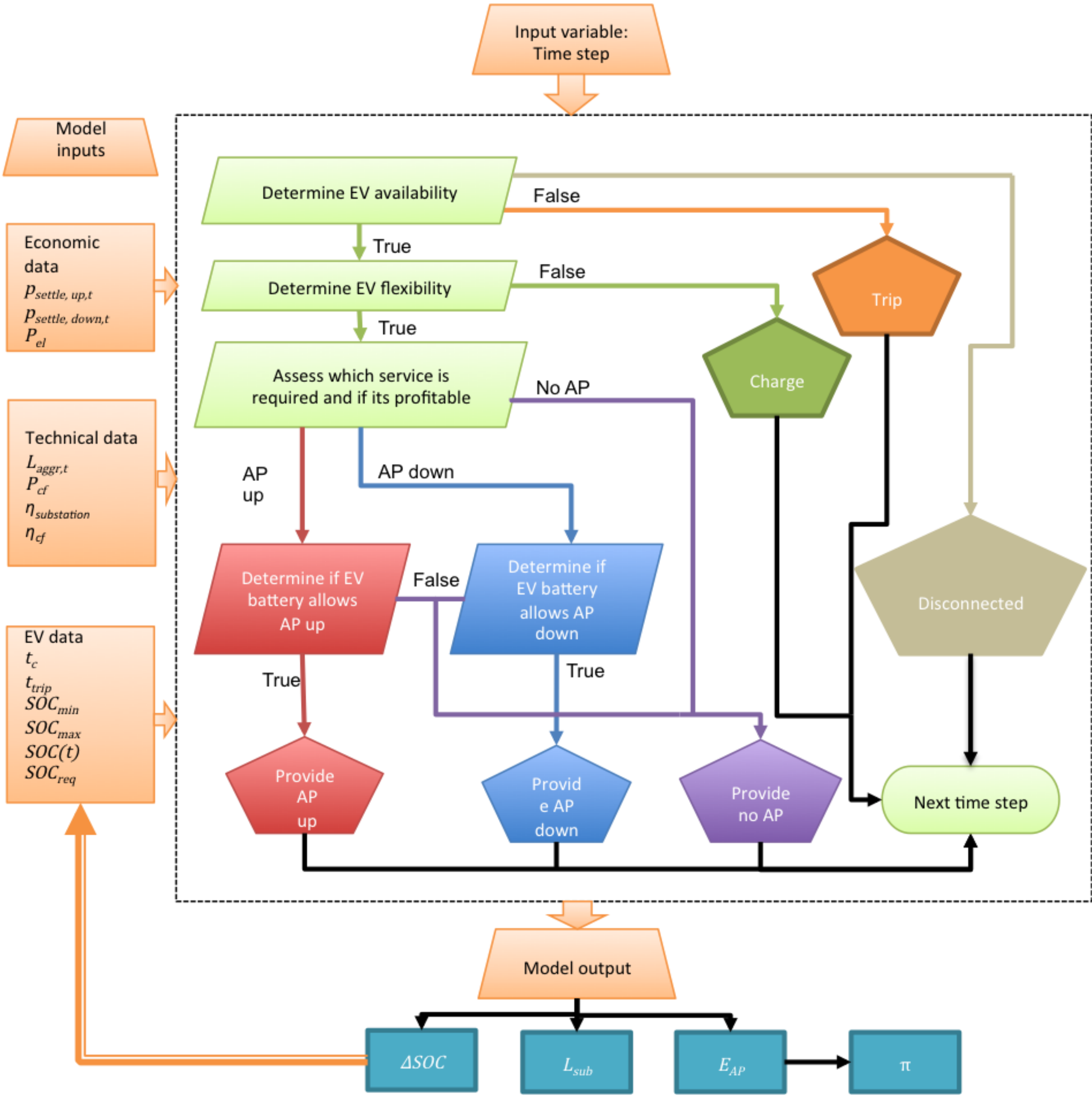

Figure 3.2.2: Schematic overview of the RRP dispatch scheme

The blocks within the dotted line in figure 3.2.2 represent the algorithm that is applied to assess the potential of RRP provision. Similar to the baseline situation, the parallelograms represent assessments that ultimately lead to a pentagonal block where calculations are made that result in model output that can be compared to the baseline situation. The model output always consists of the change in SOC, the resulting load on the substation, energy exchanged with the system and associated profits.

1. Determine EV connection

The first parallelogram is identical to the baseline scenario and associated calculations.

2. Determine if the EV has flexibility

This assessment checks if the EV has the flexibility to provide RRP. An EV will be used for transport at time step t_{trip} at which point it will prefer at least a certain SOC ($SOC_{trip}(t_{trip})$) (Van der Kam, 2013; Vandael et al., 2013). This value does not necessarily represent the technically required SOC for a trip, but could also take on a value preferred by the EV driver. Depending on the charging capacity of the EV a certain amount of time is needed to reach $SOC_{trip}(t_{trip})$. The blue line in figure 3.2.3 illustrates this. In this case the EV takes a one-hour trip at 8:00 and 17:30, similar to a working day routine. To make this trip the EV driver prefers a SOC_{trip} of 100%. The blue line represents the minimal SOC (SOC_{req}) of the battery that is necessary at each time step t in order achieve 100% SOC at the time of departure (t_{trip}). When the SOC at time step t, $SOC(t)$, is equal to or smaller than $SOC_{req}(t)$ then the EV has to charge and therefore possesses no flexibility to provide RRP. This yields a false signal and initiates charging similar to the baseline charging scheme. If $SOC(t)$ is higher than $SOC_{req}(t)$ then this yields a true signal where after the model proceeds with the next assessment regarding the provision of RRP. The conditions for flexibility are described in equations 3.7 and 3.8.

$$SOC(t) > SOC_{req}(t) \tag{3.7}$$

$$SOC_{req}(t) = SOC_{trip}\left(t_{trip}\right) - P_{cf} * \eta_{cf} * (t_{trip} - t) \tag{3.8}$$

With: P_{cf} = Vehicle's charging power capacity
η_{cf} = Charging conversion efficiency

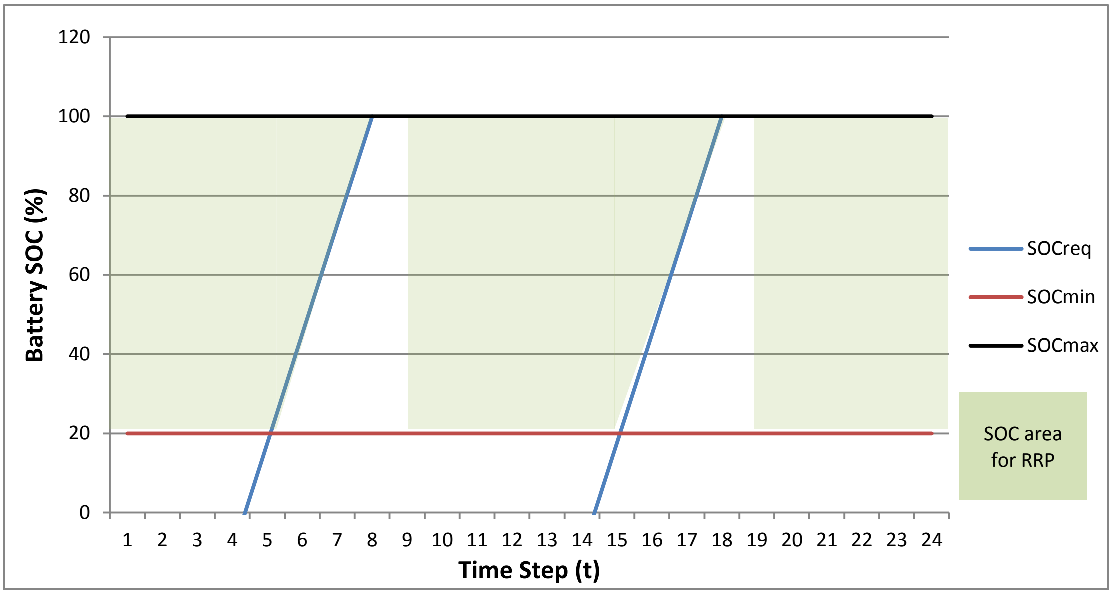

Figure 3.2.3: Graphical representation of possible battery SOCs

3. Assess which form of power is required and if it's profitable

At this point there can be 4 options: provide RRP up, provide RRP down, charge and provide no RRP. Each of these options has its specific costs and benefits (table 3.2.1). Firstly the algorithm assesses which form of power is required. Secondly, it assess if it is profitable to deliver that power. Providing RRP up always results in receiving settlement price ($p_{settle,\ up}$) from TenneT. Providing RRP down results in paying settlement price ($p_{settle,\ down}$) to TenneT. Based on these prices alone, one could state that the provision of RRP is profitable if the prices are positive for RRP up and negative for RRP down. Using these conditions would yield a positive return for each transaction with the market for RRP. However, such a charging scheme could prove to be unfavourable in case more RRP up than -down is called at a lower price than the electricity price. In such a situation the EVs would mostly be discharging and therefore have a low SOC at the time that the flexibility constraint is met. The EV then has to charge at the rate of the electricity price until the battery reaches its preferred SOC. In short, it occurs that a unit of electricity provided as RRP up at a settlement price of $p_{settle,up}$ has to be replaced by a unit of electricity obtained by regular charging at rate of p_{el}, which is higher than $p_{settle,up}$ and therefore induces losses. To ensure that this never occurs RRP up is considered profitable when the settlement price for RRP up is higher than the electricity price. RRP down is considered profitable when the settlement price for RRP down is lower than the electricity price. These specific profitability conditions are hereafter referred to as risk-averse, because under these conditions it is not possible to generate less profit than under the baseline charging scheme.

	Condition	Benefits (per kWh)	Costs (per kWh)
Upward RRP	$p_{settle,\ up} > p_{el}$	$p_{settle,\ up}$	
Downward RRP	$P_{settle,\ down} < p_{el}$	-	$p_{settle,\ down}$
Charging	$SOC(t) < SOC_{req}(t)$		p_{el}
No RRP		-	-

Table 3.2.1: Variables used for determining costs and benefits

If it is profitable to provide either RRP up or down, then technical feasibility with regard to the battery SOC will be assessed. If providing no RRP is most profitable the model will proceed to the next time step.

4. Determine if battery SOC allows selected option and RRP calculation

In this step the technical feasibility of the selected option is tested. Providing RRP has an impact on the battery SOC and this should be taken in consideration when providing RRP. If the provision of RRP is feasible calculations are made for the change in battery SOC and the provided RRP.

Providing RRP up discharges the battery according to equation 3.10. If RRP up is selected then it can only be provided if the resulting SOC is more than both the minimum SOC and required SOC of the battery (equation 3.10). This is illustrated in figure 3.2.3 by the red and blue line. The green area indicates which SOCs are possible at each time step, hereafter referred to as the SOC area. The amount of RRP delivered to the TSO is calculated according to equation 3.10.

$$SOC(t+1) = SOC(t) - P_{cf} * \Delta t \qquad (3.9)$$

$$E_{RRP,up,t} = \begin{cases} \frac{(SOC(t+1) - SOC(t)) * \eta_{cf}}{\eta_{sub}} & if \quad SOC(t+1) \geq SOC_{min} \wedge SOC(t+1) \geq SOC_{req} \\ 0 & else \end{cases} \qquad (3.10)$$

Providing RRP down charges the battery similar to the baseline scenario. In case RRP down is selected it can only be provided if the resulting SOC is less than the maximum SOC of the battery. Providing regulation down charges the battery and therefore no more regulation can be provided if the battery is full. The black line in figure 3.2.3 illustrates this. The amount of RRP delivered to the TSO is calculated according to equation 3.11.

$$E_{RRP,down,t} = \begin{cases} \frac{SOC(t+1) - SOC(t)}{\eta_{cf} * \eta_{sub}} & if \quad SOC(t+1) \leq SOC_{max} \\ 0 & else \end{cases} \qquad (3.11)$$

Failing to comply with the constraints with regard to battery capacity results in a “False” signal, whereby no RRP will be delivered. When conditions are met a “True” signal will be produced and RRP will be delivered. Figure 3.2.2 shows that both the “False” and the “True” signal result in a pentagonal block where model output is calculated.When charging is required this is identical to the baseline situation. For RRP provision the settlement price is paid or received and therefore there is a slightly different formula used (equation 3.12).

$$\pi_{t,RRP} = E_{RRP} * p_{settle} \qquad (3.12)$$

3.3 Key performance indicators

One of the aims of this research is to determine the value that can be generated by EV owners by providing RRP. This can be expressed as the profit (π) that is obtained over period T. Since this research uses the regular charging scheme as the comparative base, these profits are defined as the difference between the revenues obtained by providing RRP and the revenues obtained in the baseline charging scheme (equation 3.13).

$$\pi = \sum_{t=1}^{T} \left(\pi_{t,RRP} - \pi_{baseline,t}\right) \tag{3.13}$$

A second important indicator is the SOC distribution. By providing RRP the SOC follows an irregular trajectory, contrary to baseline charging where the SOC trajectory is relatively predictable as charging starts immediately after connection and continues until the battery is full. In case of unplanned trips it is therefore more likely that the EV has sufficient SOC to make that trip. The irregular SOC trajectory that characterizes the provision of RRP yields the possibility that there is insufficient SOC for these kinds of trips. To compare the SOC trajectories of both charging schemes their respective distribution is calculated. The distribution can subsequently be used to identify two more performance indicators; the percentage of time that each SOC value is available in the battery and the depth to which the battery is discharged.

Third important set of indicators is the impact on the battery throughput and depth of discharging cycles. In section 2.2.5 it is explained how these parameters influence battery degradation and therefore costs. Both the number of cycling and the depth of discharge are mentioned as key characteristics for determining battery degradation costs. Because a quantification of degradation costs was not feasible within the time constraints for this research this assessment will be limited to general statements regarding battery throughput and cycle depth and the implications it has for battery degradation.

The final indicator under investigation is the resulting load on the substation. The provision of RRP results in a less predictable load on the substation. Density plots will be composed in order to visualize the impact of different charging schemes on the load on the substation.

3.4 Input data

3.4.1 Economic data

In the model two kinds of economic data inputs are used, settlement prices and electricity prices. Usually, electricity prices consist of the following components: supply costs, network costs and taxes. With regard to charging EVs some additional costs apply. Settlement prices are "energy-only' prices and subject to a 21% VAT. The following subsection will explain these prices and how they are used in the model in order to make a substantiated comparison between the different charging schemes.

3.4.1.1 Settlement prices

For 2014 the balance delta with prices was retrieved from Tennet. This dataset lists the amount of settled regulating-, reserve- and emergency power and associated settlement prices on a minute basis. The dataset only lists the highest price for activated RRP up and the lowest price for RRP down. Using these prices means that in case of RRP up the EV gets the highest possible price and in case of RRP down the EV pays the lowest possible price. As a result each transaction in the simulation assumes that the aggregator possesses perfect information on the bids that will be selected and can therefore place each bid in such a way that the maximum value will be generated.

For regulating power is it can occur that within one minute dispatch takes place in both directions. In the dataset this occurs 9431 times, which is around 2% of the time. When this occurs the model will favour RRP up, as in the profitability assessments this option is firsts assessed. Because this will yield a "True" signal RRP down will not be assessed on profitability and the model will proceed making the calculations for RRP up.

The total dataset contains 525556 time-steps, which means that 44 are missing as a full year consists of 525600 time-steps. The missing values are given the value of 0, thereby assuming that at that time no RRP is called. Figure 3.4.1 shows for which percentage of time each situation applies.

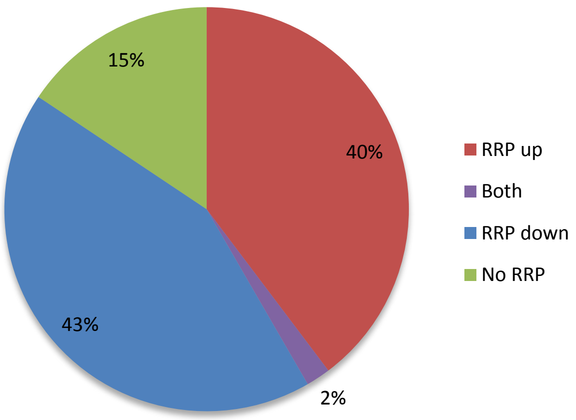

Figure 3.4.1: Occurrence of RRP in the dataset based on settlement prices

Figure 3.4.2 shows the distribution of the settlement prices for RRP up and down. For RRP up the settlement prices mainly range between € 0.025/kWh and € 0.075/kWh, with a smaller peak around € 0.12/kWh and € 0.35/kWh. The settlement prices for RRP down are more concentrated. Most values range between € 0,00/kWh and € 0.05/kWh, with a very large peak around € 0.025/kWh. Negative settlement prices occur relatively little, which indicates that RRP down will mostly contribute to lower charging costs and not to direct profits.

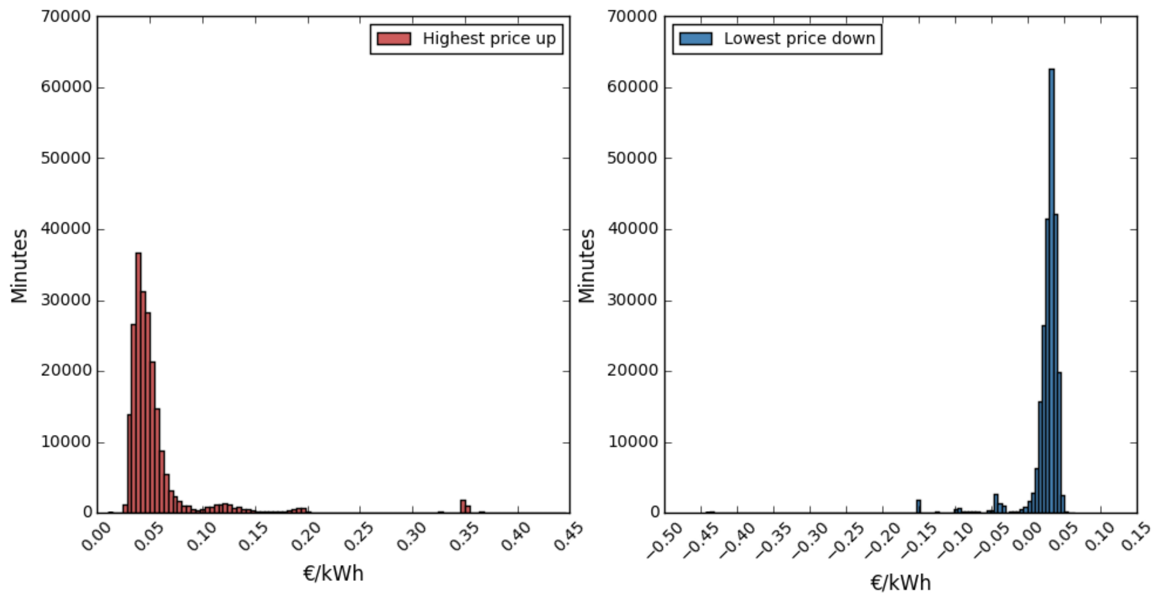

Figure 3.4.2: Distribution of settlement prices for RRP

3.4.1.2 Electricity prices for EV charging

Prices for charging at charging facilities are built up from several components and differ depending on the provider[3]. In general the price of charging is composed of the following components (Jop Spoelstra, personal communication, 13-08-2015):

- Energy price. The price paid for electricity. Generally speaking this lies around 24 cents per kWh, including 21% VAT. The electricity price is in turn composed of supply costs, network costs and environmental – and value-added taxes.
- Service-provider fee. This is basically the price paid for all services surrounding the actual charging transaction, such as the fee for charging passes and administrative costs. This fee is charged in different ways depending on the provider. Some choose for a fee per kWh charged, while others use a fixed fee per transaction or month.
- Installation remuneration (In Dutch: “Installatievergoeding”). This fee is only applied for public charging facilities operated by “Stiching E-Laad” and consists of a 50 cents starting fee and 0,05 cent per kWh, excluding VAT.

Due to the diverse and sometimes opaque composition of the electricity price for charging, it is chosen to only assess the energy price in the calculations. Additionally, since settlement prices are currently not subject to network costs or any of the service fee’s discussed above, it is decided to use the supply costs of electricity as input for the model. Based on the supply costs used in Claessen (2012) and the breakdown of the average electricity price of the three largest electricity providers in the Netherlands[4], it is assumed that the supply costs of electricity is around 44% of the electricity price. This yields 10,56 cents/kWh based on the energy price provided by Spoelstra. In the model this will be rounded down to 10 cents/kWh.

3.4.2 Technical data

Two types of technical data are used in the model. Firstly the assumptions surrounding the capacity- and efficiency of the substation and the external network are presented. Secondly the construction and use of the aggregated load is discussed.

[3] For an overview of charging providers and associated charging prices in the Netherlands see: www.zerijden.nl/laden/laadpassen

[4] https://www.energiewereld.nl/energienota/de-opbouw-van-de-energierekening

3.4.2.1 Infrastructure

Distribution grids are tailor-made for each specific service area with its specific load patterns and therefore it must be stated that there is no such thing as an "average" distribution grid. In order to make a representative assumption of infrastructure capacity a series of key figures was provided by Thijs Turel (personal communication, August 3rd, 2015) who is employed at Liander, a large Dutch DSO. These figures will be used to make assumptions used in the model.

The ratio between residential- and commercial use is difficult to specify. Mattheo van der Molen of Allego, a subsidiary of Alliander that focuses on electric mobility, suggested that a ratio of 30 businesses vs. 70 households could be realistic based on his observations in the center of Arnhem.

To account for transmission losses that occur between the high- and low voltage network the Dutch average is used (Van Oirsouw, 2012). Transmission losses in the Netherlands range between 3% and 10% with an average of 8%. This means that each unit of energy exchanged with the external grid is subject to 8% transmission losses. In general this works beneficial for RRP provision by EVs as under these assumptions 1 MW of RRP provided from the LV grid results in 1.08 MW of RRP at the HV level.

	Key figures	Used in model
Number of connections	200	200
Transformers capacity (kVA)	150, 200, 400, 630	400
Substation capacity (KW)	360[1]	360[1]
Ratio residential/commercial	70:30	70:30
Efficiency (%)	3-10	8

Table 3.4.1: Values used in the model

[1]The capacity of the substation is calculated using a power factor of 0.9

3.4.2.2 Aggregated load

In this research the aggregated load is defined as the load that is placed on the substation by households and businesses. To determine this, load profiles are constructed for the residential- and commercial load respectively based on actual consumption data. The construction of these profiles is presented in appendix 1. Combining these profiles according to the ratio between- and the number of residential and commercial connections yields the aggregated load profile that is representative for urban areas. This profile is presented in figure 3.4.3. In figure 3.4.4 it is shown how the residential and commercial load form the aggregated load during one week in March.

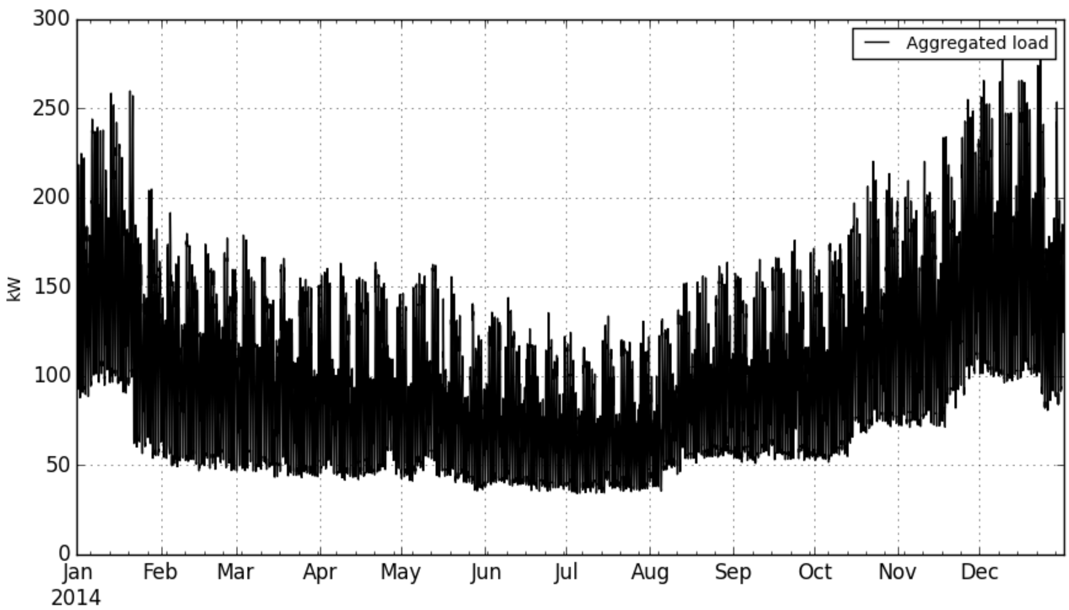

Figure 3.4.3: Aggregated load

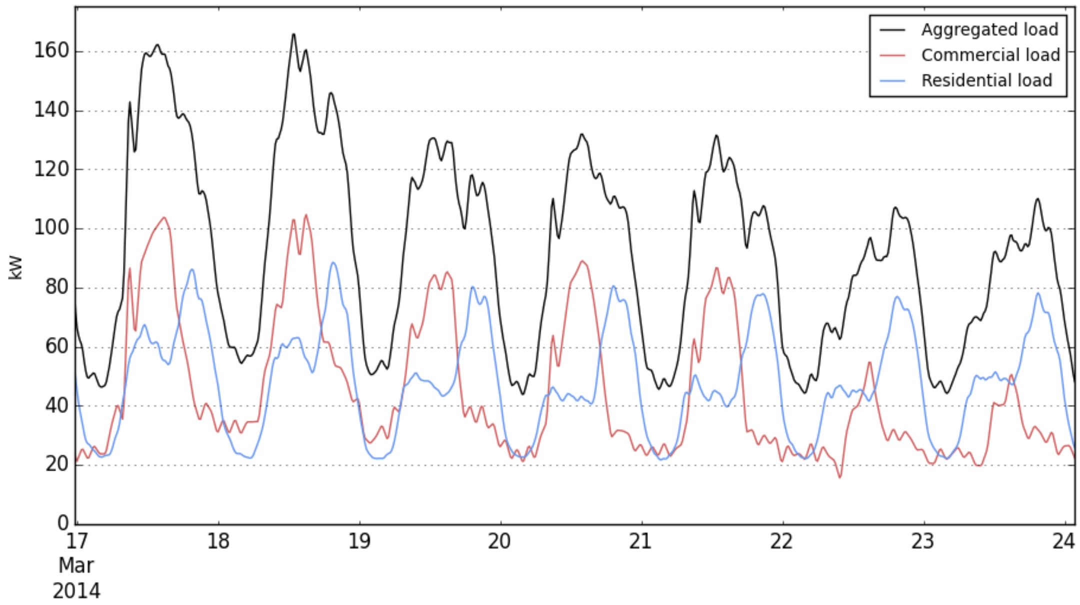

Figure 3.4.4: Loads in an urban area

3.4.3 EV data

This section presents the EV data used in the model simulations. Thereby a distinction is made between vehicle characteristics, which focus on the technical components of the EVs, and user-related characteristics, where the focus is placed on the EV driver's routines and preferences.

3.4.3.1 Vehicle characteristics

The vehicles selected for the model are the 2 most commonly used battery electric vehicles (BEV) and the 2 commonly used plug –in hybrid electric vehicles (PHEV). The overview in chapter 2.2 shows that the Volvo V60 is the second most sold PHEV, but since it has very similar specifications as the Mitsubishi Outlander, the Opel Ampera was selected as second PHEV. Each car has different specifications with regard to battery capacity, charging power and –efficiency. These specifications (table 3.4.2) are either retrieved from manufacturers, thenewmotion.com and literature or assumed in case of missing data. With regard to the minimal SOC all EVs are assigned a value that corresponds to 20% of the SOC. This is based on both values found in publications ((Saxena, MacDonald, & Moura, 2015; Van der Kam, 2013) and on personal communications with Bart Sloep of Mitsubishi Motors. Note that for the Tesla Model S and Nissan Leaf two values are presented for charging power. The Tesla's 22 kW charging power refers to fast charging. Fast charging is accompanied by low time ratios and will therefore be less suitable for RRP provision. Unless otherwise stated, the Tesla's performance will be modeled under a power capacity of 11 kW. The Nissan Leaf has a rated charging power of 3,7 kW (single phase, 16 Ampère) and 6,6 kW (single phase, 28 Ampère). In the model a charging power of 6,6 kW is used. In order to make statements regarding the driving range of the EVs the trip efficiency is retrieved. For the Outlander this value was not found. Like the Ampera, the Outlander has a secondary propulsion system. This should be taken in consideration when interpreting the results that relate to range.

	Battery capacity (kWh)	Minimal SOC (kWh)	Charging power (kW)	(Dis)charging efficiency (%)	Average power consumption (kW)	Driving efficiency (kWh/km)
Tesla Model S	85[1]	17[4]	11/22[2]	85[4]	8.5	0.200[5]
Nissan Leaf	24[1]	4,8[3]	3,7/6,6[2]	85[4]	7.2	0.137[5]
Mitsubishi Outlander	12[2]	2,4[1]	3,7[2]	85[4]	3.6	-
Opel Ampera	16[2]	3,2[4]	3,7[2]	85[4]	4.8	0.229[5]

Table 3.4.2: Technical specifications of the EVs used in the model.
[1] Manufacturers, [2] www.thenewmotion.com, [3] Saxena, MacDonald, & Moura (2015) & Van der Kam (2013), [4]Assumption, [5] http://www.verbruiken.nl/autos

3.4.3.2 User-related characteristics

In section 2.2.4 user-related characteristics of Dutch EV drivers are presented. Here a distinction is made between several user types, of which resident-commuters (RC), residents and commuters will be under investigation in this study. The RC user type is characterized by two charging sessions per day, one during the day and one during the night. The resident- and commuter user type both engage in one charging session per day. For the resident user type this is during the night and for the commuter user type during the day. Thus, the user types have different connection times and therefore differ in the time that they are available for RRP provision.

Each user type has identical preferences regarding trip times and required SOC. Note that required SOC is a constraint posed by the user's preferences and not directly by the distance that the user needs to travel. For example, a user with a required SOC setting of 100% wishes to have a full battery at the time of departure, while he or she will only consume 30% on a trip.

With regard to the trip times a duration of one hour is assumed, partly based on the commute time found in a publication of Kennisinstituut voor Mobilieitsbeleid (2013). In Helmus and Van der Hoed it is stated that the mean daily energy transfer for a resident or commuter is 60% of the vehicles SOC. Since residents and commuters only charge once a day and complete two trips, this means that the average energy consumption of a trip is 30% of the SOC of the EV. For the Tesla a lower amount of energy consumed is assumed as it has a significantly larger battery. If the assumption of 30% of the maximum SOC would be maintained for the Tesla this would result in a trip length of 128 km. This is extremely large considering that the used travel time is only one hour and the travel distances of the other EVs is much lower. Therefore the Tesla is assumed to consume 10% of its SOC during a trip. In table 3.4.3 and 3.4.4 the inputs are summarized.

	Initial SOC	Required SOC	SOC at time of connection		
			RC	Resident	Commuter
Tesla	100%	100%	90%	80%	80%
Leaf			70%	40%	40%
Outlander			70%	40%	40%
Ampera			70%	40%	40%

Table 3.4.4: Battery assumptions used in the model

	Trip times	Trip distance	Connection times		
			RC	Resident	Commuter
Tesla	8:00 – 8:59, 17:30 – 18:29	43 km	0:00 – 7:59, 9:00 – 17:29, 18:30 – 23:59	0:00 – 7:59, 18:30 – 23:59	9:00 – 17:29
Leaf		53 km			
Outlander		-			
Ampera		21 km			

Table 3.4.5: Assumptions used regarding to trip times

3.5 Sensitivity analysis

The inputs used to generate the results are to a certain extend based on assumptions regarding user-related characteristics, namely required SOC, minimal SOC and the duration and power consumption of trips. The sensitivity analysis investigates the impact of changes in these characteristics on the initial results. Additionally, the impacts of an increasing fleet size will be assessed.

Required SOC

The required SOC links to the driver's preferences, which hold a relation with their experience in using an EV and their planning of trips. Research from Spoelstra (2014) and Vandael (2015) shows that over time drivers become more aware of their energy needs and travel patterns. This implies that a very experienced driver could exactly state how much SOC he or she needs in order to complete the trip. Therefore the required SOC does not have to be 100% at the time of departure, which increases the SOC area for RRP. The EVs will be modeled under required SOC settings between 60% and 100% to assess the impact it has on the initial results.

Minimal SOC

The minimal SOC is varied in order to represent the driver's preferences. A driver who prefers a lower minimal SOC is can be more likely to have insufficient battery SOC in case of an unexpected trip, but increases its SOC area for RRP provision. Drivers who are more risk averse can avoid this by setting their preferred minimal SOC to a higher value. It is in particular interesting to assess if higher minimal SOCs have a negative effect on profits. If not, then concepts as range anxiety needn't be a limiting factor for RRP provision by EVs. Multiple minimal SOC settings between 20% and 90% will be applied to the EVs to investigate the impact of this setting.

Duration and power consumption of trips

In the initial simulations it is assumed that the EVs consume 30% of their battery SOC during a trip that lasts for 60 minutes. In case EV's consume less energy and drive for a shorter time this will lower the costs of charging and yields more available energy to provide as RRP up. Contrarily it yields less available capacity for RRP down and more time for RRP in general. The opposite applies when EVs consume more energy and engage in longer trips. In this analysis the results will be assessed for a trip durations that are respectively 15 minutes shorter and longer. The energy consumption of those trips is assumed to charge proportionally.

Number of electric vehicles

In this assessment the impact of a larger fleet of EVs on the loads on the substation is investigated. This is done by multiplying the fleet used in the initial simulations with a factor of 2, 3, 4 and 5, respectively.

4 Results

The methodology and input data described in the previous chapter are used to simulate the four EVs during one year, based on 2014. This is done three times, one for each user type. Due to the irregular charging patterns in the weekends, only working days are assessed. To exclude the EVs during the weekend they maintain their SOC of Friday 23:59 until Sunday 23:59 and during this period they do not engage in any trips, RRP or charging. Essentially, they are treated as if they are parked and disconnected from any charging facility. This chapter will consist of three parts. Firstly, the baseline charging- and RRP dispatch scheme will be compared in section 4.1 and 4.2. To illustrate the impact of the user types and the two dispatch schemes on the loads, SOC and profit generation of each EV, section 4.1 presents one day of the results. In section 4.2 the annual results will be presented. Section 4.3 will describe the relation between RRP provision, battery capacity and charging capacity.

4.1 Comparing the dispatch schemes based on one day

In figure 4.1.1 the load on the substation, SOC of the EVs and profits are plotted during one day for the different user types under the baseline charging scheme. The left y-axis shows the load on the substation in kW and the absolute SOC in kWh. The right y-axis shows the profits in €. The red, green, blue and orange solid lines represent the load that is placed on the substation by the Tesla, Leaf, Outlander and Ampera, respectively. If the EVs are charging the load will increase according to the EV's charging capacity. The black line represents the load on the substation without any EVs, which is the aggregated load constructed in chapter 3.4.2.2. The purple line presents the final load that is the result of the activities of all EVs combined. The dashed lines represent the absolute SOC of the EVs in kWh. The dotted lines represent the profits that are made by the EVs and are plotted against the right y-axis. Under the baseline charging scheme these profits are always negative, since only charging costs are made.
The RC user type is plotted in upper plot in figure 4.1.1. Here it can be seen that the substation experiences two moments where loads are increased by the EVs, directly after 9:00 and 18:30 when the EVs connect to the charging facilities. The duration of charging depends on the combination of consumed energy during the trip and the charging capacity of the EV. With regard to the vehicles under investigation this means that the Tesla has the shortest charging time, followed by the Outlander, Leaf and Ampera. Closely inspecting the loads also shows this sequence. When assessing the SOC of the EVs a decrease becomes visible as soon as a trip starts at 8:00 and 17:30, which is immediately followed by an increase in SOC when they connect to a charging facility and start charging one hour later. Note that the lines of the SOC all have different slopes due to their different power consumption and charging capacities. During charging the EVs pay the electricity price per unit of electricity charged to the battery. Again the impact of charging capacity becomes visible, as higher capacities results in higher costs per unit of time.
In the plot for the resident user type a different picture is seen. Since the EVs are fully charged the day before, the loads are not altered until the next charging session, which takes place at 18:30. Because the EVs have completed two trips without any charging a longer charging session is required, which becomes clearly visible in the loads. With regard to the SOC it can be seen that this is discharged during the trip, stays at a constant value during working hours, is further depleted during the return trip, and is subsequently recharged to its maximum SOC. In line with the longer uninterrupted charging time this leads to a longer uninterrupted time of cost generation.
The final plot represents the commuter user type. Like the resident user type, the commuter only engages in one charging session per day where it has to recharge the energy consumed by two trips. For the commuter this session takes place at 9:00 after the morning commute. After the return trip the EV spends the whole night at the same SOC, until it departs again the next morning.

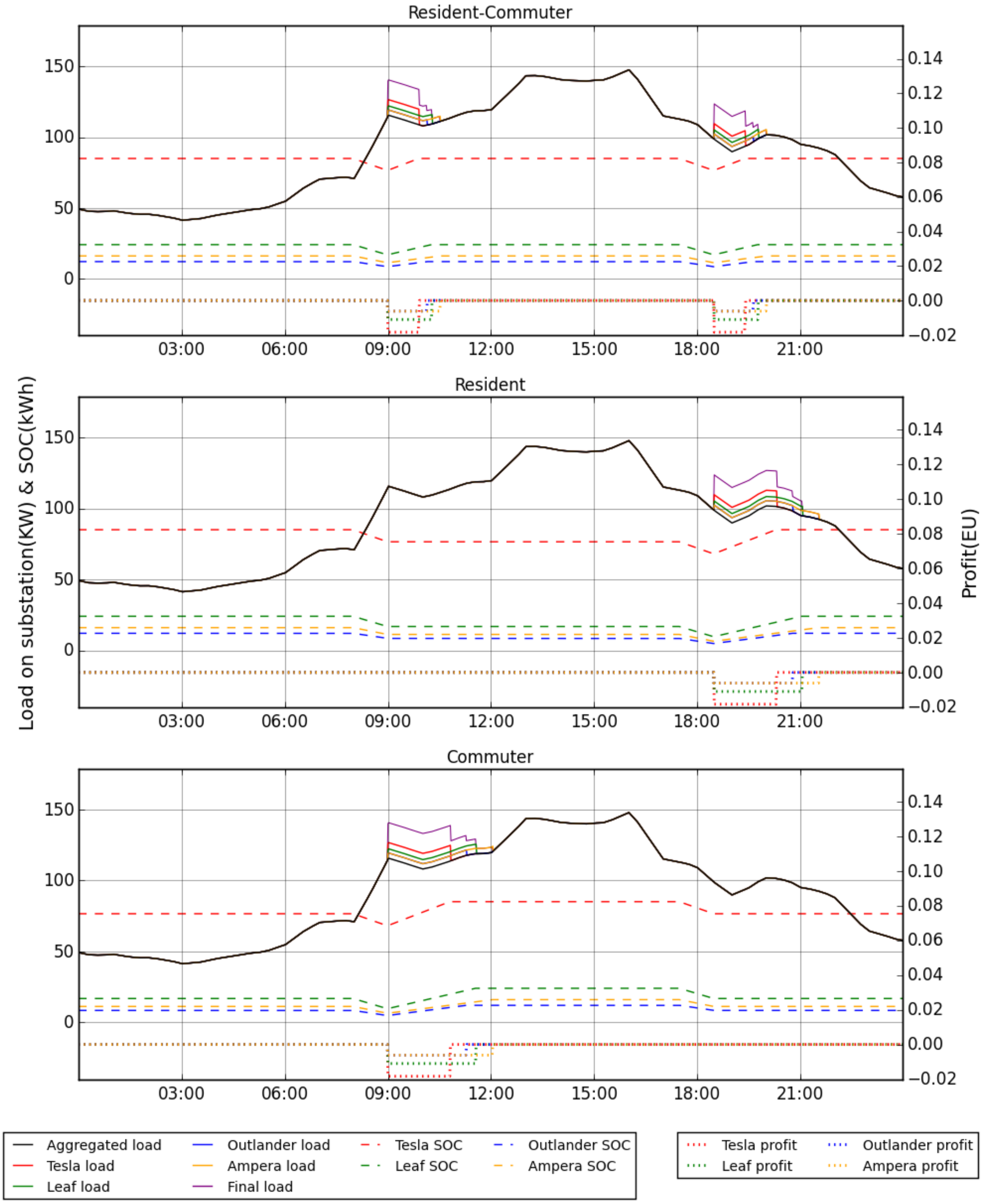

Figure 4.1.1: Load, SOC and profits during one day (10th April) for different user types under the baseline charging scheme

In figure 4.1.2 the load on the substation, SOC of the EVs and profits during one day are presented for each user type under the RRP dispatch scheme. When assessing the RC user type it can be seen that the first 9 hours are identical to the baseline charging scheme, which means that during that time the settlement prices are unfavorable for RRP up. Prices could be favorable for RRP down, but this cannot be provided since each EV has a full battery. Shortly after the morning commute the EVs start providing RRP down, which results in increased load and SOC. Note the profit line becomes negative because the settlement price is to be paid to the TSO. The profits are however less negative in comparison with the baseline scenario. The Tesla is the first to reach a SOC of 100% and therefore stops providing RRP down around 11:30. The other EVs have lower charging capacities and can continue to provide RRP down, with an interruption around 11:45 where prices apparently become unfavorable for a short time. Around 13:30 there is a short call for RRP up, which is shown by a decrease in load and SOC and a positive profit. Note that in this case energy is sold to the TSO at a much higher price than what it was bought for a short while earlier. After that there is either no call for RRP or only at prices that violate the profitability condition and therefore no RRP is delivered. This results in an unaltered load and constant SOC. Before the evening commute there are two more short periods of RRP down provision, which is sufficient to yield a full battery at the time of departure. After the evening trip there is again need for RRP down as shown by the increasing load and SOC directly after connection. During the rest of the evening the EVs only engage in three short periods of RRP, once in upwards direction and twice in downwards direction.

The resident user type can only provide RRP during its connection times between 18:30 and 7:59 the next day. The plot for the RC user type showed that there are favorable prices for RRP down provision and it can be seen that the resident user types benefits from those prices in a larger extent. At the time of connection the EVs have a relatively low SOC due to the two trips that were made without charging in between them. This provides more battery capacity for RRP down provision, which becomes visible in the longer duration of increased load, SOC increase and profit generation.

The commuter user type can only provide RRP between 9:00 and 17:29. Like the resident user type the EVs have a relatively low SOC at the time of connection and therefore can provide RRP down for a longer period. At 13:00 all EVs reach a SOC of 100% and follow the same pattern of RRP provision as the RC user type, until 17:29 when the EVs disconnect and are not capable to provide any RRP until 9:00 the next day. Note that in this case the EVs reach sufficient SOC through the provision of RRP down to make the upcoming trip.

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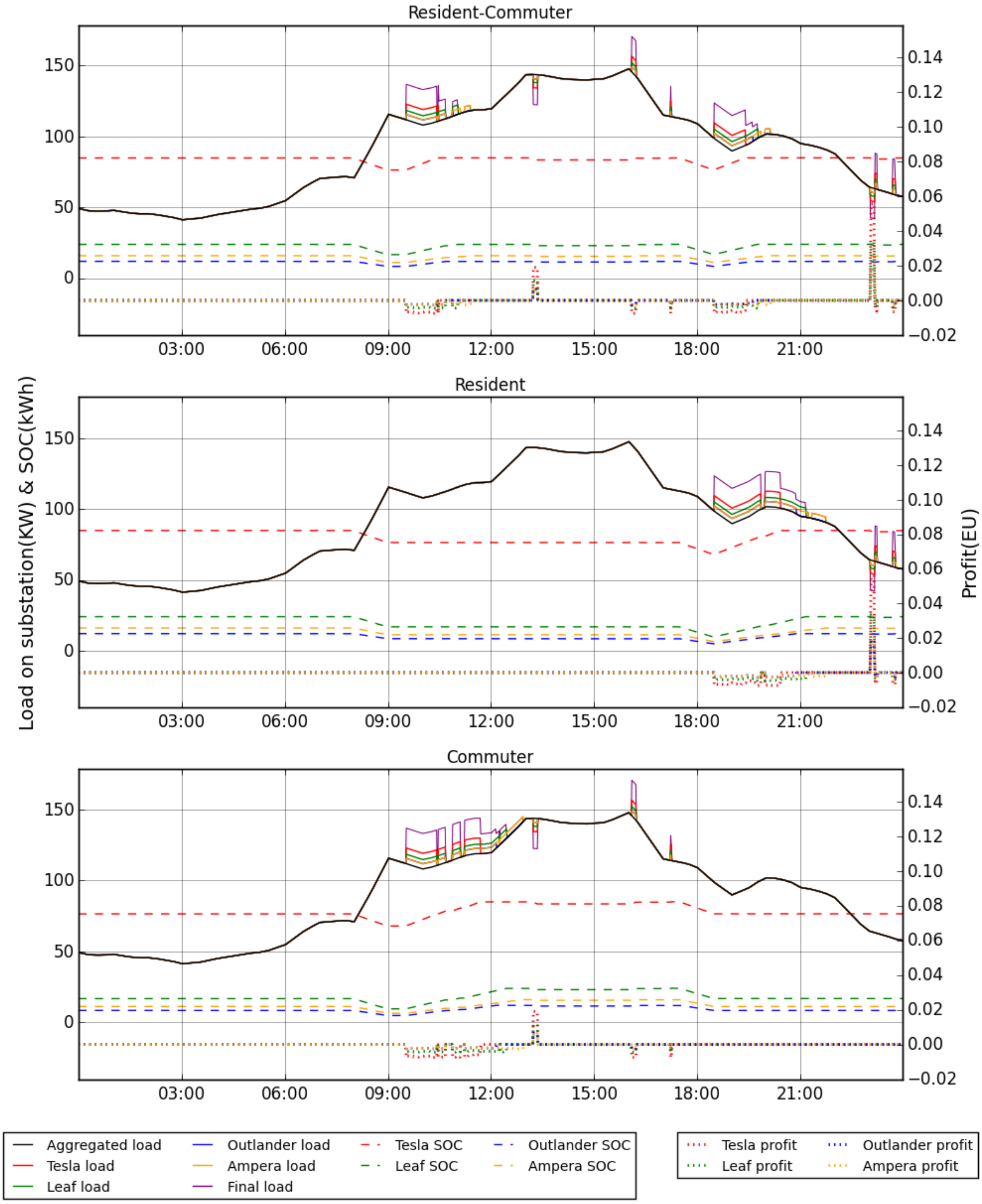


Figure 4.1.2: Loads, SOCs and profits during one day (10th April) for different user types under the RRP dispatch scheme

4.2 Comparing the dispatch schemes based on one year

In this section the annual results of the baseline charging- and RRP dispatch scheme are presented and compared. This comparison is divided in three sections. Firstly the battery KPI are assessed followed by the loads on the substation and finally the economic KPI.

4.2.1 Battery KPI

In figure 4.2.3 the SOC distributions of the EVs under the baseline charging- and RRP dispatch scheme are shown. From left to right each column of four subplots presents the SOC distribution of the EVs for the RC-, resident- and commuter user type respectively. The plot shows the percentage of time that a certain SOC or SOC range is observed.

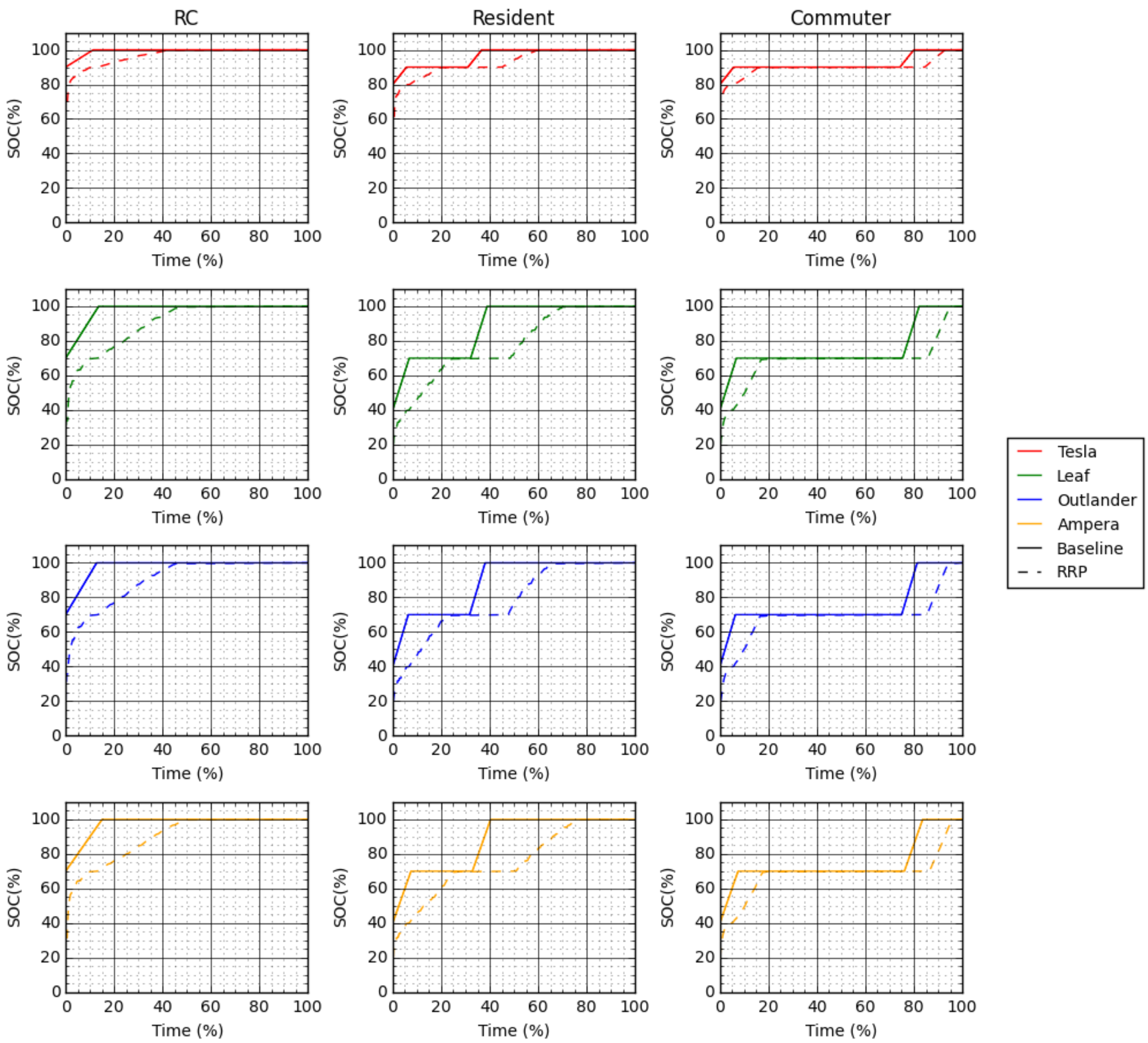


Figure 4.2.3: SOC distribution of the EVs for one year for different user types under the baseline charging-(solid) and RRP dispatch scheme (dashed)

To explain how figure 4.2.3 should be interpreted the SOC distribution of the Tesla is described for the RC user type under the baseline charging scheme. In this case the Tesla has a SOC of 100% for around 90% of the time. In this research an unexpected trip is assumed to have the same energy requirements as a normal trip. Taking into account that the minimum SOC is 20% this means that the Tesla needs at least 30% SOC to make an unexpected trip. This value is never reached and therefore an unexpected trip can always be made. When looking at the other EVs for the RC user type similar percentages can be found for the occurrence of a full battery and the occurrence of sufficient SOC to make a trip.

The other user types show a lower SOC distribution due to the fact that they only charge once a day. In addition, the EVs spend a lower amount of time at their maximum SOC. This is between 60% and 65% for the resident user type and between 25% and 20% for the commuter user type. It can also be seen that the SOC stays horizontal at the SOC value that is reached after a trip. For the commuter this value is maintained longer as it spends more time parked and not charging. Under these user types the Tesla is the only EV who is always capable of making an unexpected trip. The Leaf, Outlander and Ampera have smaller battery capacities and endure a slight loss in the ability to make an unexpected trip (table 4.2.1).

	Ability to make an unexpected trip
	Resident & Commuter
Tesla	100%
Leaf	98%
Outlander	98%
Ampera	97%

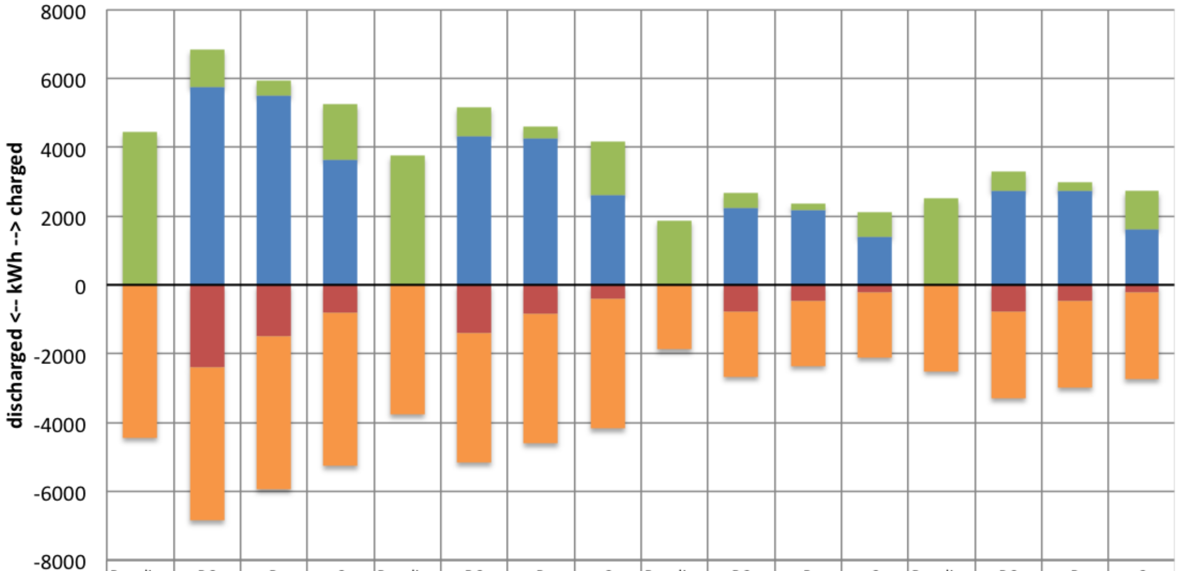
Table 4.2.1: Percentage of time that an EV has sufficient SOC for an unexpected trip under the baseline charging scheme

Under the RRP dispatch scheme SOC values below the SOC value after a trip become visible as a result from RRP up provision. Additionally, the EVs spend a shorter percentage of time at a SOC of 100%, since the battery is only charged in case RRP down is provided or if charging takes place to satisfy the required SOC. The provision of RRP has some implications for the ability to make unexpected trips. In table 4.2.2 it can be seen that under the RRP dispatch scheme the ability to make unexpected trips is lower than under the baseline charging scheme. The Tesla, benefitting from a larger battery, is still able to make an unexpected trip for 100% of the time, regardless of the user type. When assessing the other vehicles it can be seen that they do lose the ability to make an unexpected trip for a small percentage of the time. For the RC user type this percentage is still rather small, but this becomes larger for the resident- and commuter user type.

	Ability to make an unexpected trip		
	R-C	Resident	Commuter
Tesla	100%	100%	100%
Leaf	99%	88%	90%
Outlander	98%	88%	90%
Ampera	99%	86%	90%

Table 4.2.2: Percentage of time that an EV has sufficient SOC for an unexpected trip under the RRP dispatch scheme

The battery throughput is defined as the total amount of energy that is cycled through the battery and is obtained by the taking the absolute sum of all changes in SOC values. In figure 4.2.4 these are displayed for each EV and user type. Under the baseline charging scheme the user type has no influence on the battery throughput, consisting of ‘charged’ and ‘driven’, since the travel pattern and energy requirements of each EV is the same. Therefore figure 4.2.4 only shows one column per EV for the baseline charging scheme. Under the RRP dispatch scenario RRP up and RRP down are added as components of battery throughput. When providing RRP user type does have an influence on battery throughput and therefore each user type is presented separately.



	Tesla				Leaf				Outlander				Ampera			
	Baseline	RC	R	C	Baseline	RC	R	C	Baseline	RC	R	C	Baseline	RC	R	C
Charged	4437	1097	446	1603	3758	832	346	1541	1879	418	166	718	2506	556	262	1109
Driven	-4437	-4437	-4437	-4437	-3758	-3758	-3758	-3758	-1879	-1879	-1879	-1879	-2506	-2506	-2506	-2506
Down	0	5746	5489	3645	0	4329	4259	2624	0	2249	2187	1390	0	2734	2720	1617
Up	0	-2406	-1498	-820	0	-1403	-847	-414	0	-788	-474	-232	0	-784	-477	-225

Figure 4.2.5: Annual battery throughput for different EVs and user types under the RRP dispatch scheme

When comparing the EV between different user types a relation can be identified between the connection time and battery throughput, since user types with longer connection times have a higher battery throughput. However, the relation between connection time and battery throughput is non linear. The RC user types are connected for more than twice as long as the commuter user type, but the throughput is not twice as large.

When assessing the individual EVs it can be observed that the battery throughput is higher for EVs with a higher battery- and charging capacity. All EVs show a large share of RRP down provision, which reduces the need for charging. Especially for resident user types, who nearly eliminate the need for charging by providing RRP down.

If the provision of RRP up is compared between the different EVs a relation with charging capacity can be observed. The Outlander and the Ampara, who have the same charging capacity, provide almost the same amount of RRP up. The Leaf has a charging capacity that is a factor 1.78 higher, which is roughly the factor that is obtained when comparing the provided RRP up. The relation between battery capacity, charging capacity and RRP provision will be discussed more extensively in a separate section.

When throughput under the RRP dispatch scheme is compared with the baseline charging scheme a significant increase can be observed for each user type. Additionally the SOC distribution shows that under each user type the cycle depth is twice as large as under the baseline charging scheme. This indicates that the EVs experience increased battery degradation under the RRP dispatch scheme.

4.2.2 Impact on the load on the substation

The charging and discharging of EVs has an impact on the loads on the substation. In figure 4.2.6 the occurrence of loads for both dispatch scenarios are presented in a density plot. The black line represents the loads without any EVs. The colored lines represent the loads under the different user types.

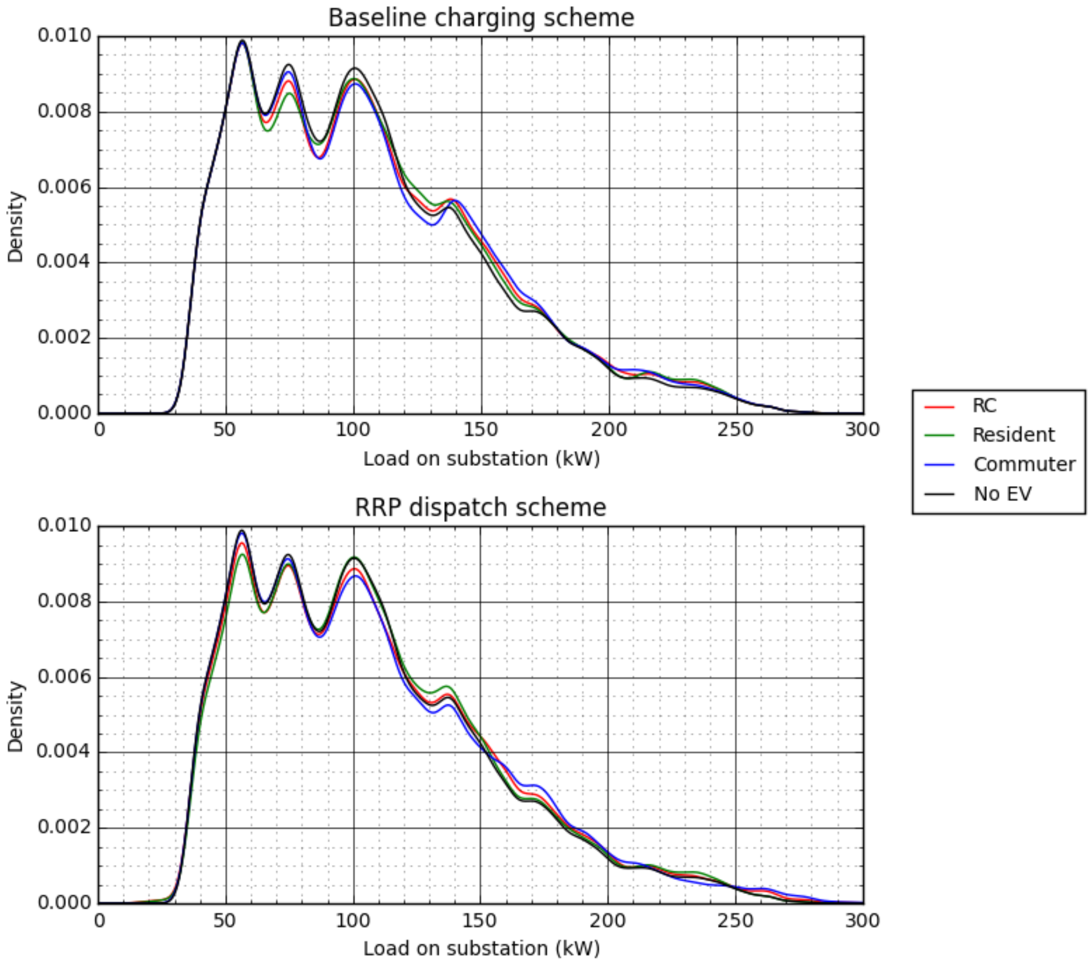


Figure 3.2.6: Density plot of loads under the baseline charging- (upper) and RRP dispatch scheme (lower) for one year

Under the baseline charging scheme the RC user type completes 2 short charging sessions and resident- and commuter user type one longer session, respectively in the evening and morning. It can be observed that the EVs shift loads in the range 60 kW to 130 KW to the range 130 kW to 180 kW and 180 kW to 240 kW. In other words, the EVs charge at times where the load on the substation without EVs would have a value between 60 kW and 130 kW. At those times the loads are increased which results in a higher occurrence of higher loads. The EVs are not charging at midday, which results in an unaltered peak load.

Under the RRP dispatch scheme loads can be placed on the substation over the entire timespan that the EV is connected to the charging facility. This has multiple impacts on the load on the substation when compared to the baseline scenario. Initially, the provision of RRP up reduces load at the time of delivery. However, since eventually this volume of energy has to be replaced, it causes an additional load on the substation when this is recharged through RRP down provision or regular charging. In contrary to the baseline charging scheme a shift in loads in less clearly seen. What does become visible is that through the provision of RRP a wider range of loads is altered. In the baseline charging scheme the loads stay equal to the situation without EV until a load of 60 kW. When further inspecting the density plot it can be seen the each line more or less follows the line that represents the situation without any EV, although a slight increase in peak loads is visible for the RC- and commuter user type. This is as expected as only those user types user type are active during the time where peak loads already occur.

4.2.3 Economic KPI

Under the baseline charging scheme the economic KPI are, like the battery throughput rather straightforward as the EVs undergo the same charging costs on each weekday. Over one year this results in €522.-, €442.16, €221.08 and €294.21 charging costs for the Tesla, Leaf, Outlander and Ampera, respectively.

Under the RRP dispatch scheme this is not the case as the provision of RRP leads to a varying monetary flow during the year. To assess this difference the cumulative daily profits are plotted in figure 4.2.7 for each user type.

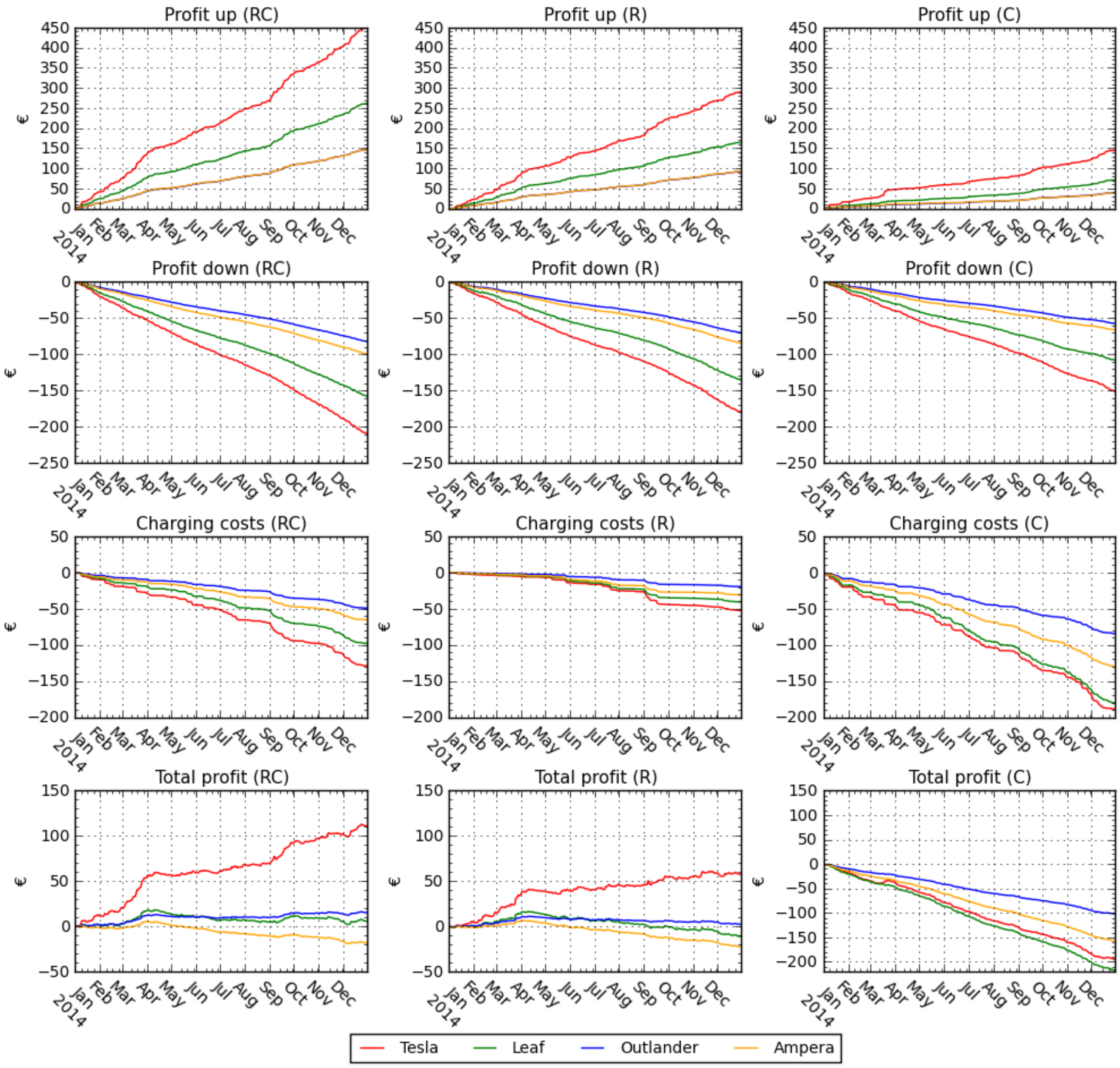


Figure 4.2.7: Breakdown of cumulative profits for each user type during one year

Profit generation through RRP up provision

When the profit generation for RRP up is assessed it can be seen that for the RC and resident user type the line increases steadily throughout the year, meaning that RRP up is delivered on a regular basis. The commuter experiences moments where the line is nearly flat, indicating that little to no RRP up is provided. An interesting observation is that the Outlander and Ampera follow exactly the same line, which can be explained by their identical charging capacities.In general, charging capacity seems to be a determining factor for profit generation. When for each EV the ratio between the profits generated from RRP up is compared with the ratio between the charging capacities it is found that these are identical when comparing the Leaf, Outlander and Ampera. The ratio between the charging capacities of the Leaf and Outlander/Ampera is approximately 1.78

and when the profits for RRP up are assessed roughly the same ratio is found. This finding does not apply to the Tesla, since in profits are higher than one would expect based on the difference in charging capacities . This can be explained by the findings in table 4.2.3 where for each EV and user type the profit per kWh of delivered RRP, transaction time and profit per minute of transaction time is presented.

User type	EV	Up		
		Average profit per kWh (€)	Transaction time up (min)	Average profit per minute transaction time (€)
RC	Tesla	0.187	219	2.057
	Leaf	0.186	213	1.230
	Outlander	0.186	213	0.689
	Ampera	0.187	212	0.691
Resident	Tesla	0.194	136	2.131
	Leaf	0.195	128	1.285
	Outlander	0.194	128	0.719
	Ampera	0.194	129	0.719
Commuter	Tesla	0.177	75	1.944
	Leaf	0.172	63	1.135
	Outlander	0.171	63	0.632
	Ampera	0.173	61	0.639

Table 4.2.3: Profit per unit of RRP up provided, transaction time and profit per minute of transaction time.

In table 4.2.3 it is shown that for each user type the Tesla can spend slightly more time providing RRP up than the other EVs, who all provide RRP up for roughly the same amount of time. An explanation for this difference can be found in the available SOC area. Recall how available SOC area is constraint by the minimum- and maximum capacity of the battery and the required SOC (figure 3.2.4). In figure 4.2.8 this is shown for the EVs under investigation at two points in time, shortly after connection and three hours before departure. The arrowed lines show the SOC trajectory in case uninterrupted RRP up or -down is provided. If the leftmost trajectory for RRP up is followed, it can be seen that the Leaf, Outlander and Ampera reach a constraint, the minimum SOC, at approximately the same time, while the Tesla can continue to provide RRP up for a longer amount of time before reaching its constraint, the required SOC. The large battery capacity of the Tesla in combination with a relatively high SOC at the time of connection gives it a considerable advantage for the provision of RRP up. Note however that this is not valid if RRP up would be called closer to the time of departure and required SOC becomes a constraint for all EVs. In those cases all EVs would have the same time for RRP up provision. This is illustrated in figure 4.2.8 where we see the EVs delivering uninterrupted RRP at 2 different timespans until departure. The second series starts at 14:30 and shows that under these circumstances all EV can spend the same amount of time for RRP up.
In table 4.2.3 the average profit per kWh is also presented. Here it is shown that per user type the EVs make more or less the same profits per unit of RRP up delivered, which indicates that they sell against the same prices and thus provide RRP simultaneously. It appears that prices for RRP up seem to be more favorable between 18:30 and 8:00 as the resident user type generates the highest average profit per kWh of RRP delivered. When the average profit per unit of transaction time is assessed it can be seen that these values are proportional to the differences in charging capacities.

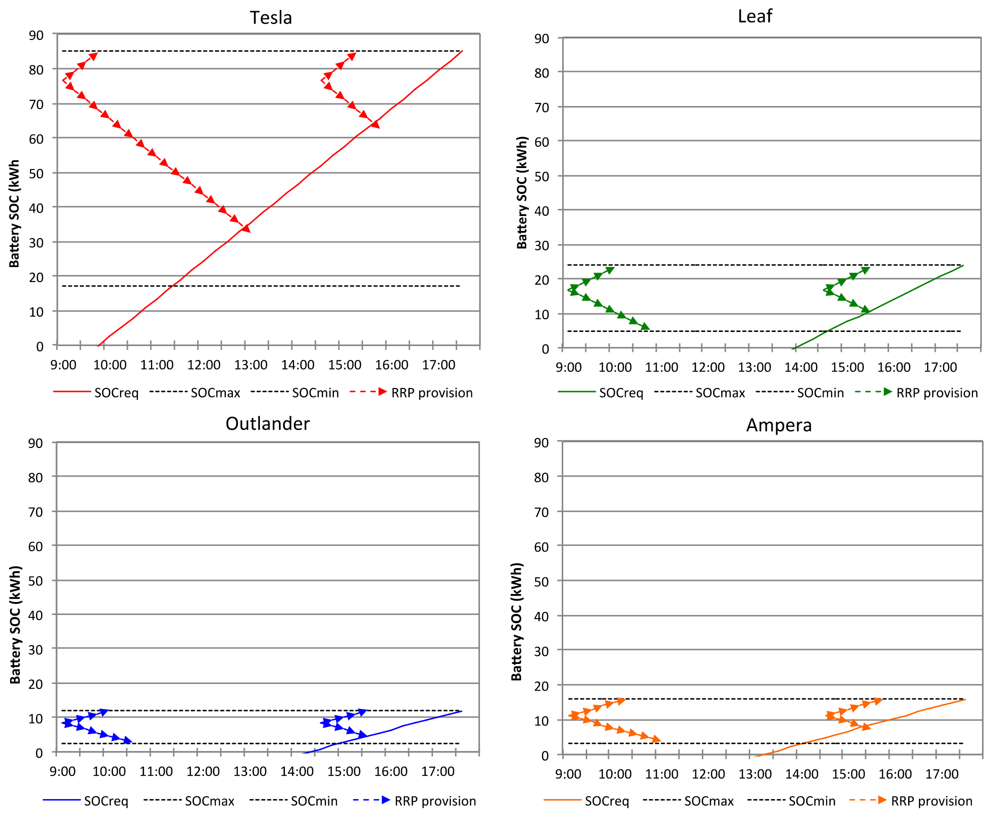


Figure 4.2.8: Role of different constraints at different points in time

Profit generation through RRP down provision

Under the RC user type all vehicles except for Tesla have a SOC that is 70% of their maximum SOC when connecting to a charging facility (see chapter 3.4.3.2). That means that they have 30% of their battery capacity available for RRP down. Since all EVs have different battery capacities the absolute amount differs per EV, which explains the separate lines found in figure 4.2.7. The Tesla has most capacity available, followed by the Leaf, Ampera and Outlander. The same order is seen in the plots. With regard to the other user types the same mechanism applies, but with an SOC of 80% for the Tesla and 30% for the other EVs at the time of connection.

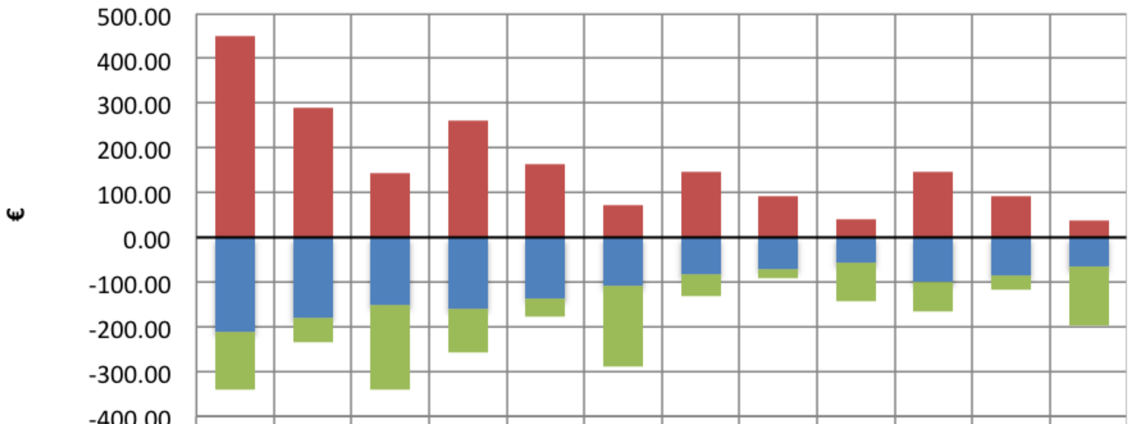
User type	EV	Down		
		Average profit per kWh (€)	Transaction time up (min)	Average profit per minute transaction time (€)
RC	Tesla	-0.037	615	-0.343
	Leaf	-0.033	772	-0.205
	Outlander	-0.033	715	-0.115
	Ampera	-0.032	869	-0.115
Resident	Tesla	-0.033	587	-0.307
	Leaf	-0.033	759	-0.179
	Outlander	-0.033	695	-0.101
	Ampera	-0.032	865	-0.098
Commuter	Tesla	-0.042	390	-0.390
	Leaf	-0.033	468	-0.232
	Outlander	-0.033	442	-0.131
	Ampera	-0.032	514	-0.130

Table 4.2.4: Profit per unit of RRP down provided, transaction time and profit per minute of transaction time.

Table 4.2.4 shows that all EVs now pay a very low price for electricity between 3.3 and 4.2 cents. With respect to the transaction time a different picture is shown in comparison to RRP up. The EVs have different transaction times with the Tesla having the least. The explanation for this observation can be found in figure 4.2.8 that shows that vehicles with a higher charging capacity spend less time providing RRP down, since they meet the maximum SOC sooner.

Charging costs

The provision of RRP down is not sufficient to fully replace regular charging, as costs for charging are still visible in the simulations for all user types and EVs. The resident user type benefits most from RRP down provision, as it generates the least charging costs. When looking at the cumulative plot it can be seen that for certain periods the line is flat, indicating that during that time no charging is required. The commuter user type has the highest charging costs, since under the commuter user type the ratio between the time that the EVs are connected and the amount of energy that needs to be transferred to the battery is the lowest. Summing the profit flows and charging costs over one year yields the breakdown presented in figure 4.2.9.

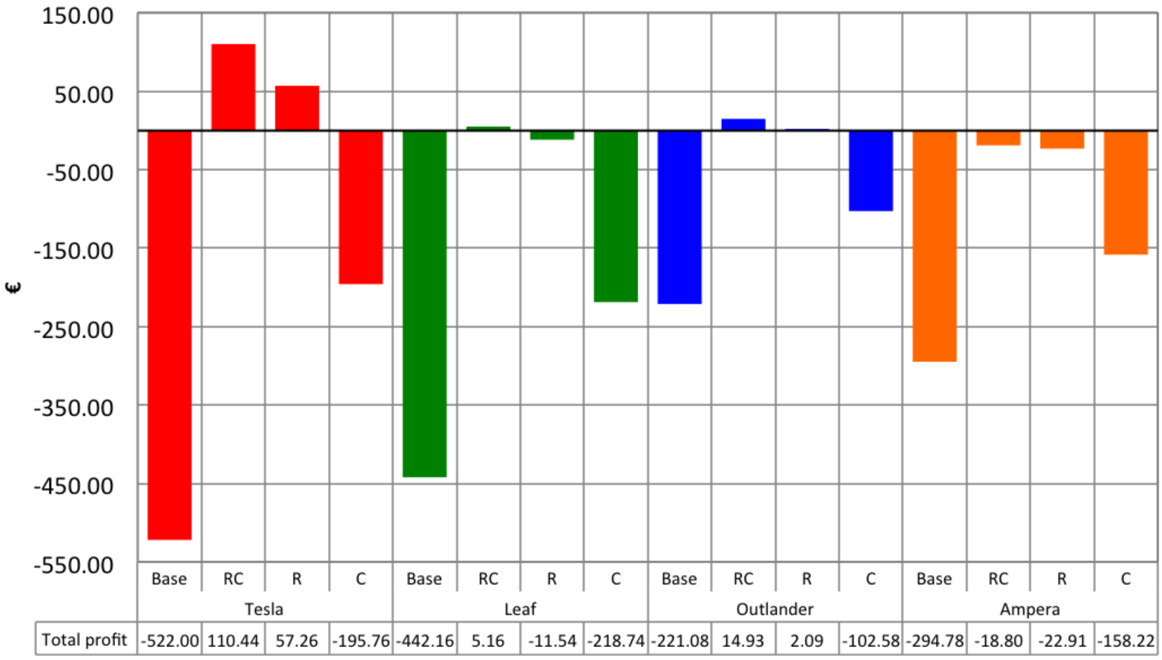


	Tesla			Leaf			Outlander			Ampera		
	RC	R	C	RC	R	C	RC	R	C	RC	R	C
Charging costs	-129.03	-52.51	-188.63	-97.88	-40.66	-181.31	-49.19	-19.54	-84.44	-65.39	-30.81	-130.49
Profit down	-210.52	-180.45	-152.02	-158.42	-135.67	-108.56	-82.57	-70.40	-57.73	-99.88	-84.77	-66.68
Profit up	449.99	290.22	144.89	261.45	164.79	71.14	146.69	92.03	39.59	146.47	92.67	38.95

Figure 4.2.9: Breakdown of annual profit for each EV and user type under the RRP dispatch scheme

Total profit and relation to baseline

Consolidating the different profits and charging costs yields the total profits depicted in figure 4.2.10. For each EV the results for the RC- and resident user type under the baseline charging scheme is presented in the leftmost column. This picture shows that the EVs can generate considerable benefits from the provision of RRP. Under the RC user type three of the four EVs even generate positive profits. Under the resident user type this is only the case for the Tesla. Note however that all other EVs still benefit significantly when comparing with the costs made under the baseline charging scheme. The same applies for all EVs under the commuter user type.



	Tesla Base	Tesla RC	Tesla R	Tesla C	Leaf Base	Leaf RC	Leaf R	Leaf C	Outlander Base	Outlander RC	Outlander R	Outlander C	Ampera Base	Ampera RC	Ampera R	Ampera C
Total profit	-522.00	110.44	57.26	-195.76	-442.16	5.16	-11.54	-218.74	-221.08	14.93	2.09	-102.58	-294.78	-18.80	-22.91	-158.22

Figure 4.2.10: Annual profit under the baseline and RRP scenario for the different user types and EVs

4.3 Relation between RRP provision, battery capacity and charging capacity

In the previous section brief statements were made with regard to the role that the different battery- and charging capacities of the EVs play in RRP provision and subsequent profit generation. To gain a better understanding of the effect of charging- and battery capacity 3 EVs are simulated under battery capacities ranging between 10 kWh and 60 kWh. This simulation is made three times, one for each user type. The EV's have charging capacities of 3.7, 6.6 and 11 kW. In order to ensure that only the impacts of battery capacity and charging capacity can be clearly analyzed the EVs have identical characteristics regarding energy consumption of trips and required SOC at time of departure. These inputs are summarized in table 4.3.1.

Charging capacity	**Connection times**			**Trip times**	**Energy consumption per trip**	**Required SOC**
	RC	Resident	Commuter			
11 kW	0:00 – 7:59, 9:00 – 17:29, 18:30 – 23:59	18:30 – 23:59	9:00 – 17:29	8:00 – 9:00 17:30-18:30	8 kWh	100%
6.6 kW						
3.7 kW						

Table 4.3.1: Inputs used to assess the relation between battery capacity, charging capacity and RRP provision

Under these settings all EVs start at the same SOC when they connect to a charging facility. This results in the situation depicted in figure 4.3.1, where the SOC areas at the lowest- and highest battery capacities are shown. Similar to 4.2.1 and 4.2.8 the arrowed lines represent the SOC that results from uninterrupted RRP provision and the solid lines the constraints formed by the battery capacity and required SOC (SOCreq).

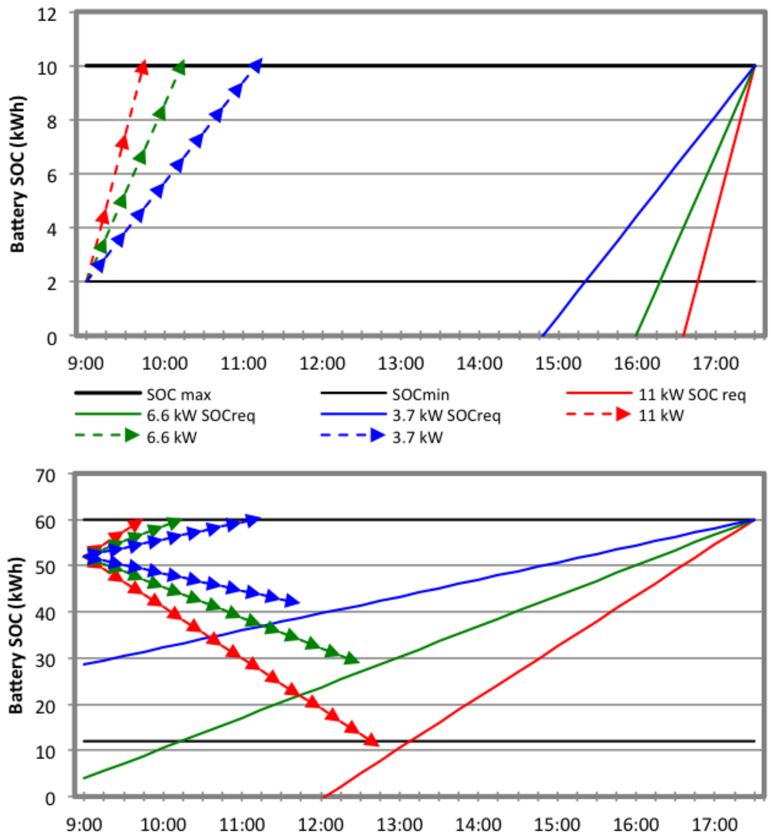


Figure 4.3.1: SOC areas after connection for EV with a battery capacity of 10 kWh (upper) and 60 kWh (lower) for the RC and commuter user type.

In the upper plot in figure 4.3.1 it can be seen that under a low battery capacity the required SOC forms less of a constraint, as it does not influence the available SOC area until 15:00 hours. Until then the maximum and minimum SOC form the main constraint. Having a higher charging capacity only leads to a relatively small increase in SOC area and therefore only a slightly higher potential to provide RRP. In the lower plot in figure 4.3.1 this situation is depicted for a battery capacity of 60 kWh. If the available SOC area under these circumstances is assessed it becomes visible that charging capacity has a considerably larger impact, since a higher charging capacity makes a larger contribution to the available SOC area. Note also that after a certain battery capacity the available SOC are is no longer affected by the increase in battery capacity since the required SOC and the maximum SOC become the only constraints.

Simulating the 3 EVs under the different user types and battery capacities yields the results presented in figure 4.3.2 and confirms the statement made above. Note that the resident and commuter user type are only included at capacities larger than 20 kWh. Including them at lower capacities would result in a negative SOC at time of connection due to the setting of the energy consumption per trip.

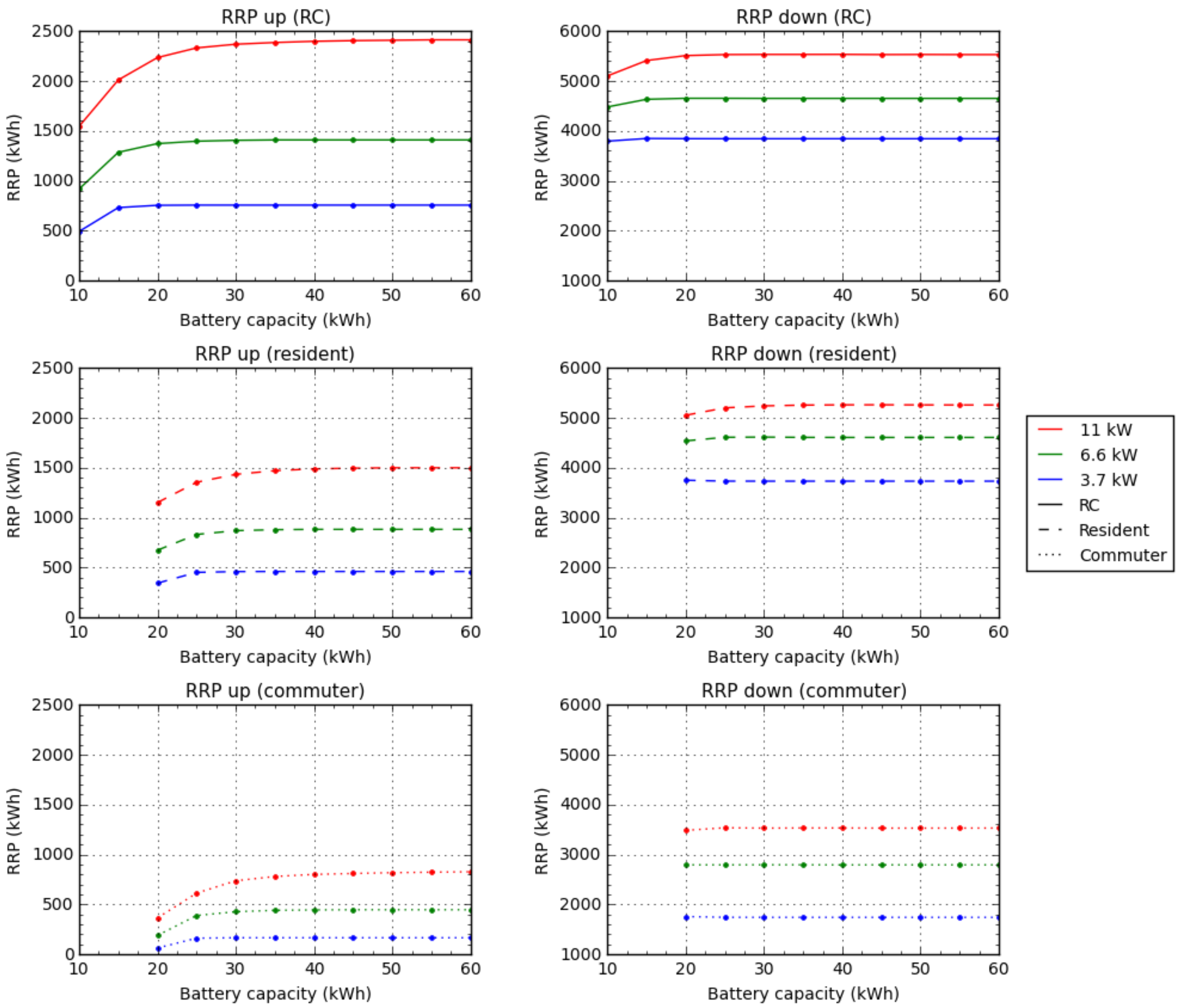


Figure 4.3.2: RRP provision under different charging capacities and user preferences.

When the provision of RRP up is assessed it can be seen that this stabilizes when higher battery capacities are reached. The role of charging capacity becomes visible, as for a lower charging capacity the RRP up provision stabilizes earlier that for a higher charging capacity. With regard to RRP up provision and charging capacity several mechanisms can be identified:

- At sufficiently high battery capacities where required SOC forms the only constraint for RRP up a higher charging capacity leads to more time until the required SOC condition is met.

- At sufficiently high battery capacities where required SOC forms the only constraint for RRP up a higher charging capacity leads to more RRP that can be delivered until the required SOC condition is met.
- At battery capacities where the minimum SOC forms a constraint a higher charging capacity causes this constraint to be met sooner.

In figure 4.3.3 the transaction times are shown for the provision of RRP up. The mechanisms described above become clearly visible at the higher range of battery capacity, where it can be seen that higher charging capacities can spend more time providing RRP up under each user type. In the lower ranges, between 10 and 40 kWh, the transaction times change differently per EV. Under the RC user type 11 kW at 35 kWh can spend more transaction time than all other charging capacities, but at 15 kWh the opposite is true. This is because at the lower capacities the EVs face constraints by both the minimum SOC and the required SOC. Which constraint apply depends on the moment of delivery. If RRP is delivered shortly after connection it is more likely that the minimum SOC forms a constraint. When the time of departure comes closer the required SOC will become a more important constraint. For EVs with a low charging capacity this will happen sooner. This is shown graphically in figure 4.3.4. For this reason the transaction times for RRP up take on somewhat irregular values at lower battery capacities.

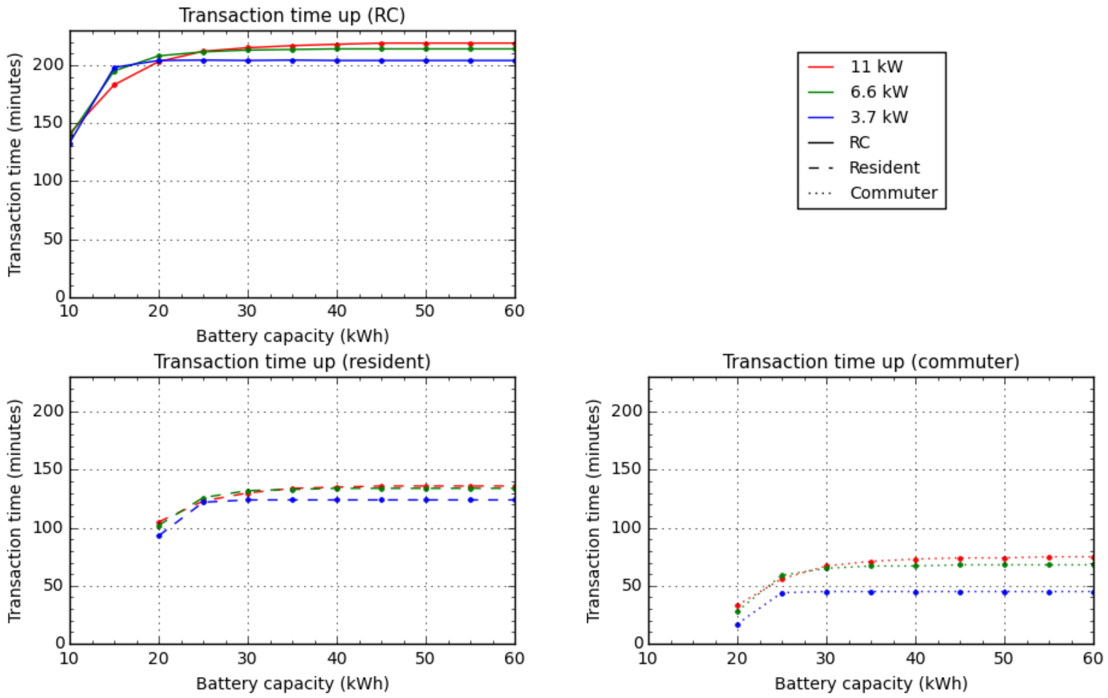


Figure 4.3.3: Transaction times for RRP up under different user types

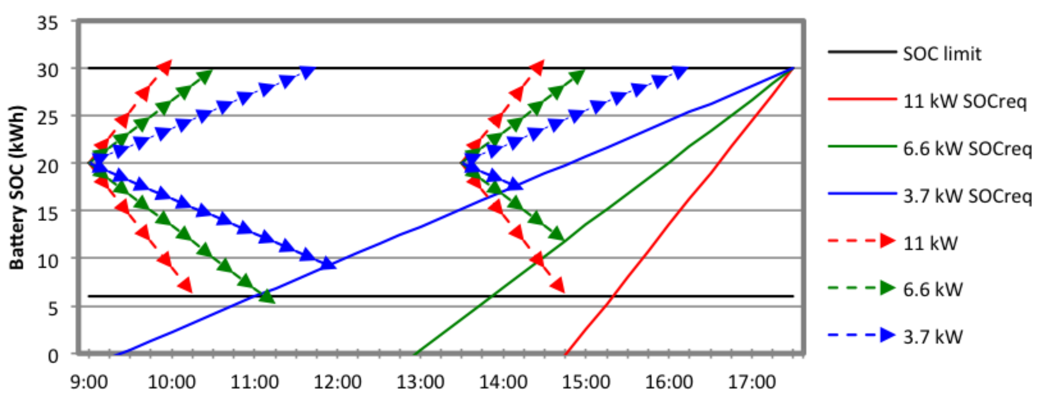


Figure 4.3.4: Constraints for RRP provision at different times till departure

If RRP down provision is assessed it can be seen that larger charging capacities have less influence in comparison with RRP up. This is because RRP down provision is constraint differently than RRP up. Firstly, increasing the battery capacity doesn't influence the amount of RRP down that can initially be provided since this is always the amount of energy consumed during a trip, which stays equal for all simulated battery capacities. Secondly, RRP down is constrained by the maximum SOC and the maximum SOC always has the same value, unlike the required SOC who's value changes over time. Therefore for the provision of RRP down the following mechanisms can be identified:

- Under higher charging capacities EVs can engage is less transaction time until the maximum SOC is reached.
- Under higher charging capacities EVs have more time until the required SOC condition is met.

When looking at the transaction times for RRP down the first mechanism can clearly be identified for all user types, as the highest charging capacity always results in the least transaction time. If charging capacity was the only factor of influence the difference between transaction times should be proportional to the difference in charging capacity. This is however not the case since for the RC and resident user type the connection time of the higher charging capacity is lower that one would expect based on charging capacity. This can be explained by the fact the higher capacities enjoy more time until the required SOC constraint is reached. For the commuter type this doesn't hold when comparing 6.6 kW and 3.7 kW charging capacities. Based on the findings for the RC and resident user type one would expect the transaction time down to be higher. The only cause for this difference can be the impact of required SOC. Because connection times are shorter for the commuter user type the required SOC becomes a limitation earlier in comparison with the other user types. Situations could occur that RRP down is called late in the connection session when the lowest charging capacity no longer has flexibility to provide RRP down and is already charging, while the other EVs still can. This means that for the lower charging capacity more charging should occur. This statement is supported by the figures presented in appendix 2, where charging costs and other KPI are listed.

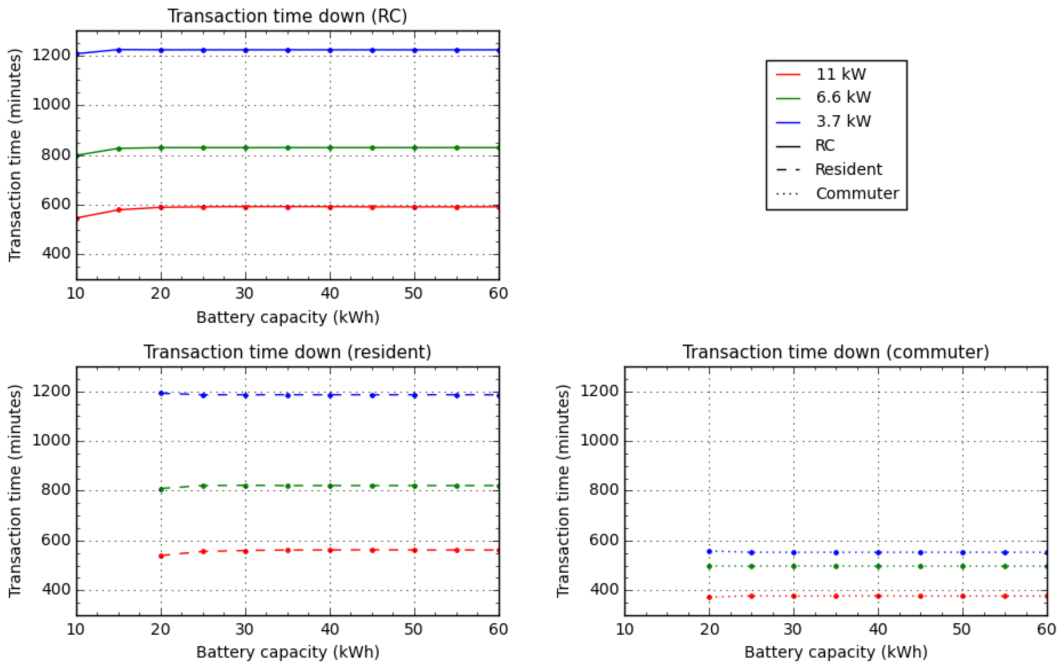


Figure 4.4.5: Transaction times for RRP down under different user types.

5 Sensitivity analysis

In the previous sections the KPI for four EVs where presented for different user types. Additionally, section 4.3 explained the relation between battery- and charging capacity and the provision of RRP. That analyses showed the different mechanisms that are active and how RRP provision is constrained. A particular important factor for RRP provision turned out to be SOC area. With these findings in mind the results of the sensitivity analysis can be better understood. Firstly, the impact of required SOC and minimum SOC will be assessed. For these assessments the results of chapter 4.3 are especially valuable since charging these parameters have a direct change in SOC area as a consequence. Secondly, the impact of the duration and power consumption of trips will be analyzed. These two assessments contribute to answering the research question regarding user characteristics. Finally, the impact of multiple EVs on the load on the substation will be analyzed, which contributes to answering the research question regarding an increased fleet size.

5.1 Required SOC setting

The aim of this analysis is to identify the impact that the required SOC setting has on the outcomes. Because the resident- and commuter user types need to complete 2 trips per charging session the required SOC range can only be varied between 80% and 100%, since lower values would cause the Leaf, Outlander and Ampera to have insufficient SOC to make trips. Under the RC user type the required SOC can be varied between 50% and 100%. The Tesla's large battery capacity allows it to operate under lower required SOC values, which are included in the analysis. To illustrate the impact of the required SOC and resulting change in SOC area figure 5.1.1 is constructed. The grey dashed lines indicate the constraint at a required SOC of 100% and the solid colored lines show a required SOC of 60%.

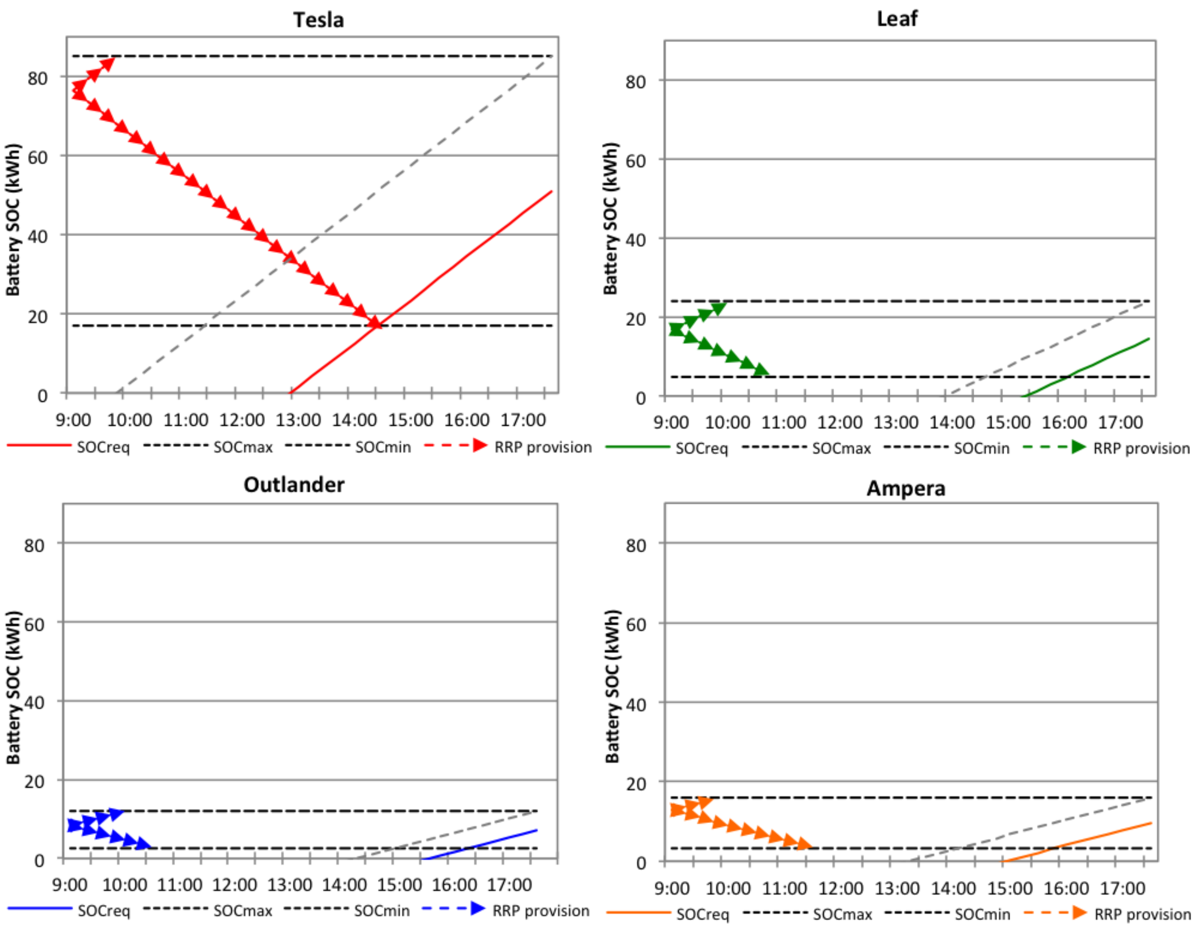


Figure 5.1.1: SOC area under a required SOC of 100% (grey-dashed) and 60% (coloured-solid)

Figure 5.1.1 shows that EVs with a higher battery capacity gain relatively more SOC area than EVs with a lower battery capacity, which provides them more time to deliver RRP. In figure 4.4.2 the provision of RRP and charged electricity is depicted under different required SOC settings. From left to right, the columns represent the results under the RC-, resident- and commuter user typ. In each plot the red, green, blue and orange lines represent the Tesla, Leaf, Outlander and Ampera respectively.

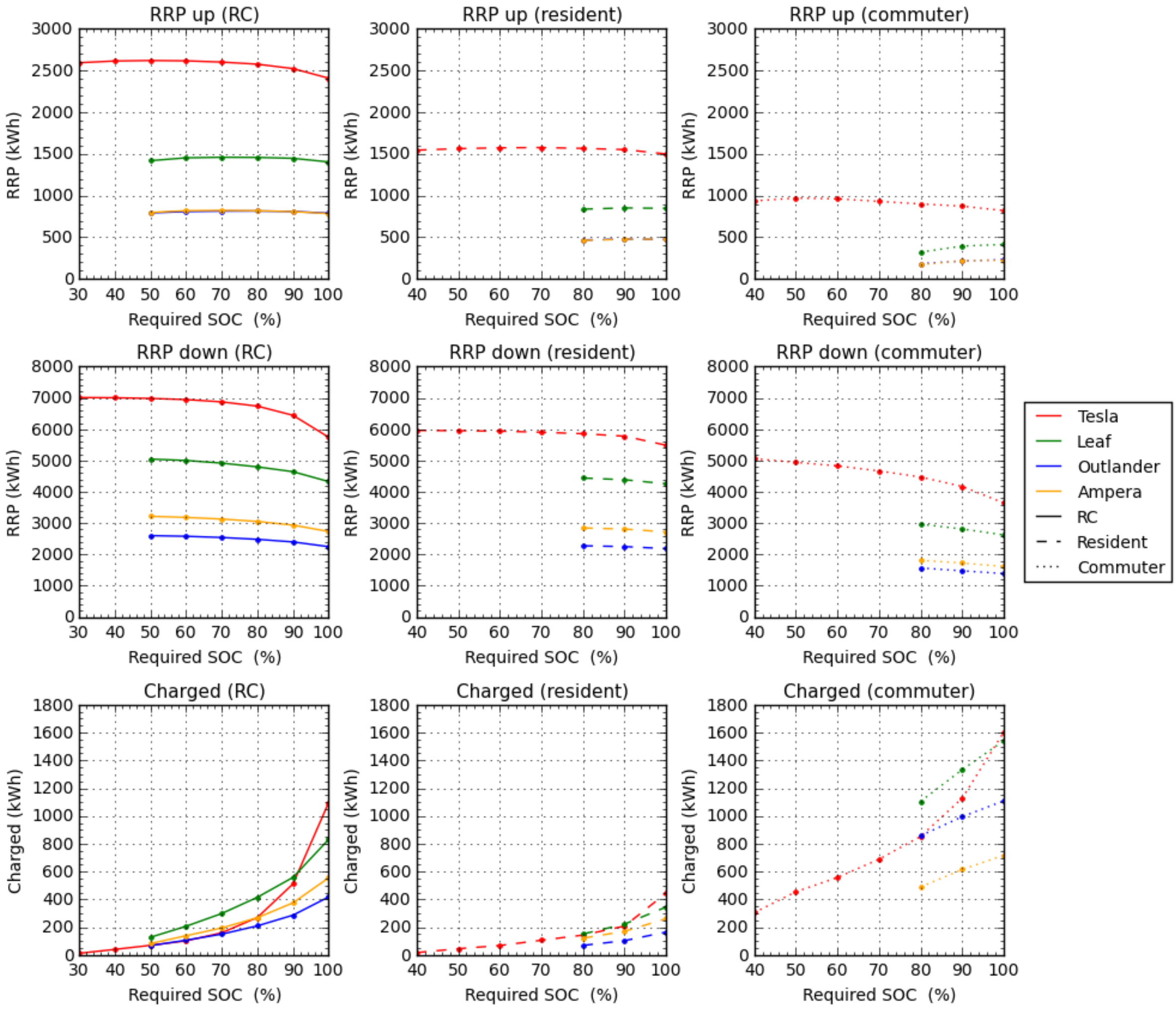


Figure 5.1.2: RRP provision and charging under different required SOC settings

Figure 5.1.2 shows that under the RC and resident user type the RRP up provision takes a light parabolic shape. Initially a lower required SOC leads to more RRP up provision, but below a certain point RRP up provision decreases again. Under the commuter user type the Leaf, Outlander and Ampera even experience an immediate decrease in RRP up provision if the required SOC is decreased. This shows that required SOC has two effects. First effect is the increase in SOC area, which provides more potential to provide RRP up. Secondly, a lower required SOC could result in a lower SOC at the time of connection and therefore less power to provide as RRP up. For example, under a required SOC of 100% a Leaf under the commuter user type would always have a SOC of 40% when connecting to a charging facility, enabling it to provide 20% of its battery to provide RRP up before reaching the minimum SOC. Under a required SOC setting of 80% it could occur that the Leaf only has an SOC of 20% at the time of connection, which is the minimum SOC. In order to provide RRP up the EV will first have to increase it's SOC by providing RRP down. Thus, firstly settlement prices for RRP down have to be profitable, followed by profitable settlement prices for RRP up. Remember that under the commuter user type the EVs have the shortest connection time, which decreases the odds this sequence occurs. When this mechanism is compared with the other user types it can be seen that over longer connection times these odds improve, yielding more RRP up provision.

Each user type shows that a decreasing required SOC yields an increase in RRP down provision. This is as expected, since a lower required SOC yields more time to provide RRP down and could result in a lower SOC at the time of connection. This provides more SOC availability to provide RRP down. More provision of RRP down reduces the need for charging, which explains the fact that the plot for charged energy is more or less the mirror image of the plot for RRP down. Additionally, in cases the required SOC condition is met less charging is required.

When the above findings are combined to yield battery throughput it can be seen that the required SOC setting only has a small impact on battery throughput (figure 5.1.3). However, for the RC- and commuter user type deeper discharging can be seen which is undesirable with regard to battery degradation (figure 5.1.4).

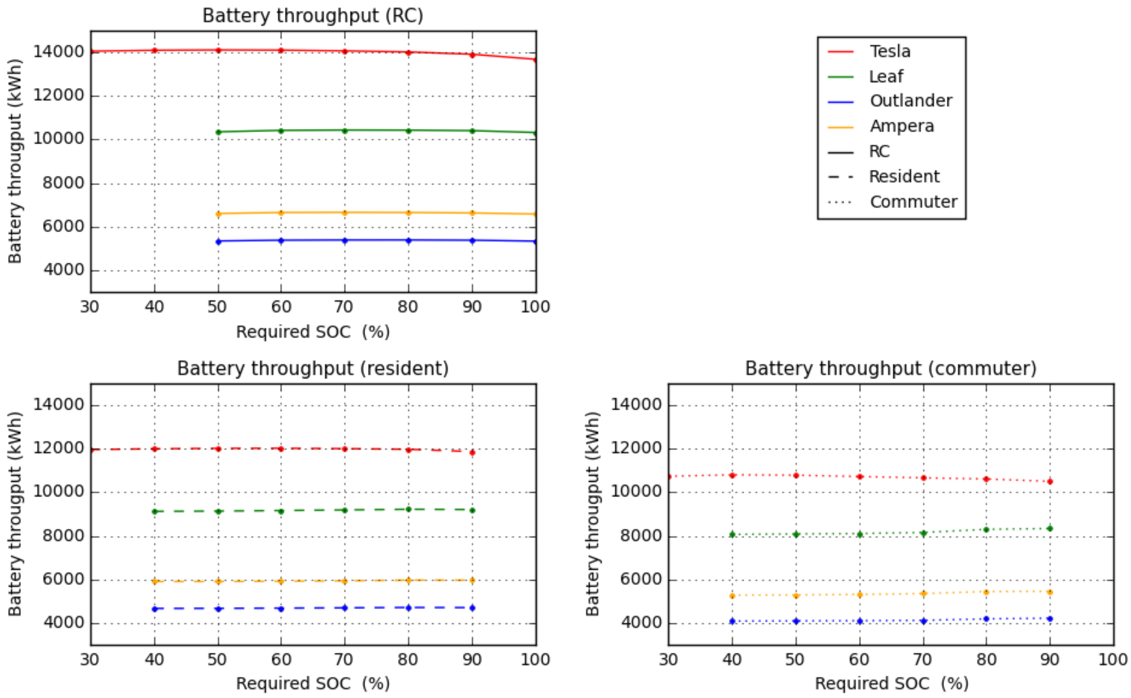


Figure 5.1.3: Battery throughput of the EVs for under different user types and required SOC settings.

In figure 5.1.4 the SOC distributions of the EVs under different user types and required SOC settings are presented. For each EV the highest- and lowest required SOC setting are plotted. For the Tesla the lowest required SOC setting is 30% under the RC user type and 40% under the resident- and commuter user type. For the other EVs this is 50% and 80% respectively.

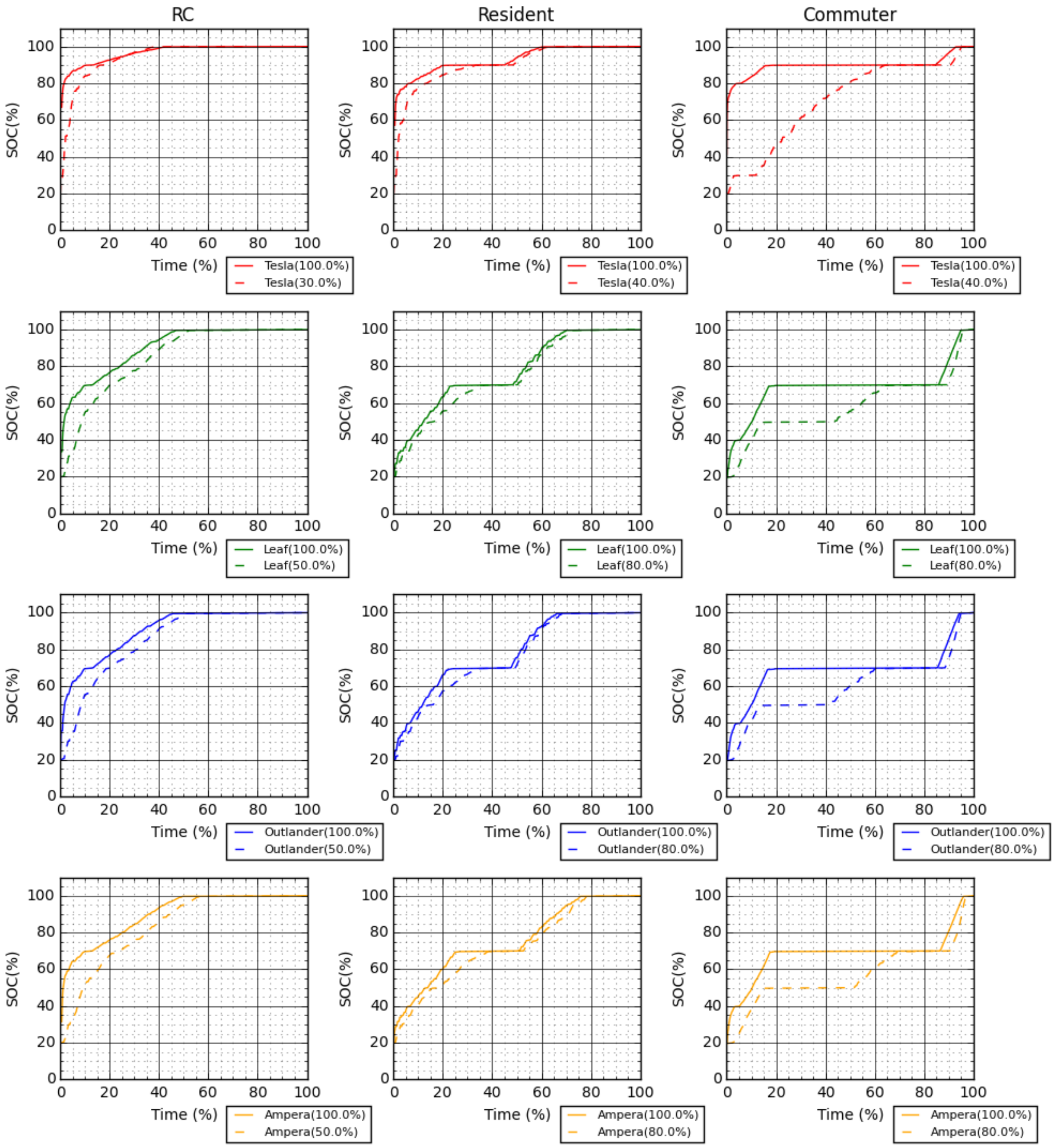


Figure 5.1.4: SOC distributions for one year for the highest-(solid lines) and lowest (dashed lines) possible required SOC setting

For each EV and user type a lower required SOC setting results in a lower SOC distribution. Note however that this decrease is smaller for the RC- and resident user type than for the commuter user type. When looking at the SOC distributions of the Leaf, Outlander and Ampera for the commuter user type it is noticeable that the SOC line spends a lot of time at a value of 50%. This is the value that is achieved when an EV starts a trip at 80%, which is the required SOC. This means that for the commuter type RRP provision is often constraint by the required SOC setting.

The results regarding the ability make an unexpected trip are presented in table 5.1.1. Although all vehicles have a reduced ability to make unexpected trips, all of them can still make these trips for a large share of the time.

Ability to make an unexpected trip						
User type	R-C		Resident		Commuter	
Required SOC setting	Highest	Lowest	Highest	Lowest	Highest	Lowest
Tesla	100%	98%	100%	98%	100%	95%
Leaf	99%	91%	88%	84%	90%	85%
Outlander	98%	91%	88%	84%	90%	86%
Ampera	99%	91%	86%	83%	90%	85%

Table 5.1.1: Ability to make an unexpected trip under the highest- and lowest required SOC setting

The ability to make unexpected trips can be valuable for an EV driver and therefore has to be offset by an increase in profits. In figure 5.1.5 the total profits are shown for different required SOC settings.

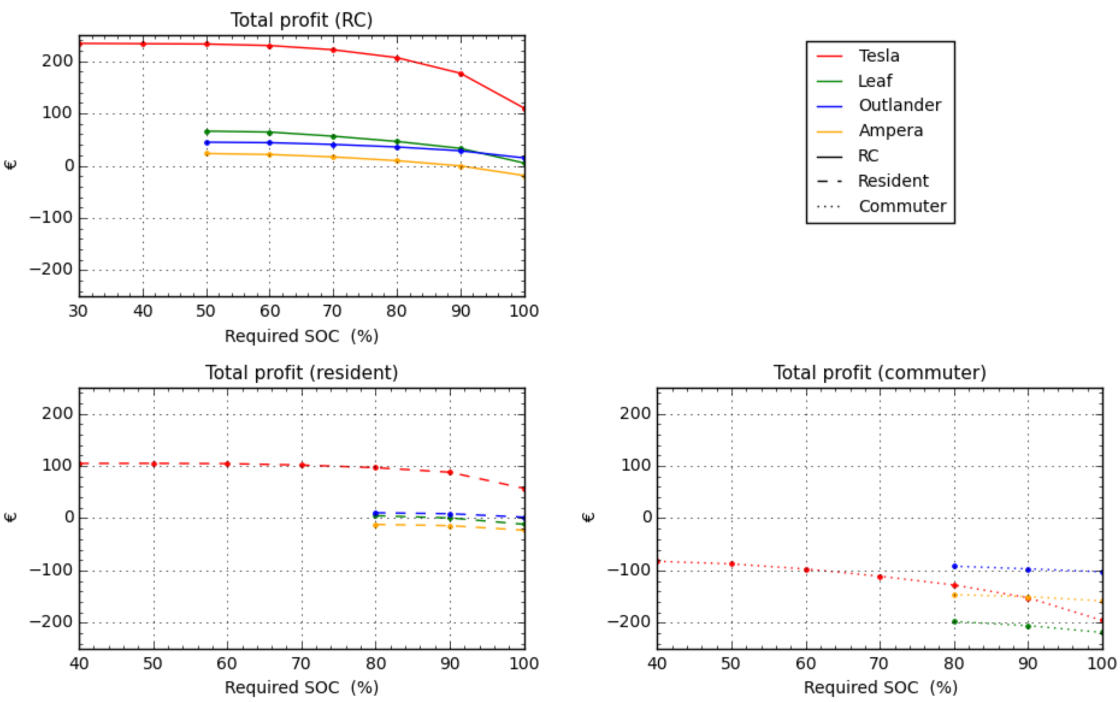


Figure 5.1.5: Annual profits of the EVs for different user types and required SOC settings.

Figure 5.1.5 shows that only the Tesla reaps the largest benefits from a lower required SOC setting. For the other EVs smaller increases in profits are seen. This is mainly attributed to the avoidance of charging costs, which decrease significantly with a lower required SOC. Under the RC- and resident user type the charging cost even approach zero at the lowest setting.

5.2 Minimal SOC setting

The impact of the minimum SOC setting on RRP provision is assessed by running simulations using minimal SOC values in the range between 20% and 90%. Note that a minimum SOC of 20% is also used in the initial simulations and that a minimum SOC of 100% would yield the results from the baseline charging scheme. In figure 5.2.1 the impact of raising the minimum SOC condition on available SOC area is depicted graphically.

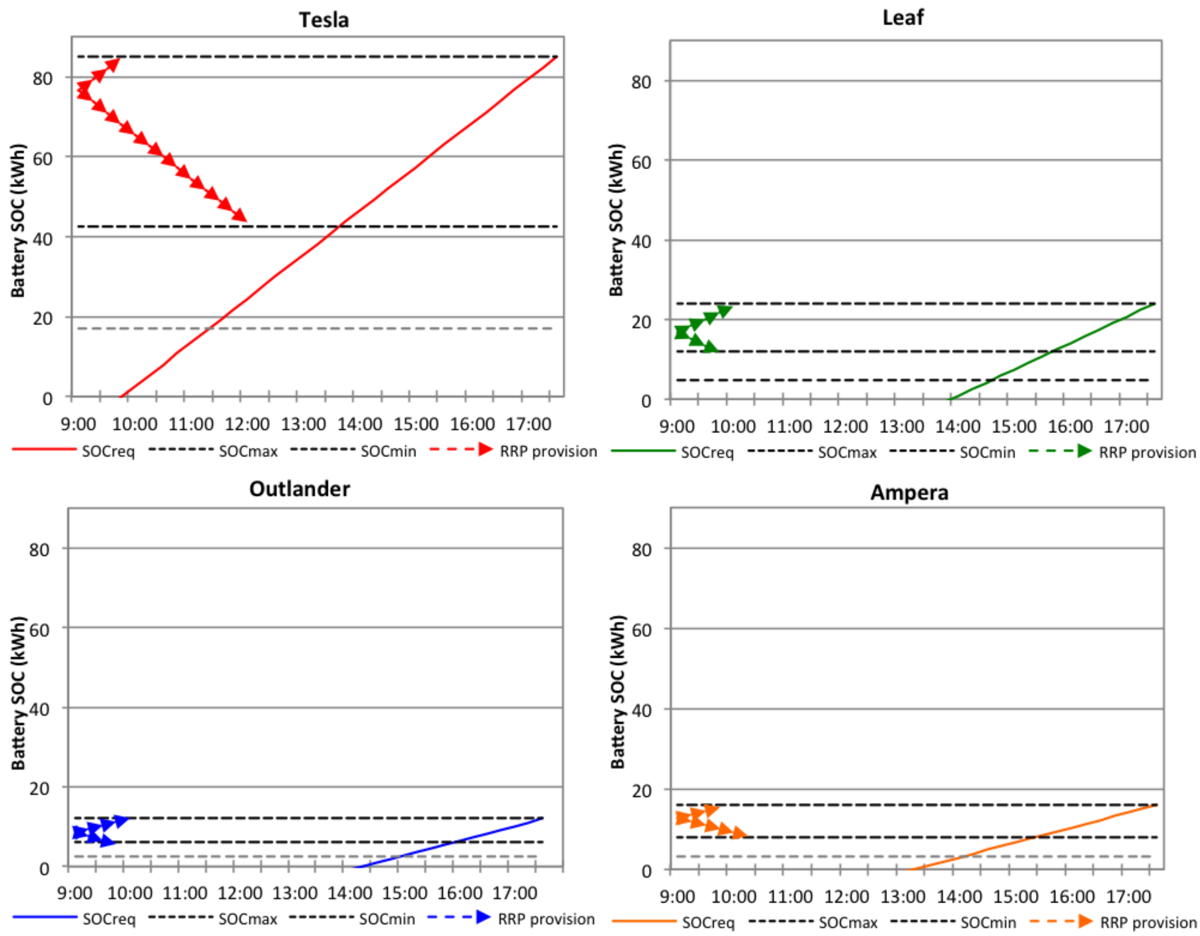


Figure 5.2.1: SOC area under a minimum SOC of 20% (lower dashed line) and 50% (middle dotted line)

Under some of the minimum SOC settings the EVs will have values below this condition at the time of connection. For instance, a Leaf under a resident user type has a SOC of 40% at time of connection. This means that for minimum SOC settings higher than 40% this constraint will always be violated at the time of connection. For the other EVs the SOC values after a trip are presented in table 4.4.2. It is important to realize that, in contrary to the initial RRP simulations, in these cases the minimal SOC is not a technical minimum, but a preferred minimum. The model has been adapted to ensure that in these cases the EVs start charging until they reach their minimum SOC. If the minimum SOC is reached charging stops and the SOC stays equal until RRP down is called or the required SOC constraint is reached.

	RC	Resident	Commuter
Tesla	90%	80%	80%
Leaf	70%	40%	40%
Outlander	70%	40%	40%
Ampera	70%	40%	40%

Table 5.2.1: SOC values of the EVs after a trip under the different user types

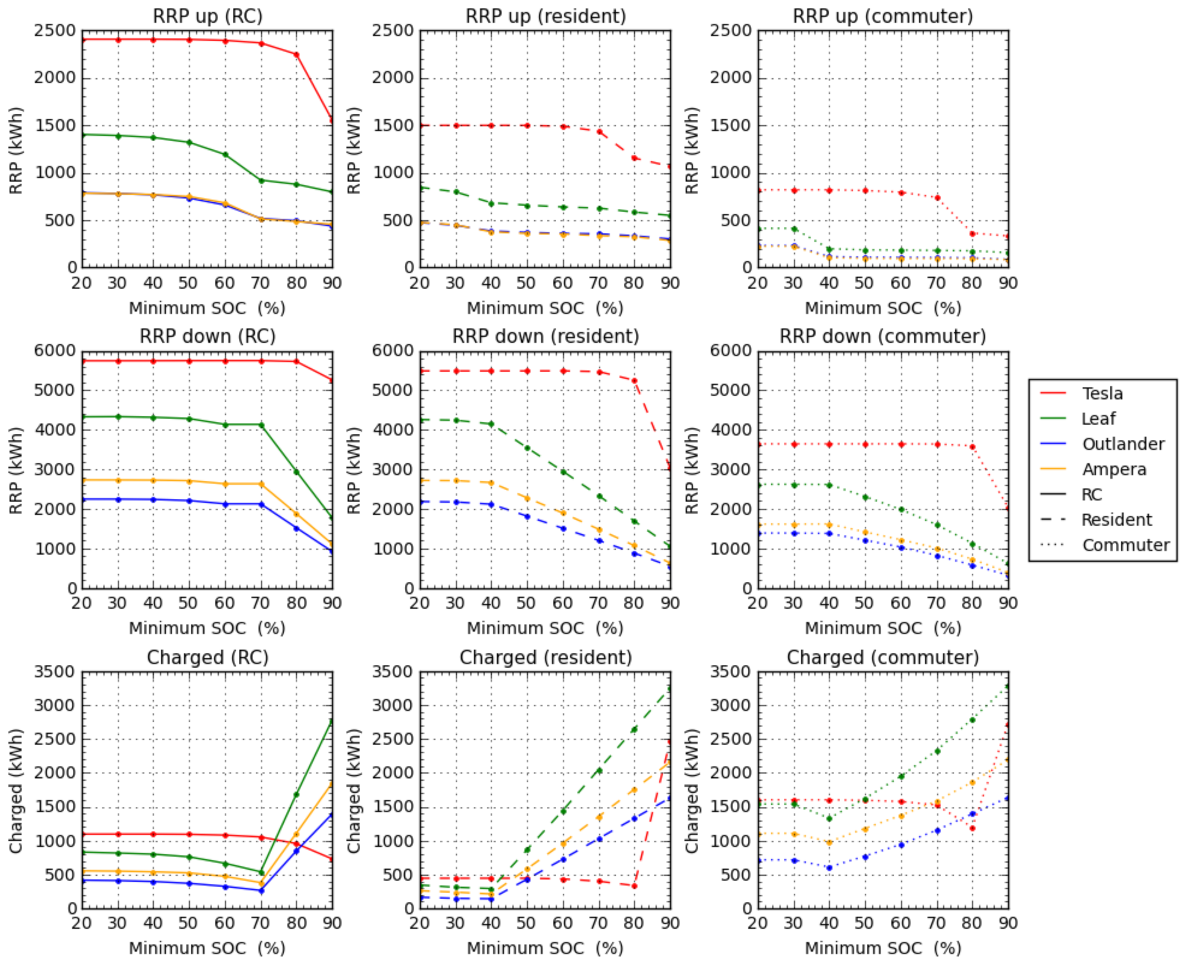


Figure 5.2.2: RRP provision and charging under different minimum SOC settings

In the plots of 5.2.2 a breaking point is shown when the minimum SOC becomes higher than the SOC value after a trip. Until then a rise in minimal SOC setting increasingly limits RRP up provision. When minimum SOC settings are higher than the SOC after a trip a decrease in RRP up provision holds, but at a different rate. RRP down experiences a relatively small impact from a higher minimum SOC setting until the moment the SOC setting exceeds the SOC value after a trip. From there on charging becomes dominant and substitutes RRP down.

When looking at the battery throughput (figure 5.2.3) a similar pattern can be seen. Battery throughput is affected when the minimal SOC setting reaches the SOC value after trip.

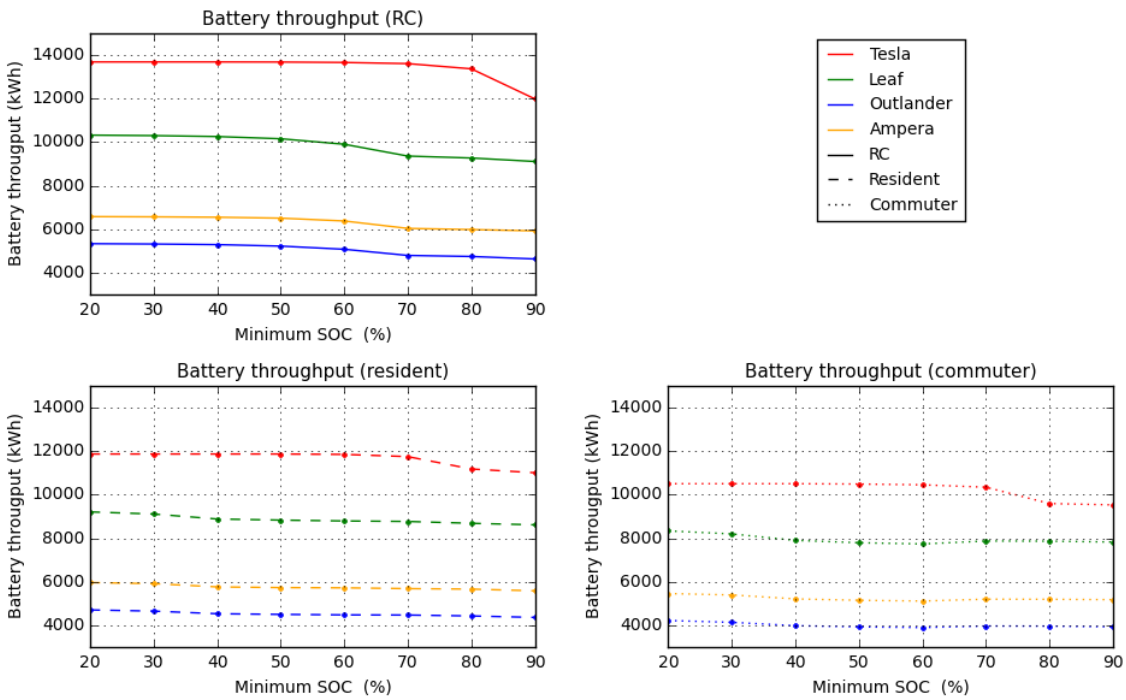


Figure 5.2.3: Battery throughput of the EVs under different user types and minimum SOC settings

In figure 5.2.4 the SOC distributions are presented for selected minimum SOC settings. These settings are respectively 20%, 30%, 40% and 90%. These values are chosen for the following reasons:

- 20% because it is the technical minimum that is also applied in the initial simulation. It therefore forms a base of comparison for the other settings.
- 50% because under this setting an EV would always be able to make an unexpected trip. Risk-averse users who want to benefit from providing RRP, but still remain capable to make unexpected trips could prefer this setting.
- 70% and 90% to show the impact of minimal SOC setting on cycle depth.
- Under lower minimal SOC values the distributions were very close to the 20% setting. As a result these SOC distributions were hardly visible in the plots. Therefore it is chosen to only present the ability to make an unexpected trip for these values in table 5.2.2.

	Ability to make unexpected trips								
User type	RC			Resident			Commuter		
Minimal SOC setting	*20%*	*30%*	*40%*	*20%*	*30%*	*40%*	*20%*	*30%*	*40%*
Tesla	100%	100%	100%	100%	100%	100%	100%	100%	100%
Leaf	99%	99%	99%	88%	88%	91%	90%	90%	90%
Outlander	98%	98%	99%	88%	88%	91%	90%	90%	90%
Ampera	99%	99%	99%	86%	86%	90%	90%	90%	90%

Table 5.2.2: The ability of the EVs to make an unexpected trip under different minimal SOC settings

When the SOC distributions are assessed it can be confirmed that higher minimum SOC settings lead to shallower cycles. In combination with lower throughputs this lowers the battery degradation. Under the RC user types the impact of a minimum SOC setting of 50% is negligible. When the minimum SOC setting of 70% is assessed a small increase in SOC distribution is shown. The reason for this is that under the initial minimum SOC settings the SOC very rarely comes below 50% or 70% and therefore they follow more or less the same pattern. This also explains why for the Tesla only the impact of a 90% minimum SOC is seen. Under the other user types the effect does become visible as is these cases the battery is deeper discharged before connection is made.

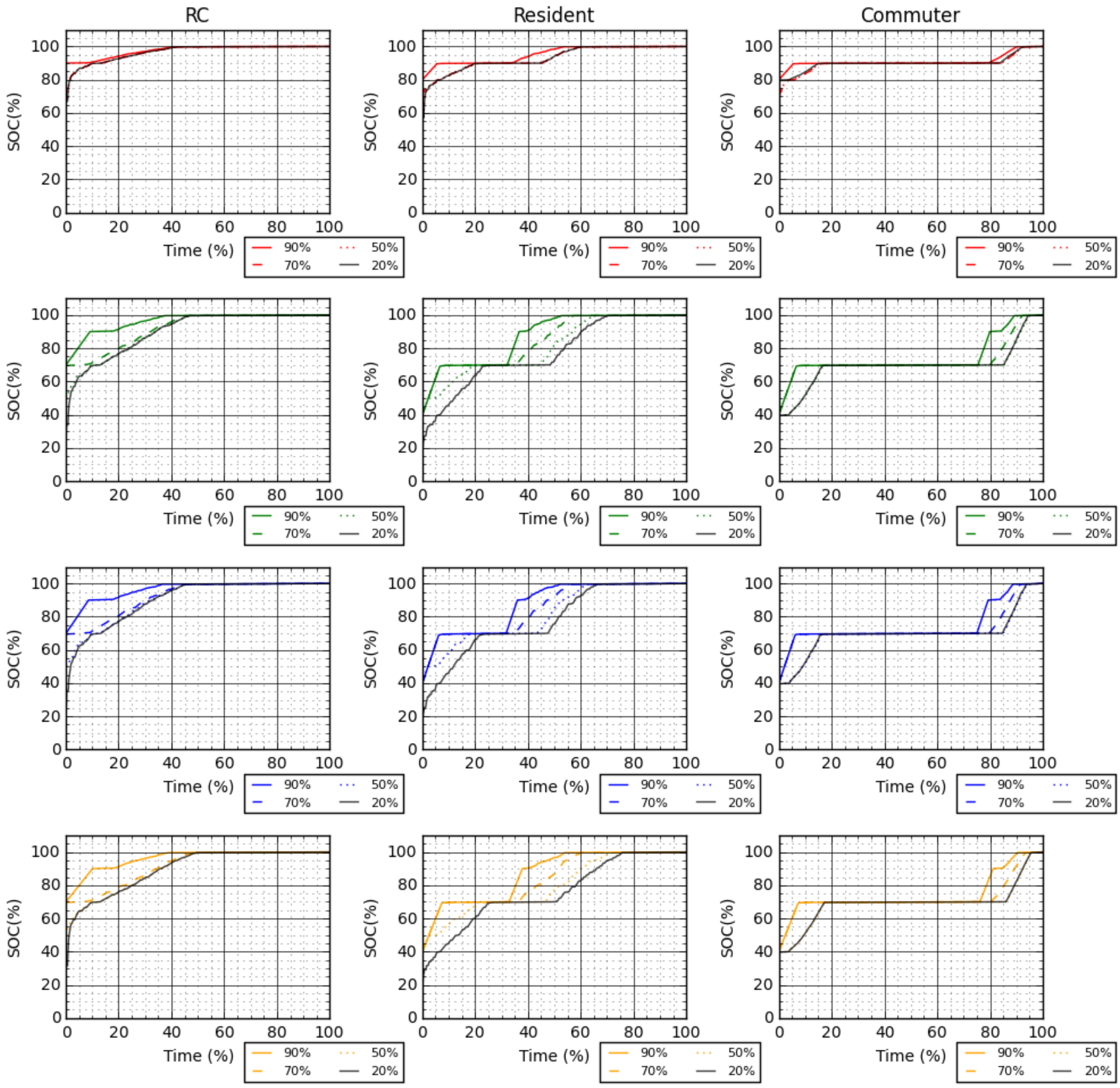


Figure 5.2.4: SOC distributions under selected minimum SOC settings.

In figure 5.2.5 the total profits are shown for all user types under different minimum SOC settings. In line with previous findings the profits are slightly declining until the SOC after trip value is reached. From there onwards a steep decline in profits is visible due to the increased costs associated with charging. An interesting finding is that under the RC user types the EVs can still make relatively favorable profits under a minimum SOC setting of 50%. This ensures that they don't lose any ability to make an unexpected trip in comparison with the baseline charging scheme, while maintaining a reasonable profit that is not much lower than under a minimum SOC of 20%. Under the other user types this doesn't hold, as they would need a minimum SOC of 80% to ensure the same situation. At those minimum SOC settings the EVs already make quite larger costs in comparison with the 20% setting. However, when compared to the baseline charging scheme this option is still beneficial.

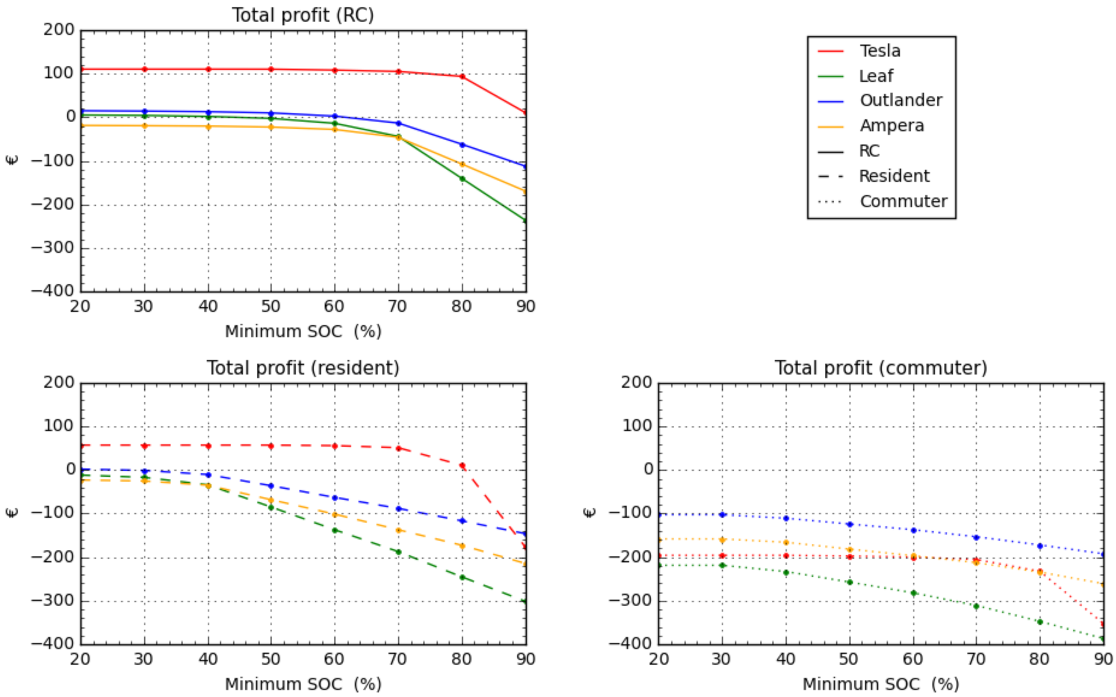


Figure 5.2.5: Total profits of the EVs under different user types and minimum SOC settings

5.3 Duration and power consumption of trip

In this section the influence of trip duration and associated energy consumption on the KPI will be tested by varying the trip duration between 45 and 75 minutes. As a result the energy consumed during a trip will be 25% lower or higher as well. The focus of this assessment lies on the provision of RRP and therefore no new baseline charging calculations are made. Additionally, under the baseline charging scheme the results would be rather straightforward as the KPI are only dependent on the trips and energy consumed during those trips. Therefore a trip that is 25% shorter would yield 25% less charging and thus 25% less costs. Under the RRP dispatch scheme this does not apply since the EVs now have a different timespan to provide RRP and a different SOC area.

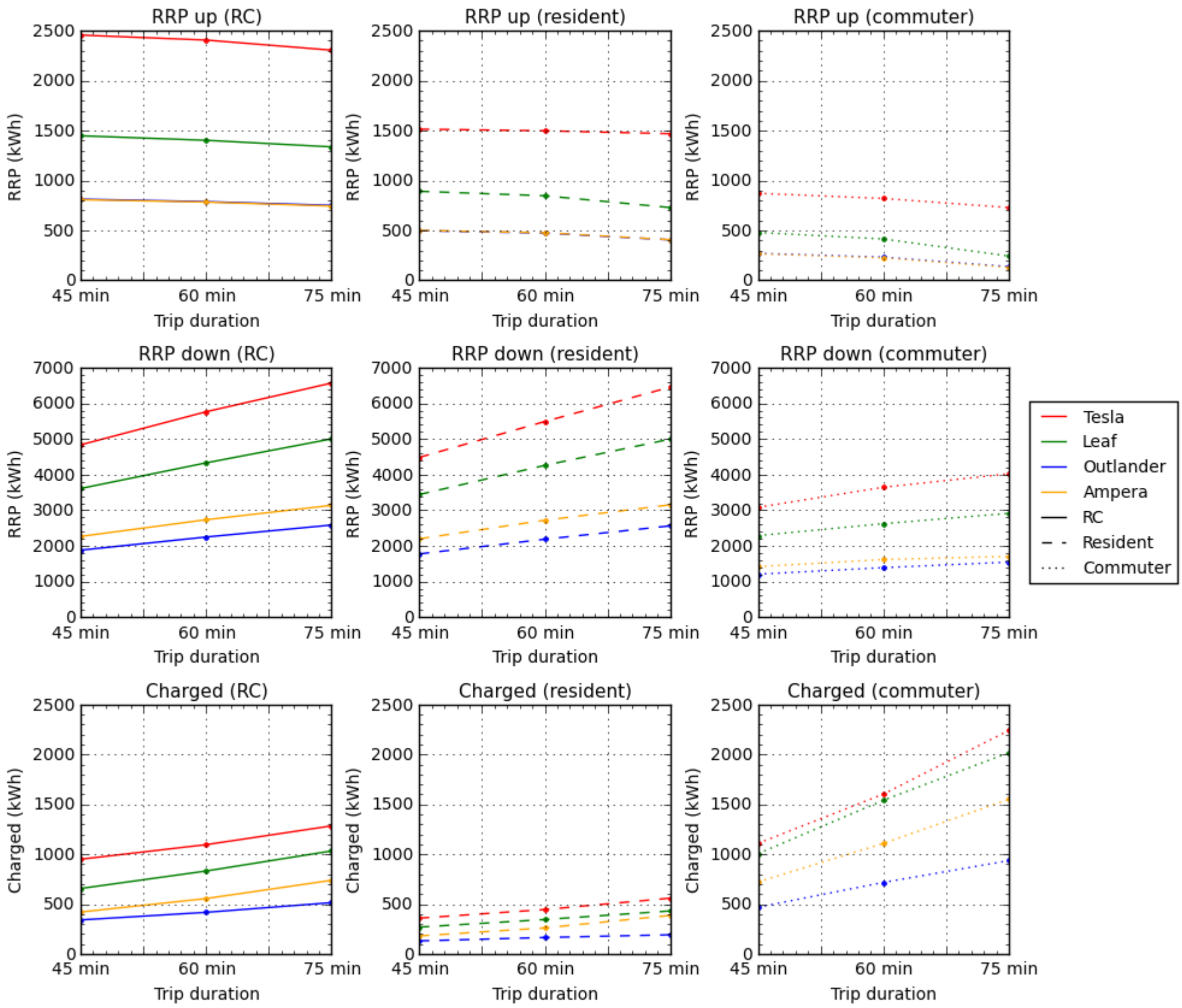


Figure 5.3.1: RRP provision and charging under different trip durations

In figure 5.3.1 the RRP provision under different trip durations is shown. Longer trips result in a lower SOC at the time of connection. This is reflected in the results as a reduction in RRP up can be seen when trip duration increases. The opposite holds for RRP down provision, as a lower SOC provides more potential for RRP down. This effect is larger in comparison to RRP up, which can be explained by the fact that RRP down is deemed profitable more often than RRP up and therefore allows optimal utilization of the potential.

When looking at battery throughput (figure 5.3.2) it can be seen that reduction in throughput caused by the shorter trips is somewhat compensated by additional throughput from RRP provision since throughput is not 25% lower. When longer trip times are assessed the opposite holds.

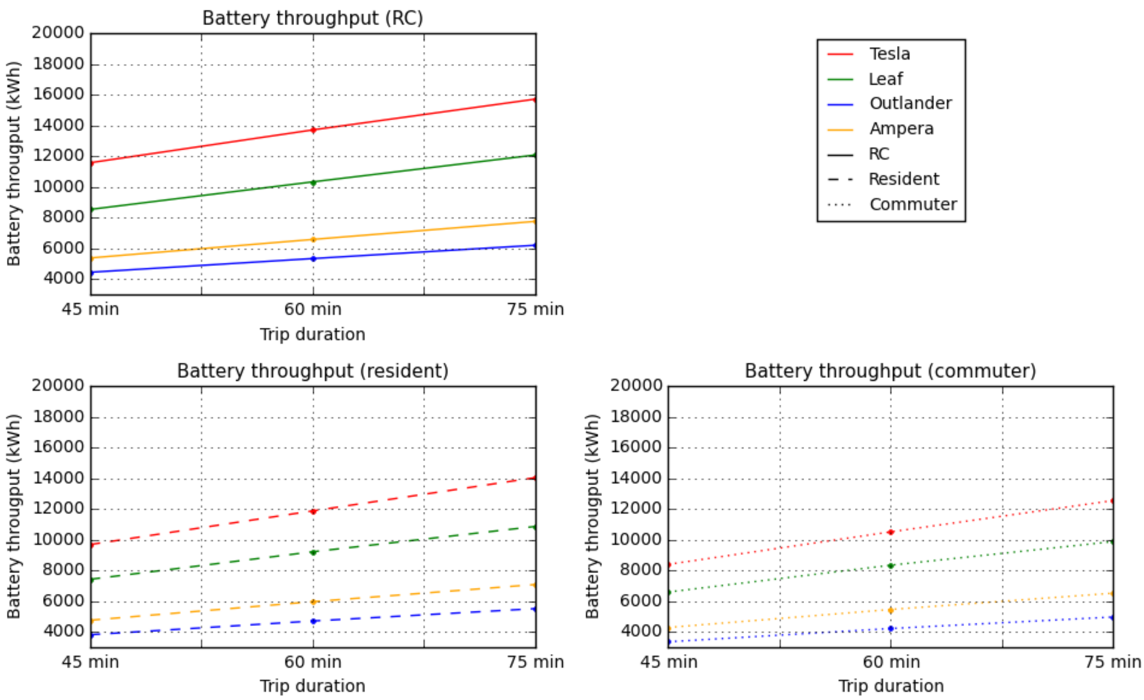


Figure 5.3.2: Battery throughput of the EVs under different user types and trip durations

If the effect on throughput from trip duration is compared with the impact on throughput from required SOC or minimum SOC it can seen that this is rather large. A 15-minute reduction in travel time gives roughly the same reduction in throughput as raising the minimum SOC setting to 90%. Since less battery throughput reduces battery degradation this is a favorable development. When the depth of cycling is included in this assessment shallower cycles can be seen, especially for the resident and commuter user types, which also reduces battery degradation (figure 5.3.3).

Since having shorter trip duration also yields a lower energy requirement the ability to make unexpected trips is improved considerably. For example, when trip duration is 45 minutes the EVs, except for the Tesla, require a SOC of 42.5% instead of 50%. Additionally, the SOC distribution under shorter trip durations is in higher. In table 5.3.1 the ability to make an unexpected trip is presented for each trip duration. Here it is shown that especially for the resident and commuter user types the ability to make trips experiences a large impact from trip duration.

	Ability to make unexpected trips								
User type	RC			Resident			Commuter		
Trip duration	*45 min*	*60 min*	*75 min*	*45 min*	*60 min*	*75 min*	*45 min*	*60 min*	*75 min*
Tesla	100%	100%	100%	100%	100%	100%	100%	100%	100%
Leaf	99%	99%	95%	99%	88%	76%	99%	90%	84%
Outlander	99%	98%	94%	97%	88%	78%	99%	90%	84%
Ampera	99%	99%	95%	99%	86%	73%	99%	90%	84%

Table 5.3.1: Ability to make an unexpected trip under different trip durations

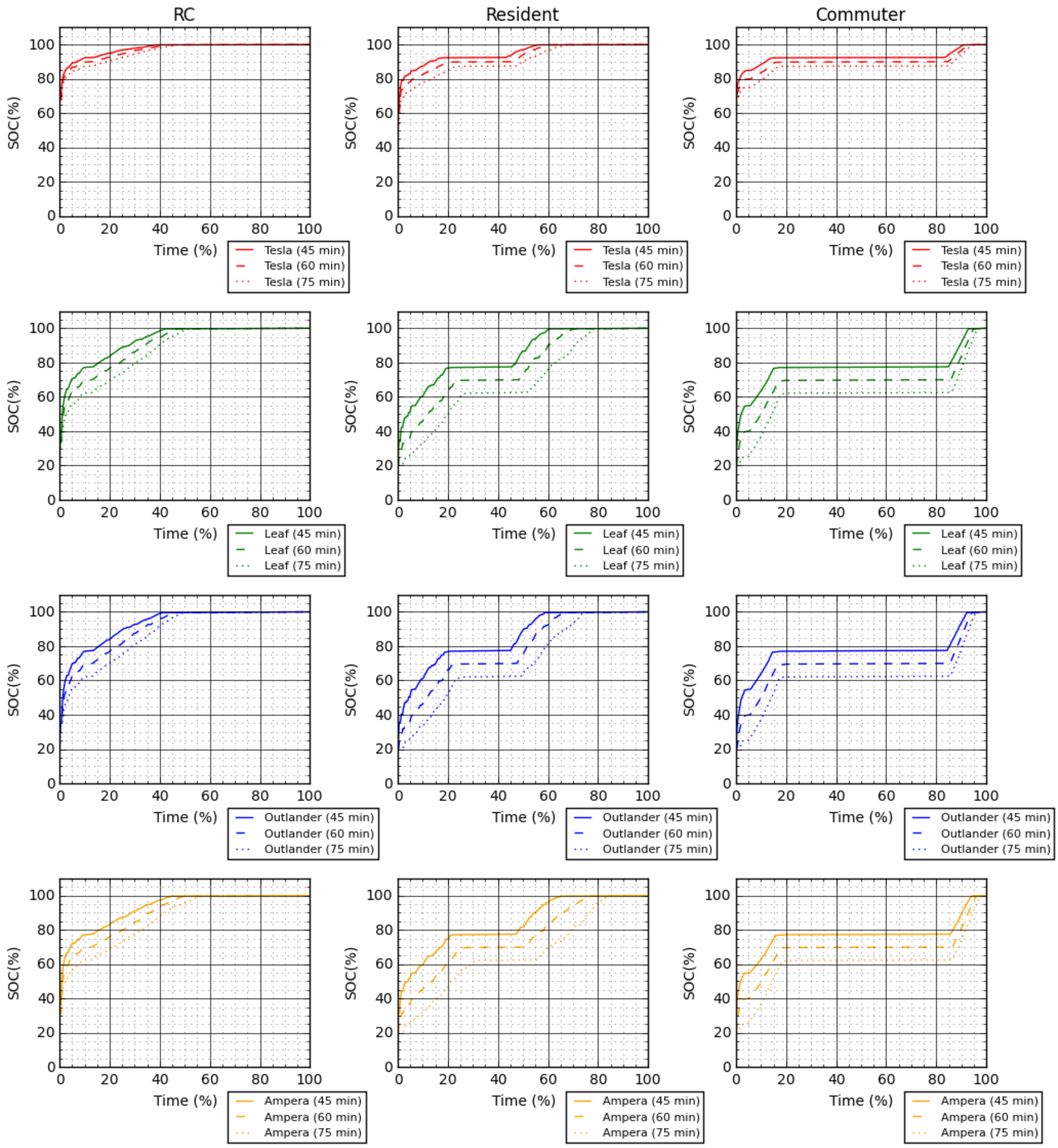


Figure 5.3.3: SOC distributions under different trip durations

The total profits in figure 5.3.4 show that shorter trip duration is favorable for all EVs. The impact is largest for the commuter user type, which is mainly attributed to the fact that is relies most on charging. A reduction in trip duration yields a reduction in energy consumption, which in turn results in a reduction in costs. Shorter trips have in general a positive effect as the ability to make unexpected trips improves, shallower cycling and less throughput occurs and profits are higher.

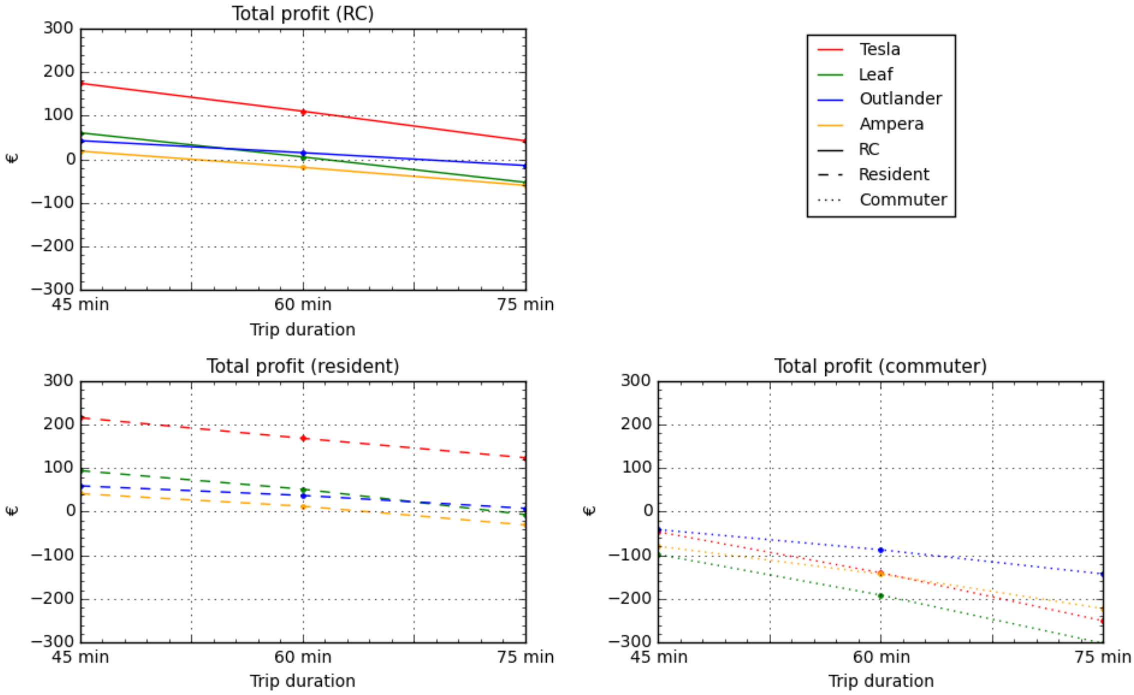


Figure 5.3.4: Total profits of the EVs under different user types and trip duration

5.4 Impact of an increasing number of EVs

Currently, the fleet consists of four EV who influence the load on one substation. Considering that the number of EVs in the Netherlands is likely to increase this assessment investigated the impact on the loads for a larger number of EVs. This is done for a fleet of 4, 8, 12,16 and 20 EVs respectively, in the same composition as in earlier simulations. In this assessment all EV connect according to the connection times that apply for each user type. Although in reality it might be unlikely that all EVs connect at the same time, they will have roughly the same connection times and since they would all react to the same settlement prices they will all provide RRP at the same time. Since each type of EV operates under the same conditions each type will have identical technical- and economical KPI. Therefore these or not discussed in this section. In figure 5.4.1 the results of the different fleet sizes on the loads are presented.

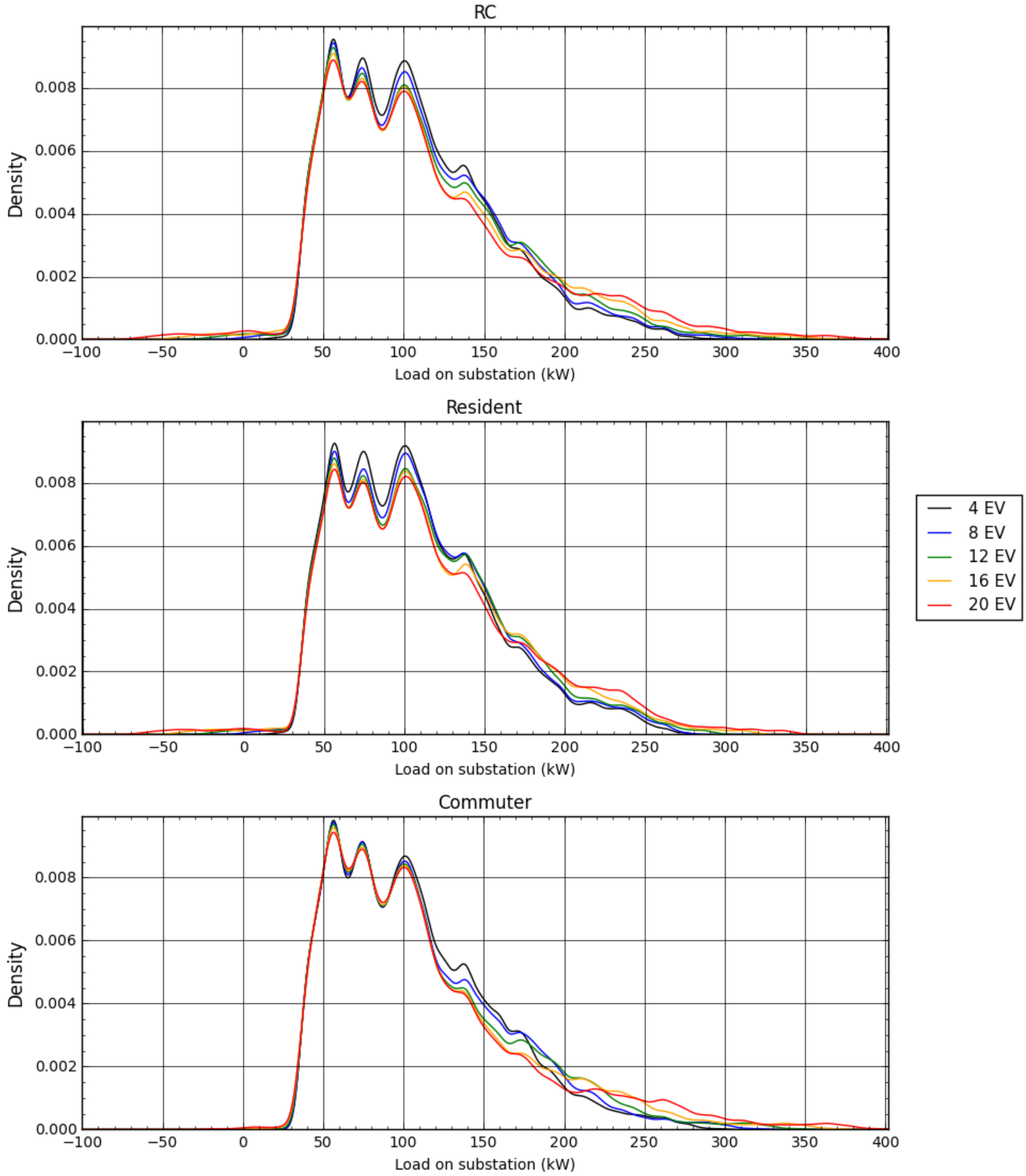


Figure 5.4.1: Loads under different fleet sizes for the different user types

When assessing these results it is important to bear in mind that the maximum load on the substation is 360 kW, as mentioned in the chapter concerning the input data. For the RC user type this value is only exceeded for a fleet of 16 EVs. Additionally it can be seen that an increasing number of EVs increases the occurrence of loads in the region 180 kW and higher and reduce the occurrence of loads that are in the range between 50 kW and 180 kW. Since now more EV can engage in providing RRP up the substation experiences reverse electricity flows. This has some implications for profits generation. Under normal electricity flows the EVs benefit from the efficiency losses in the substation, since the provision of 1 kWh at LV level amount to a correction of 1.08 kWh at the HV level. Under reverse electricity flows this mechanism works opposite and results in 0.92 kWh at the HV level. Due to time constraints for this research this effect has not been accounted for in the profit generation.
When looking at the resident user type it can be seen that lower peak loads occur due to the fact that the resident user type is mainly active during valley hours. The fact that the peak load is the same for a fleet of 4 and 8 EVs confirms this. Additionally, the maximum capacity of the substation is not exceeded. With regard to the lowest loads a similar picture can be seen as for the RC user type, with reverse electricity flows when more than 8 EVs are active.
Under the commuter user type all EVs operate during peak hours and therefore a substation overload can be seen for a fleet of 16 EVS and more. Negative electricity flows only occur when the fleet size exceeds 12 EVs.

Fleetsize	Total charging capacity	Total battery capacity
4 EVs	25 kW	137 kWh
8 EVs	50 kW	274 kWh
12 EVs	75 kW	411 kWh
16 EVs	100 kW	548 kWh
20 EVs	125 kW	685 kWh

Table 5.4.1: Total charging- and battery capacity of different fleet sizes

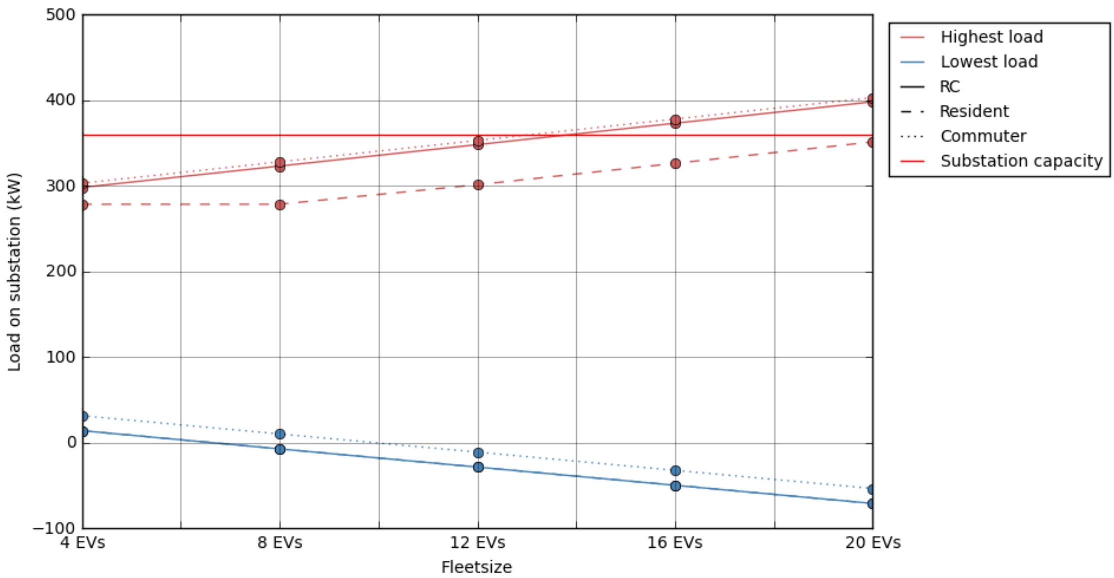


Figure 5.4.2: Highest and lowest load caused by different fleet sizes

Based on this assessment substation overloads could occur when the fleet exceeds 16 or 20 EVs (figure 5.4.2). With respect to this research this fleet would be operated by 140 households and 60 businesses within one area serviced by the substation used in the assessment. Whether if it is likely that these fleet sizes are accomplished or even surpassed is dependent on a variety of factors and outside of the scope of this research.

6 Discussion

For this research several assumption and simplifications have been made. While it was pursuit to found all assumptions on realistic data or previous findings in literature, some of these might be subject to error and could influence the results presented in the preceding chapters. Therefore this chapter will be devoted to discussing the limitations of this research.

Simplification of the infrastructure

To perform the simulations in this research some simplification and assumptions have been made regarding the infrastructure. Firstly, substation capacity has been assessed as most likely component to fail due to the increased loads form the EVs. While this could be true, there is still an effect on the cables caused by the EV, which thus has not been assessed. Secondly, cables are prone to transmission losses, especially at low-voltages. This could be an important factor as the remuneration for RRP is only delivered for the power that is delivered to the TSO. In general, the transmission between the charging facility and the high voltage grid has been simplified by using average efficiencies for all intermediate components. With regard to the charging facilities it is assumed that these are capable of both charging and discharging the EV, which is currently not the case for most charging facilities installed in the Netherlands. However, the potential is there, as shown in pilot projects[5] within Europe and the USA.

Composition of load input data

The data is based on one week in February and subsequently repeated over 52 weeks. To account for seasonal differences, weekly consumption data is used to scale the annual profile accordingly. By doing so it is assumed that electricity demand in winter is higher than summer for each moment of the day. In other words, if electricity consumption in winter is 5% higher than in summer, the current model assumes that this is true for 12:00 and 18:00. However, it could very well be that the darker winter months cause an earlier and larger evening peak and that demand during midday doesn't change much in comparison to summer. In this case the peak loads are not altered by the EVs since in used profile the peak occurs during midday.

The load that is a result of commercial activities is based on merely two load profiles. Therefore the commercial load would become very specific to these two businesses. Additionally, the commercial load shows a large increase in baseload January and September. It was not possible to determine the cause of this increase, which might lead to over estimation of the loads on the substation. In general it would be desirable to use measurement data at a substation level to create a realistic load profile of an urban area. This data however proved to be unobtainable.

Interpretation of the settlement prices

To determine the profit generated by RRP provision the balance delta from Tennet is used. As mentioned in the input data chapter, using these prices means that bids can be placed perfectly and implies that the bidder has perfect knowledge on the amount of RRP that will be called. Additionally, the dataset showed simultaneous occurrences of RRP up and down. Since the dataset is on a minute basis this means that within this minute both kinds of RRP are dispatched. However, the model can only select one type and simulates dispatch of this type for a full minute, while in reality this is less. Despite this error the impact on the results is expected to be small as this occurs relatively few times.

Possible economic components excluded from the analysis

This research considers the practical implementation of RRP through EVs to be out of scope. Therefore no attention has been gives to required control systems, new entities such as the aggregator, and their associated costs. These costs could be significant since it requires the set up of an entire communication network and people who control it.

[5] EDISON project in Denmark and the University of Delaware of are among the first who use bi-directional charging facilities for V2G services

Secondly, this research uses energy only prices, excluding taxes and fees. As a results the costs for charging are around three times lower than they would be in reality. This would result considerably more costs in the baseline scenario and lower profits in the RRP scenario, as charging is still an important component for costs. Additionally, the settlement prices are subject to taxes that have not been included. This means that RRP up would yields more profits and RRP down less profits. It is therefore recommended to further specify the components of costs and benefits in future research.

Role of the DSO
In this research the DSO was solely interpreted with regard to the technical characteristics of the infrastructure. Since the DSO will experience a deviation in loads placed on its infrastructure it is questionable whether the DSO is willing to allow RRP provision through its infrastructure. The sensitivity analysis showed that under RRP provision higher loads and reverse electricity flows are present. Both have adverse impacts on transformer aging and therefore DSO could be hesitant to allow RRP provision by EVs.

Exclusion of substation efficiency in the profitability condition
In determining the profitability of RRP provision the effect of the substation efficiency on profits is not accounted for. Due to this effect RRP should be deemed profitable at prices above 8.5 cents/kWh instead of 10 cents/kWh. Due to this less RRP up is provided. With regard to RRP down this has no effect, as all settlement prices for RRP down are still profitable at a setting of 8.5 cents/kWh

Battery characteristics
This research made some simplifications regarding the technical- and economic aspects of battery charging and discharging. Firstly, it assumes that battery charging is a linear process, while in reality charging slows down at higher SOCs. Secondly, the costs of battery degradation is not included in research, since this is a complex phenomenon dependent on many factors that lie outside the scope of this research

Determination of energy consumed per trip and consequences
In this research the assumption for the energy consumptions of the EVs during trips is based on the amount of kWh charged per charging session. This has important consequences with regards to travel distances. Since all EV's have different battery capacities they all use a different amount of kWh per trip. This is the result of using the data presented by Helmus and Van der Hoed (2015) that state that EV's charge around 60% of their maximum SOC. In addition, all EVs have different driving efficiencies with regard to the amount of energy they need per unit of distance. This yields different trip distances for each EV. For example, the Leaf has a driving efficiency and battery capacity that is almost 1.5 times as high as those of the Ampera. Under the assumptions used in this model this means that the Leaf consumes a high amount of energy under a high efficiency per trip. Therefore the Leaf has a trip distance that is considerable larger than the Ampera's, while they spend the same amount of time commuting. When looking at the average distance that applies to Dutch commuters smaller daily trip distances can be found. This would yield shorter trip times and higher SOC at the time of connections. In the sensitivity analysis the impact of shorter trip duration has been assessed and showed that this could have a significant impact on the results. While the argument could be made that EV drivers are a very distinctive group of road users who may be driving more, this is not supported by any additional research in this study. However, since electric mobility could be a more common means of transport in the future it seems desirable to account for this is future research.

Frequency of charging and exclusion of weekends
In this research it is assumed that EV drivers engage in a daily charging pattern. Although these assumptions are based on findings in scientific literature, they are still prone to uncertainty. Firstly, weekends are completely excluded from the analysis due to the inconsistent travel patterns that occur during weekend. But if EV would be modeled as available for a certain amount of that time a considerable increase in profits could be a result. Secondly, in this research consistent daily cycles of charging are assumed. However, different findings were present in literature. Spoelstra (2014) reported an average of 3.23 transaction per week, while

the research from Helmus and Van den Hoed (2015) reports at least 5 per week. Both researches exclude charging at private points. Although EV services providers stated that private charigng takes place daily, this could not be backed by data. Significant improvements in this research would be possible if the charging patterns of EV users are more thoroughly assessed.

Sensitivity analysis

Due to the limited time available for this research focuses on user-related characteristics and fleet size in the sensitivity analysis. As a result no analysis was performed on other input data, such as the efficiencies of charging facilities and –substation. However, the impact of these factors is rather straightforward and its impact on RRP provision can be fairly easy calculated. Because the selected elements have a more complex relation to the identified mechanisms that are important for RRP provision it was chosen to focus the research on those elements.

7 Conclusion

The initial aim of this research was to determine the potential monetary value of V2G in Dutch urban Areas. V2G is a rather broad definition, embodying many different services. A common service that has been explored in previous scientific studies is the provision of ancillary services and therefore these services formed the main focus after the first delineation. Ancillary services in turn are composed of different forms of power that can be dispatched for balancing purposes. With regard to the Netherlands these are divided into regulating-, reserve- and emergency power. Regulating- and reserve power (RRP) is dispatched often and was therefore selected as main service under study. Before an actual valuation could take place an assessment was required regarding the regulatory- and technical context in which RRP provision through EVs would have to be placed.

In the first assessment the operation of the Dutch electricity system was explored, thereby indicating the different parties and their responsibilities in the electricity chain. The concept of balance responsible parties (BRP) came forward as an important mechanism in maintaining grid balance. Subsequently it has been explained which instruments the TSO has at its disposal in order to act in the case unbalances do exist. This led to the more extensive introduction on RRP and the different ways it is obtained. RRP is obtained though both contractual agreements and market bids. The latter is quite important, as EVs could be suitable to place bids in these markets as well. However, TSOs have specific rules regarding the bids that are placed in the market and how they remunerate these services. To assess whether these are favorable for EVs a framework developed by Codani et al. (2014) was used. Key components of this assessment regarded the minimum size of the power bid, interoperability between DSOs and nature of the payment scheme. Although the Dutch rules and regulations are not identical to the ideal situation, it can be concluded that they are in general favorable for the implementation of RRP provision by EVs.
Since EVs and the respective charging infrastructure is operated on a LV-level it has to be assessed whether this infrastructure and its characteristics are suitable for RRP provision. Firstly the load that is already placed on the grid by households and businesses was presented. The combination of these loads lead to a profile that peaks at midday. When providing RRP the EVs will alter these loads and this has implications regarding the capacity of the infrastructure. The LV infrastructure comprises of substations and lines that both have limited capacity. The transformers in the substations are identified as most likely element to fail and therefore considered as the main bottleneck.

The second assessment focused on the composition of the Dutch EV fleet, the charging infrastructure, how EVs are used and how these characteristics hold potential for RRP provision. The number of EVs in combination with the number of installed charging facilities gives a first indication of the potential power delivery, which is sufficient to meet the minimal bid size. In order to provide RRP the EV need to be available and connected to a charging facility. Research from Spoelstra (2014) and Helmus and Van den Hoed (2015) was used to identify at which times this is the case in the Netherlands and if regular patterns can be found. This lead to the introduction of three user types: the resident, the commuter and the resident-commuter (RC), who all have specific preferences regarding trip duration, connection time and energy consumption. All these user types have in general a consistent pattern of connection- and trip times, which are suitable for RRP provision.

These two assessments are combined into a methodology that uses a simulation model to determine the value that can be generated by EVs providing RRP. This model comprises of the 4 most commonly sold EVs which are operated in a LV distribution grid with 200 connections, excluding the charging facilities. These connections consist of 140 households and 60 businesses that all place a load on the substation. The EVs are subsequently modeled for one year under each user type and two dispatch schemes, one in which a baseline is established by regular charging and one in which RRP is provided. To assess the performance of the EVs and different user types, profit, battery throughput, SOC distribution and load on the substation were identified as KPI.

Providing RRP throughout one year proved to generate significant befits for all user types. While not all EVs and user types generated absolute profits, all EVs showed net benefits when compared to the baseline-charging scheme (figure 7.1.1).

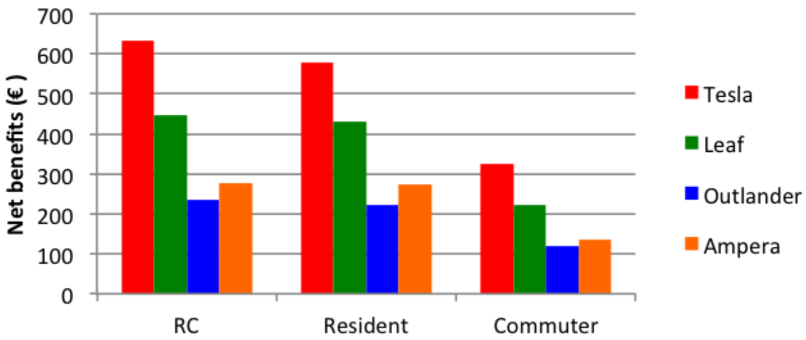


Figure 7.1.1: Annual net benefits when comparing the RRP dispatch scheme with the baseline charging scheme

The user types that benefit from longer connection times can accomplish better economic KPI than the other user types. This does lead to an increased throughput and cycle depth, but for the RC user these occur at relatively shallow cycles due to the fact that it completes two connection sessions per day.
The impact on the loads on the substation was moderate under all user types.
Additionally, it was seen that EV with a higher charging- and battery capacity achieved better results. In order to investigate this relation between battery- and charging capacity and RRP provision a second series of simulations was executed. In this assessment in became clear that higher battery capacities improve RRP provision, but are limited by the charging capacity. Therefore a high battery capacity is only favorable when charging capacity is high as well.

In order to generate these results several assumptions have been made regarding the users preferences and -travel characteristics and the size of the fleet. To investigate the impact that these assumptions have on the results a sensitivity analysis was conducted. This analysis showed that lowering the required SOC preferences results in significant improvement in profits. This reduces the costs made for charging, which in all cases has large influence on total profits, while maintaining a relatively high SOC distribution.
Raising the minimal SOC preference showed that EV users could maintain the same ability to make trips as in the baseline scenario, while still providing RRP. This would lead to lower profits than under a minimal SOC setting of 20%, but would still perform better than under the baseline charging scheme. In general the minimal SOC setting only impacts the results when it is very high.
To assess the impact of longer and shorter trips a new series of simulations was made. This showed that shorter trip duration increases the total profits and longer trip duration achieves the opposite effect. Additionally, shorter trips result in less battery throughput and a higher SOC distribution.
Finally, an assessment has been made regarding the growth of EVs and its impact on the infrastructure. Under all user types an increase in fleet size leads to an increase in peak loads. For the RC and commuter user type this happens as soon as the fleet increases. For the resident type a tripling of fleet size is required as this user type is operated at valley hours. Under all user types reverse electricity flows through the transformer and transformer overloads become visible when the fleet size increases sufficiently.

In conclusion it can be stated that the provision of RRP by EVs has potential in the Netherlands as it can generate significant benefits for its users. This conclusion is however based on a significant number of assumptions and subject to a number of simplifications. It therefore earns recommendation to further research the practical implementation and large-scale roll out of this concept.

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Appendix

Appendix 1: Construction of the aggregated load profile

Residential load

The residential load is constructed based on a dataset previously used by Claessen (2012) and Van der Kam (2013) in their master thesis's and subsequent papers. The dataset contains 15-minute data of 400 households who are randomly selected from a group of 700 households. Measurement were done during one week and based on this week and yearly variations in electricity consumption a yearly load profile were created for each household. As the data is scaled to 2050, a scaling factor of $1{,}005^{-36}$ is used to make the data compatible for 2014. The households included in the dataset are terraced houses, as specified in F. N. Claessen et al. (2014), while urban areas largely consist of apartments. For example, the residential building stock in Amsterdam consists for 88% of apartments (CBS, PBL, & Wageningen UR, 2014). To make the dataset applicable for urban areas a scaling factor is calculated based on open data retrieved from Liander (Liander N.V., 2015). This dataset lists the average annual electricity consumption of different types of houses and household composition based on measurements taken between October 2010 and December 2011. To calculate the scaling factor for converting the load of the terraced houses to the load of apartments the ratio between these types is calculated (equation 3.14).

$$Terraced\ house\ to\ apartment\ ratio\ (TAR) = \frac{E_{apartment}}{E_{terraced\ house}} \tag{3.14}$$

The TAR is calculated by dividing the average annual electricity consumption of an apartment $(E_{apartment})$ with the average annual electricity consumption of a terraced house $(E_{terraced\ house})$. This is done for each household composition and building period respectively and yields the ratios displayed in table A1.1. E.g. a "young single" household living in an apartment built after 2000 consumes on average 13% less electricity than a "young single" living in a terraced house of that same building area. The exact composition of the dataset, both in terms of household composition and building period, is not further specified and therefore it is decided to take the average of all TAR ratios. This amounts to 0,82.

Ratio electricity consumption Terraced house vs. apartment (Average ratio: 0,82)							
Building period	*Before 1940*	*1940 until 1959*	*1960 until 1969*	*1970 until 1979*	*1980 until 1989*	*1990 until 1999*	*2000 until present*
Young single	1,19	0,59	0,58	0,72	0,73	0,79	0,87
Young couple no children	0,86	0,9	0,8	0,81	0,71	0,73	0,78
Family with young children	0,76	0,78	0,78	0,87	0,74	0,94	0,76
Family with young and old children	-	0,97	1,12	0,9	0,77	0,84	0,91
Family with old children	1,04	0,9	0,74	0,79	0,71	0,67	0,7
Middle aged couple no children	1,05	0,67	0,8	0,79	0,65	0,75	0,91
Elderly couple no children	0,88	0,89	0,81	0,82	0,84	1,05	0,72
Middle aged single	0,88	0,85	0,76	0,8	0,69	0,8	0,74
Elderly single	0,66	0,84	0,89	0,94	0,91	0,78	1,09

Table A1.1: Overview of the different TARs

The average TAR is applied to each value in the dataset, making it representative for households in urban areas. Next step is to average the load profiles of the 400 households. Subsequently the 15-minute data is interpolated to one-minute data to make it compatible with the time steps used in the simulations. This yields the yearly residential load profile of an average apartment on a one-minute basis (figure A1.1). In this figure a clear difference is visible throughout the seasons, with higher peak loads occurring in darker months. This is further specified in figure A1.2 where a day in winter and a day in summer are plotted. Note that the load rarely exceeds 700 W, which is very low for a single household. This can be explained by the concept of simultaneity (Van Oirsouw, 2012) that states that different consumers are unlikely to exercise peak load at exactly the same time. When assessing individual households in the dataset peak loads up to 8 kW can be found. The opposite applies for base loads that can be as low as 0 kW. Figure A1.3 shows the maximum, mean and minimum loads for 3 days in February to illustrate this.

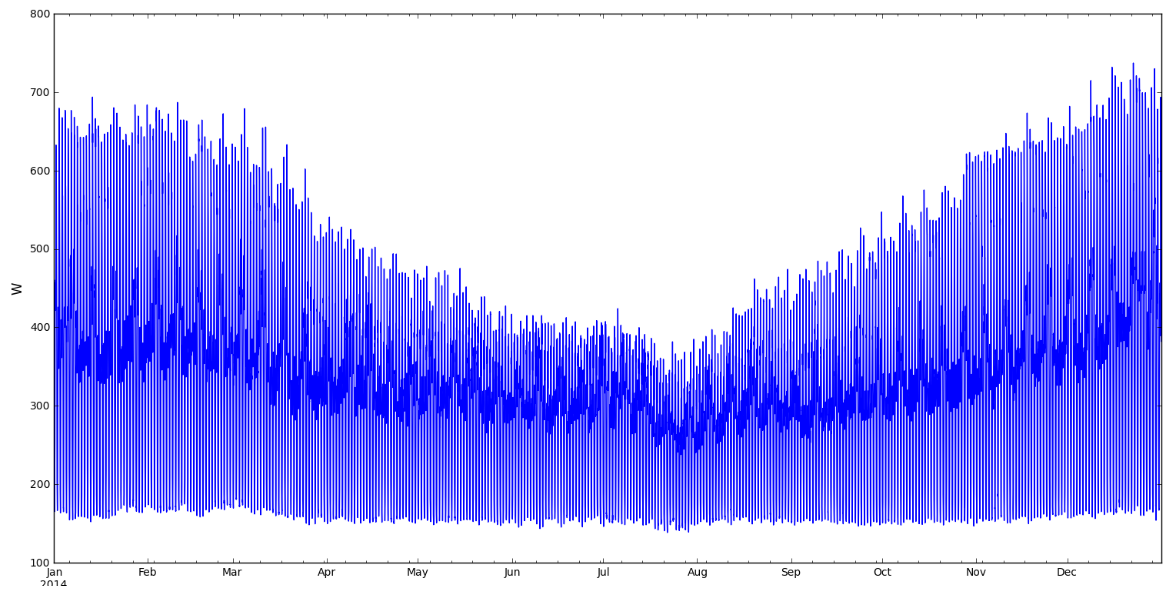

Figure A1.1: Average residential load profile

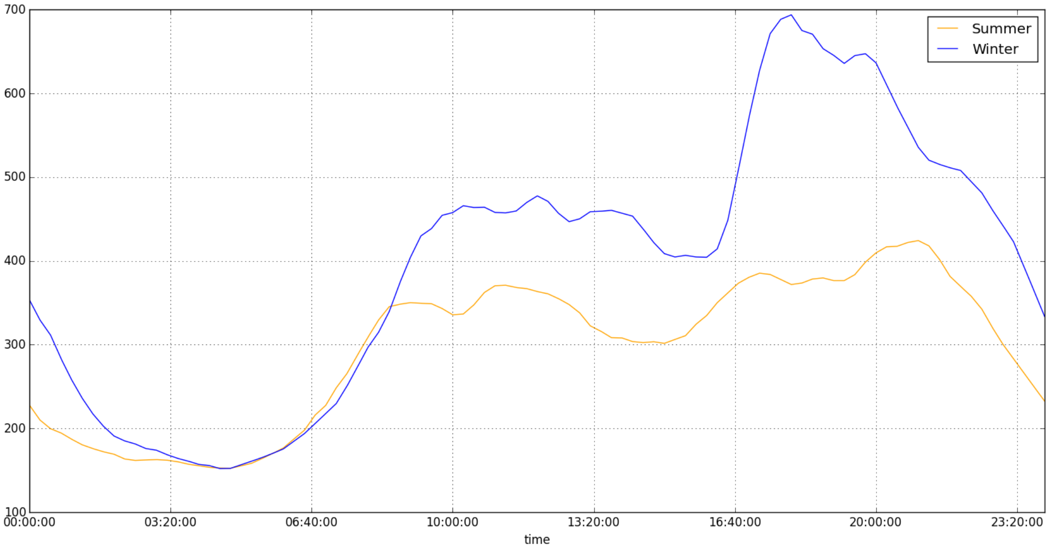

Figure A1.2: Comparison between average electricity consumption in winter vs. summer for a household

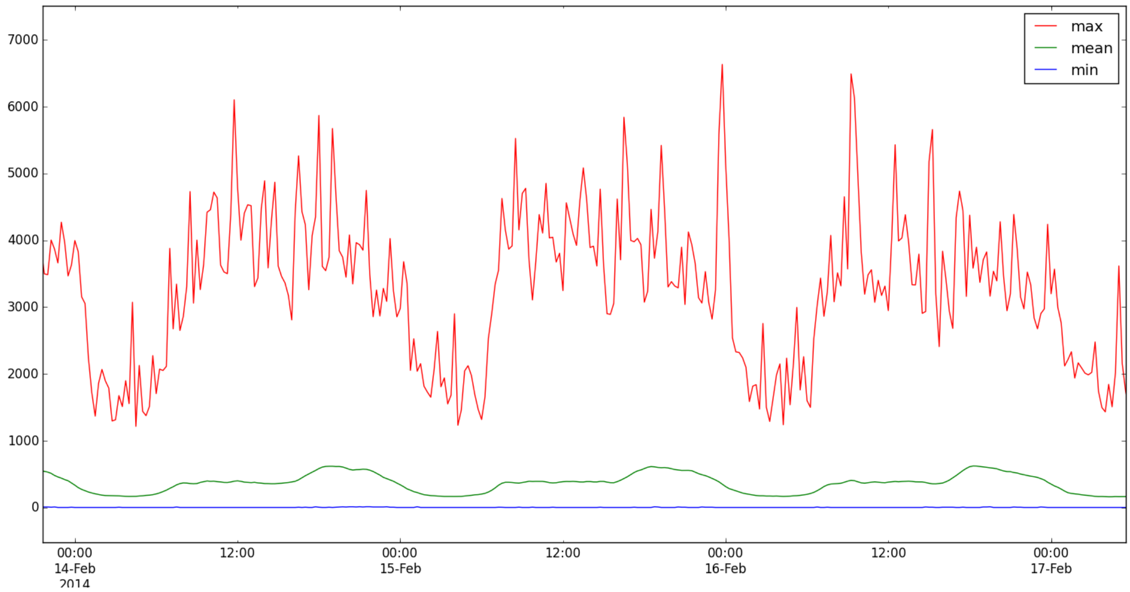

Figure A1.3: Maximum, mean and minimum residential loads

Commercial load

The commercial load is based on smart meter data that was provided by De Groene Bocht. De Groene Bocht is located in the center of Amsterdam and accommodates around 20 small businesses. The dataset offered over 3 years of data with regard to total electricity consumption and the specific consumption of the equipment used in the office. Unfortunately it was not possible to verify if all equipment was included in the measurements. Therefore it was decided to use the total consumption data. Hourly measurements were found for the period 18th May 2011 until 8th June 2012 (figure A1.4). A remarkable observation is the sudden increase in minimal consumption in August 2011, which returns to near zero again in January 2012. A possible explanation for this could be temporary installment of servers. Unfortunately it was unable to verify this hypothesis as the data is relatively old and the current staff could not remember the exact activities that took place at the time.

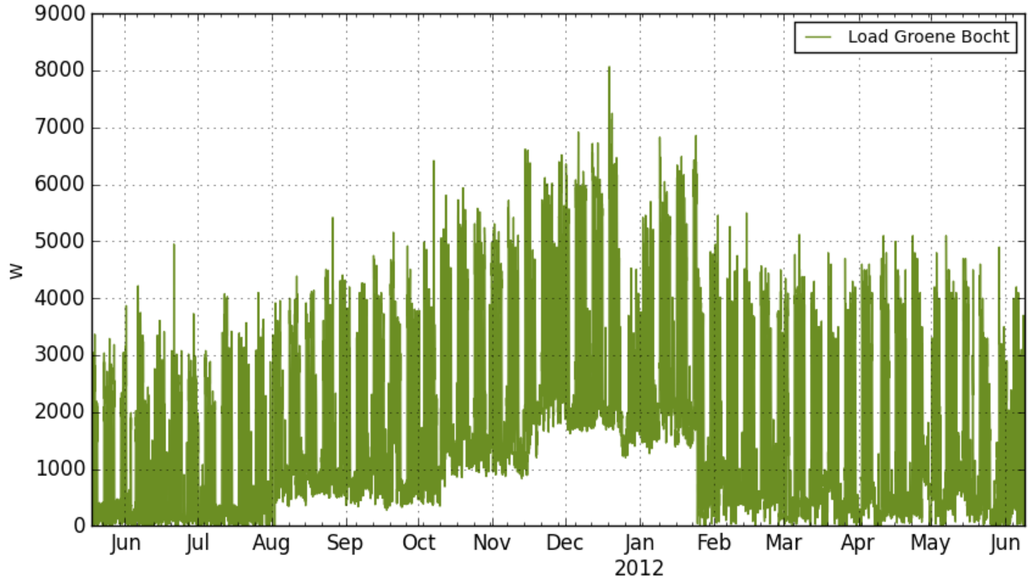

Figure A1.4: Load Groene Bocht between 18th May 2011 and 8th June 2012

Based on this dataset the load profile for 2014 was composed. First step was to make sure that weekdays, holidays and weekends were aligned, as these days tend to have a specific load profile. 2st January 2014 is a Thursday, so from the dataset the first Thursday in January was selected and pasted in the profile. Note that January 1st is not modified, as this is a public holiday. The same is done for Christmas and 31st December. Subsequently the profile was scaled to 2014 according to the methodology applied for the residential load. This yields the annual load profile in figure A1.5.

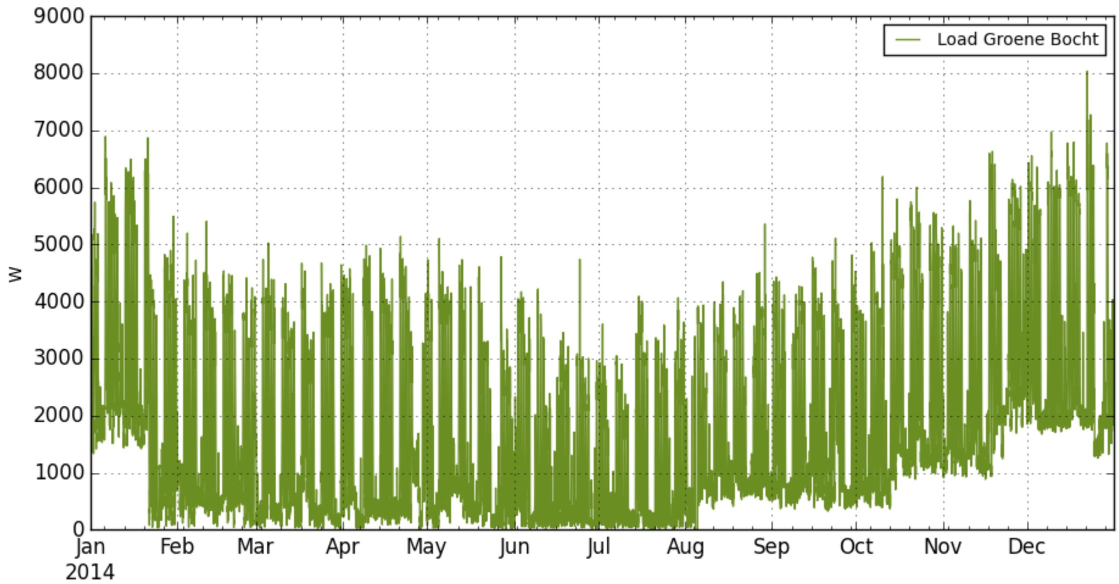

Figure A1.5: Constructed annual profile Groene Bocht for 2014

This profile cannot be used directly in the model, as this will yield high loads that are too high. Note that in the previous section simultaneity was briefly introduced. By using only this profile the peak loads would be exaggerated. Therefore a second commercial profile is added that will be used to create a more realistic average profile. This second profile was provided by Mart van der Kam who used it for his thesis (Van der Kam, 2013). This profile is based on one week of measurements at LomboXnet, an internet provider in Utrecht. This week is subsequently repeated 52 times in order to cover a year and modified to create a realistic profile. To account for seasonal variations in energy consumption the dataset is multiplied by week factors. In Van der Kam (2013) these factors are based on households. This assumes that commercial electricity is influenced in the same way as residential consumption, while this might not be the case. For example, the transition to darker, winter months has a large effect on residential electricity consumption, as they will need to turn the lights on earlier. Businesses experience this effect as well, but on a far smaller scale as they usually close before sundown. Therefore in this research the week factors will be derived from the consumption data retrieved from the Groene Bocht. Per week the electricity consumption is averaged. Since the measurements at LomboXnet were taken during the first week of November this week will be assigned a week factor of 1. The week factors for all other weeks were calculated according to equation 3.15. In figure A1.6 the week factors are presented graphically. Figure A1.7 presents the profiles after applying the weekfactors.

$$Weekfactor_{n+1} = \frac{Weekfactor_n * Average\ consumption_{n+1}}{Average\ consumption_n} \tag{3.15}$$

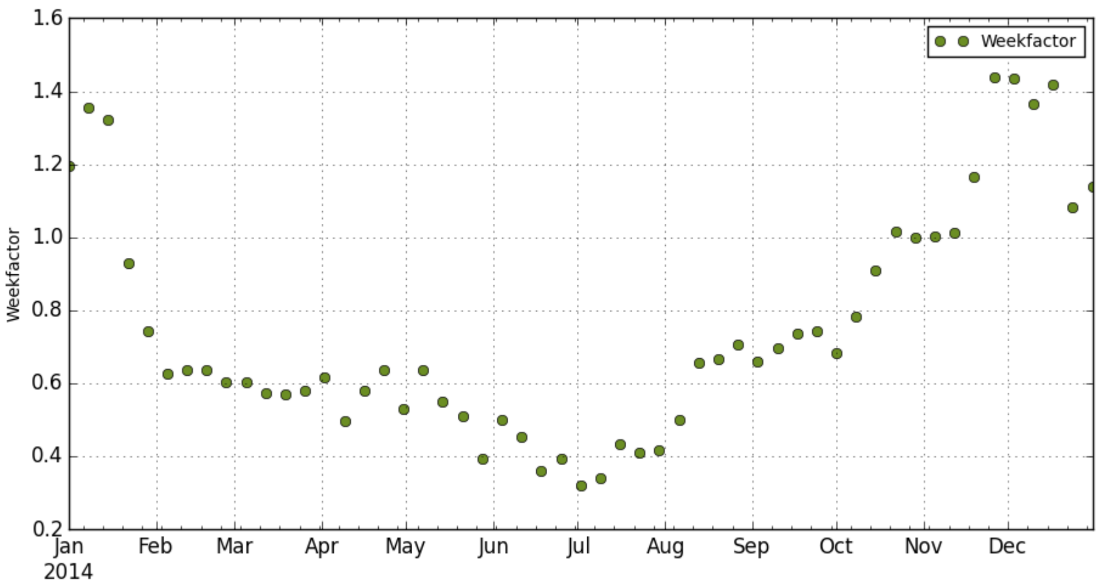

Figure A1.6: Week factors used to modify the LomboXnet profile

Basing the week factor on the consumption of De Groene Bocht has the consequence that the unexplained increase and decrease of electricity consumption are also visible in the consumption pattern of LomboXnet. As a result it cannot be stated that the week factor account for seasonal changes only. Nevertheless, the profiles of Lomboxnet and De Groene Bocht can now be used to create an average commercial load profile, which is shown in figure A1.7.

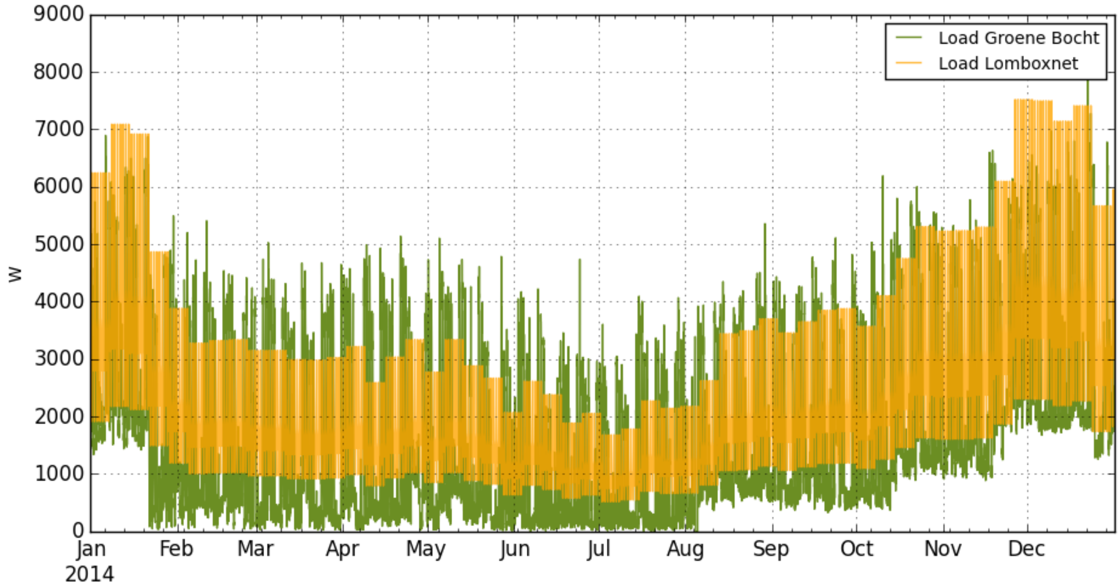

Figure A1.7: Annual load profiles Groene Bocht after applying week factors and LomboXnet

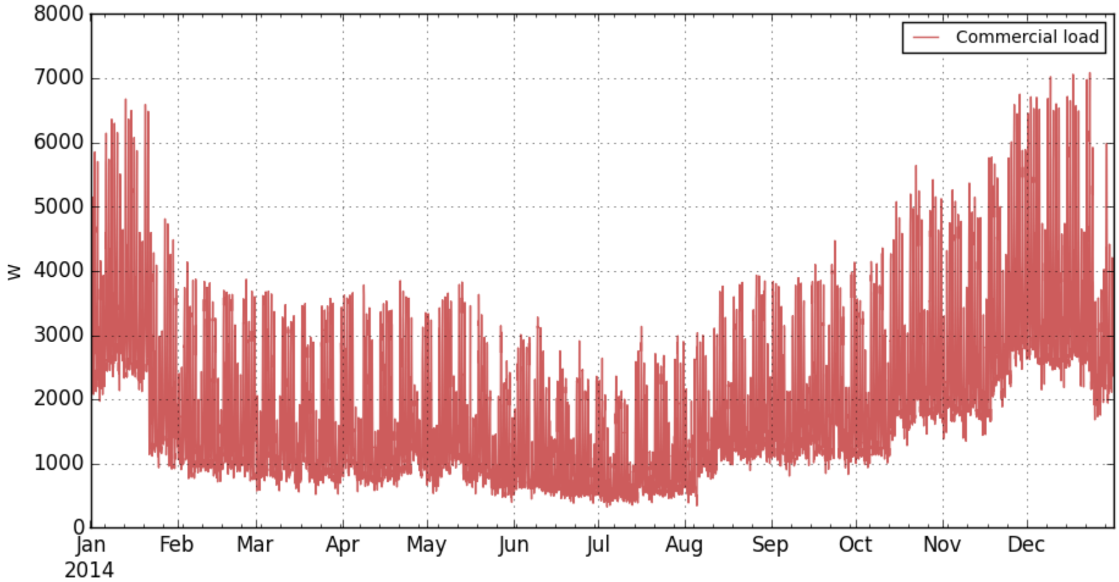

Figure A1.8: Average commercial load

Appendix 2: Average SOC under both dispatch schemes

Since the SOC distribution under the RRP dispatch scenario is lower than under the baseline charging scheme the average SOC of the EVs becomes lower as well. In figure 4.2.4 these are shown for each EV and user type, who are abbreviated as RC, R and C. The average SOC under the baseline charging scheme is shown in grey.

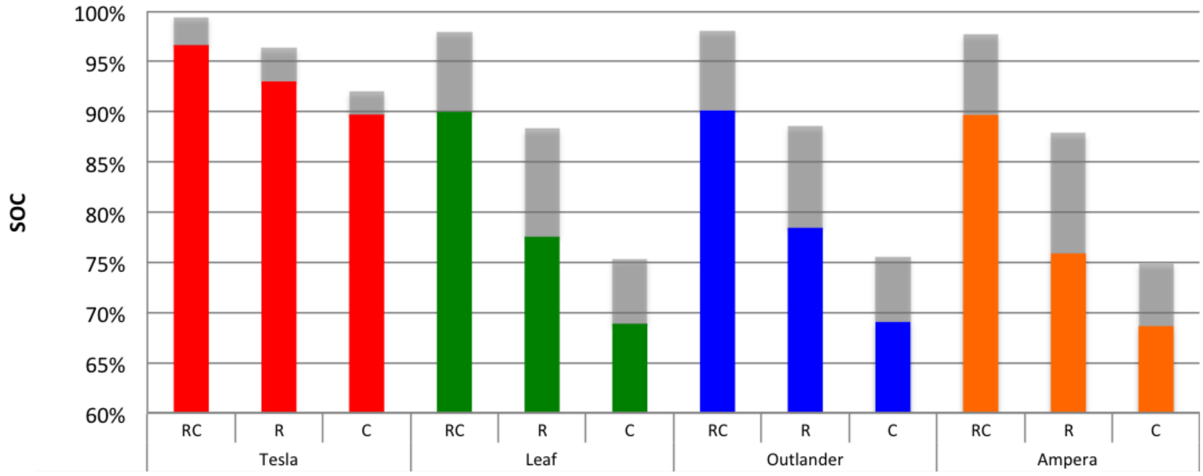

Figure A2.1: Average SOC for different EVs and user types under both dispatch scheme

Appendix 2: Economic KPI under different battery- and charging capacities

Figure A2.1 shows how the economic KPI develop for different battery and charging capacities, which support the statements made in chapter 4.3.

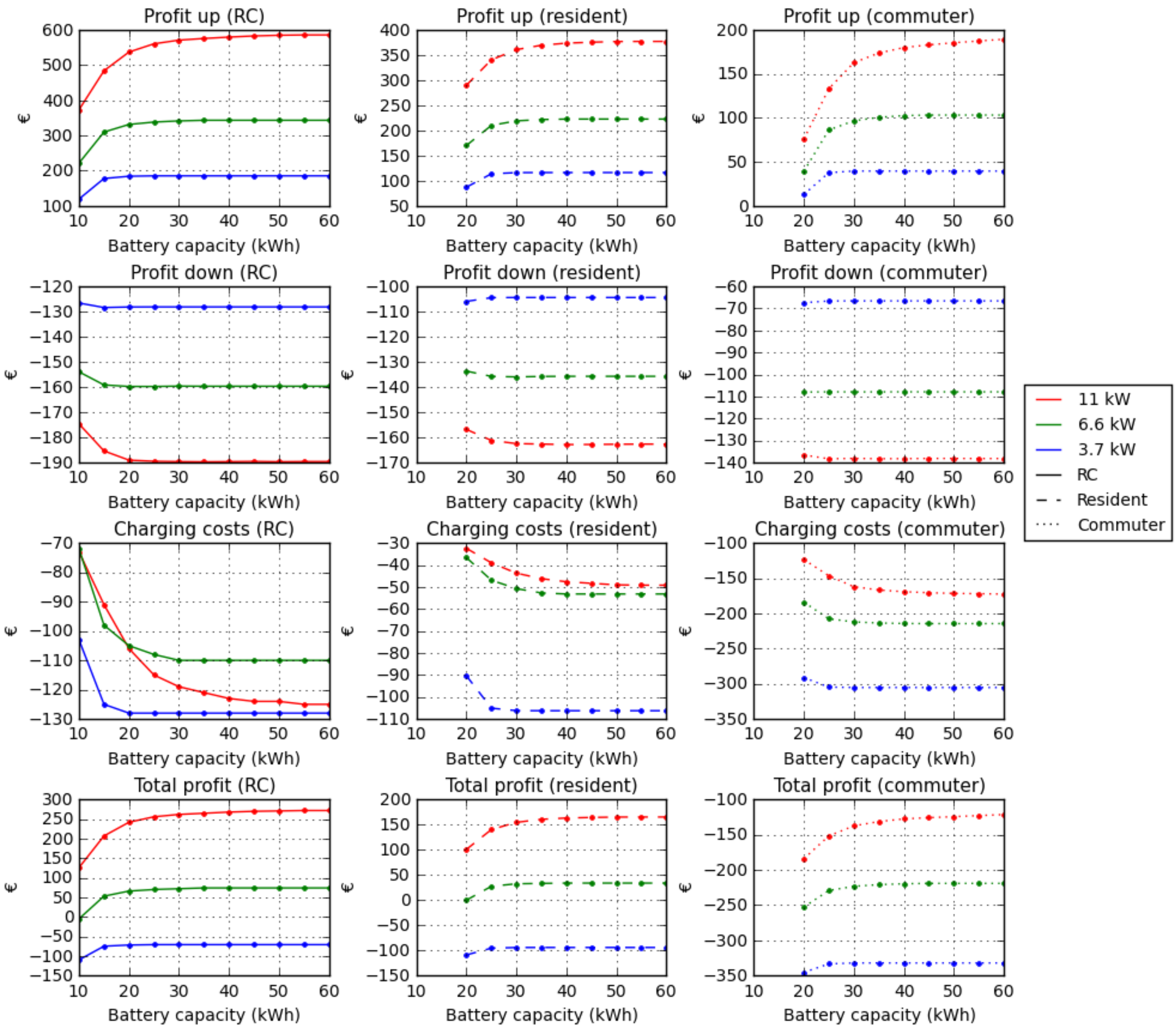

Figure A2.1: Annual economic KPI under different battery capacities.