The rise of the electric vehicle influencing the public charging infrastructure of tomorrow:

An application of a discrete choice experiment in the EV industry

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Abstract

The central topic of this thesis is the charging preferences of urban electric vehicle (EV) users who are dependent on the public charging infrastructure. Currently, most EV users own a private charging station. However, in the future when the EV will be the mainstream model, the dependency on the public charging infrastructure is expected to increase. This thesis adds to the gap found in literature regarding the urban EV user who has no opportunity of private charging. Through the use of a discrete choice experiment, the charging preferences of current and prospective EV users regarding the charging price, the distance to a public charging station, and the availability of a public charging station in an urban neighbourhood were collected. Afterwards, the data were analysed using the conditional logit choice model (CLCM). The CLCM indicated a significant negative relationship between the first alternative-specific variable of price and the selection of a public charging station, and the second alternative-specific variable of distance and the selection of a public charging station. The third alternative-specific variable of availability showed a significant positive effect on the selection of a public charging station. From these three alternative-specific variables, price is the largest differentiator. Moreover, significant associations were found between case-specific variables like initial battery level and the general choice of charging, and EV ownership and the general choice of charging. Finally, to provide a practical touch to this thesis, three different business cases were developed regarding both individual public charging stations and public charging plazas. The conclusions and further recommendations of this thesis are relevant for all stakeholders in the EV and charging industry. The results provide insights into the preferred public charging infrastructure in an urban neighbourhood.

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List of abbreviations

AC = Alternative Current

ASC = Alternative-Specific Constant

BEV = Battery Electric Vehicle

CLCM = Conditional Logit Choice Model

CLM = Conditional Logit Model

CPO = Charge Point Operator

DC = Direct Current

DCE = Discrete Choice Experiment

EV = Electric Vehicle

HEV = Hybrid Electric Vehicle

ICE = Internal Combustion Engine

IIA = Independence of Irrelevant Alternatives

LDV = Limited Dependent Variable

LPM = Limited Probability Model

MLM = Mixed Logit Model

MSP = Mobility Service Provider

PHEV = Plug-in Hybrid Electric Vehicle

SOC = State of Charge

Chapter 1. Introduction

The worldwide adoption of electric vehicles (EVs) is increasing. Nobody can deny this. The global EV stock passed five million vehicles in 2018 (International Energy Agency, 2019) showing an increase of 63% from the previous year. In the Netherlands, 271,983 EVs were registered at the end of 2019 (RVO, 2020) and this number is still increasing every month. The Dutch government wants all newly sold passenger cars to be zero-emission by 2030 (Rijksoverheid, 2017). However, only marketing and selling EVs will not do the job. The EV is part of a bigger ecosystem. An ecosystem in which the mobility, infrastructure, and energy sector will need to collaborate, and reshape the world of tomorrow.

Evidence for this need can be clearly found in the required energy for charging an EV. The annual energy consumption of an average Dutch household was 2,790 kWh in 2018 (CBS, 2020). In comparison, the annual energy consumption of an EV ranges from 2,500 to 3,000 kWh based on an average yearly covered distance of a passenger car of 13,000 km (CBS, 2018). Thus, when a household decides to purchase an EV, it puts the extra weight of an entire household on the electricity network. If all passenger cars in the Netherlands would be replaced by EVs, it would be impossible for the electricity network to accommodate this increase in requested energy. Hence, understanding the charging behaviour and preferences of (prospective) EV users is crucial to secure our energy provision. Knowledge about energy demand can help developing the tools to cope with the rise in EVs.

In general, EV users can charge at different types of charging stations. Charging points can be either public, private, or semi-public. To illustrate, the Netherlands had 27,773 public, 21,747 semi-public, and approximately 150,000 private charging points at the end of 2019 (RVO, 2020). The total number of charging points has increased steadily over the past couple of years (RVO, 2020), but the large stake of private charging points remains significant. Research has shown that most EV users prefer charging at home in the evening (Morrissey, Weldon, & O'Mahony, 2016; Sun, Yamamoto, & Morikawa, 2015; Xu, Meng, Liu, & Yamamoto, 2017), when the pressure on the energy grid is already at its peak. However according to Hoekstra & Refa (2017), at least two-thirds of the households in the Netherlands do not have access to a private parking place. More precisely, it has been estimated that approximately 8 million public on-street parking places were accessible in 2014, compared to only 1.4 million private parking facilities like driveways (Savooijen, van, Bos, Blankendaal, & Delleman, 2014). For this reason, a large percentage of the Dutch households would rely on the public and semi-public charging infrastructure when driving an EV in the future. This view does not reflect the current situation. At this moment, only one-third of the current EV users do not have the opportunity of private charging (Hoekstra & Refa, 2017). Most of the current EV users are part of the high-income group who often have private parking facilities and therefore the opportunity to install a private charging station (Wolbertus, Kroesen, van den Hoed, & Chorus, 2018). Nevertheless, if the objective is to make the EV mainstream, an appropriate strategy for the location of public charging stations should be developed.

Especially in urban areas where private parking facilities are rare, the public charging infrastructure will play a big role. Limited research has been done on charging behaviour in urban environments, while the trend shows that an increasing amount of people is moving towards the city. It is expected that by 2050, two-thirds of the world population is living in urban areas (Ritchie & Roser, 2018). Consequently, more research is needed on this topic, so that policy makers can develop sound plans for the future charging infrastructure in urban neighbourhoods. Therefore, the following research question (RQ) will be answered in this thesis:

RQ: *"What are the charging preferences of (prospective) EV users living in an urban residential neighbourhood with no opportunity of private parking?"*

This research question will be analysed from the consumer's perspective as well as the industry's perspective.

In the first part, the consumer's perspective will be investigated through a survey targeting both current EV users and prospective EV users. Since the investments in the charging infrastructure and the energy grid are very big, it is essential to understand the reasons behind the charging preferences of EV users. Jabeen, Olaru, Smith, Braunl, & Speidel (2013) investigated these reasons using a discrete choice model in which EV users had to choose from various scenarios which charging option they preferred. The discrete choice model is a good method to measure the preferences of (prospective) EV users for two reasons. Firstly, EV charging is a decision a consumer makes frequently, often weekly. Secondly, each person weighs the various factors influencing the potential choice options differently. Therefore, the DCM will be used to measure consumer preferences regarding the public charging infrastructure.

In the second part, the industry's perspective will be analysed. Interviews with EV stakeholders will be conducted to examine their views on the future charging infrastructure. This way, a better interpretation of the results can be provided. The various stakeholders in this field are, e.g., local, and national governments, charge point operators, mobility service providers, energy suppliers, parking operators, and knowledge platforms.

Afterwards, recommendations can be provided on urban citizen's preferences regarding the future public charging infrastructure. The adoption of the EV will have a huge impact on the future energy and mobility infrastructure. Hence, more research is needed to provide guidance to stakeholders, so that the EV industry can expand progressively. This research will contribute to this aim.

The remaining of this thesis is indexed as follows: Chapter 2 provides background information on the technical aspect of electric cars and charging systems. Chapter 3 provides the theoretical background used to develop the discrete choice experiment (DCE). Chapter 4 explains the corresponding methods. Chapter 5 provides an overview of the collected data and in chapter 6 the results of the analysis will be discussed. Additionally, to give a practical touch to this theoretical research, chapter 7 shows the business case for a charging station and a charging plaza. Chapter 8 will conclude this thesis together with a number of recommendations.

Chapter 2. Background information: Electric vehicles and charging

2.1 Difference electric motor and combustion engine

To comprehend the academic literature on the topic of EVs, it is important to have a general understanding of the technical differences between an EV and a regular internal combustion engine (ICE).

A regular ICE uses either gasoline or diesel as an energy source. In order to drive the car, the wheels of the car need to have movement. Power is created in the engine to drive this movement. In total, four strokes enable the production of movement within the engine. (Energy.gov, 2013) In figure 1, an illustration of the process is demonstrated. At the first stroke, the intake valve is opened, and the piston creates a suction letting a mixture of fossil fuel together with air flow into the chamber. During the second stroke, the air mixture is compressed and ignited by a spark plug. This creates a small explosion pushing the cylinder down again, making the third stroke. The power created with this third stroke, is the power all the mechanics in the ICE require to generate movement. Then the fourth and final stroke pushes the burned gas out of the chamber, leaving the car through the exhaust pipe. In order to continuously produce power, one cylinder needs to be in power stroke (TU Delft, 2019). All in all, for an engine to work many different moving parts need to operate simultaneously. All these different moving parts make the engine complex and require much maintenance. Therefore, the maintenance costs of an ICE are in theory higher than of an EV (TU Delft, 2019).

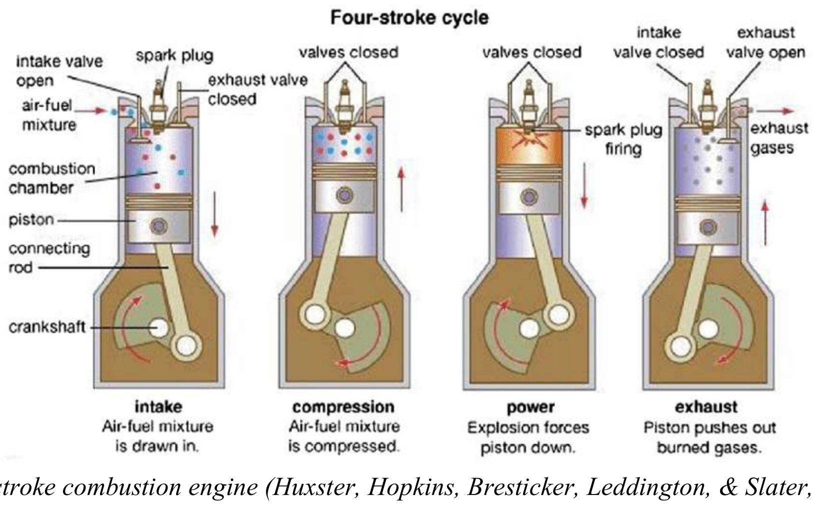

Figure 1: Four-stroke combustion engine (Huxster, Hopkins, Bresticker, Leddington, & Slater, 2017, p. 1147)

An EV works differently, as it does not have an internal combustion engine but an electric motor together with a battery pack. Inside the electric motor, there is a stator and a rotor. The rotor is located inside the stator (SaveOnEnergy, n.d.) as shown in figure 2. When starting the engine, the electricity stored in the battery pack is induced into the wires of the stator which generates a magnetic field (SaveOnEnergy, n.d.). The main principle around magnets is 'opposites attract and identicals repel'. As mentioned earlier, the rotor is located inside the stator. Hence, the rotor starts moving as the field magnets in the stator change poles (SaveOnEnergy, n.d.). This produces a rotational movement which then drives the wheels of the car. Consequently, it is possible for the car to drive without any fossil fuel needed. Compared to the ICE, an electric motor is lighter, smaller, more efficient, cheaper, and requires less maintenance (TU Delft, 2019). This makes the electric motor a valuable alternative for the ICE.

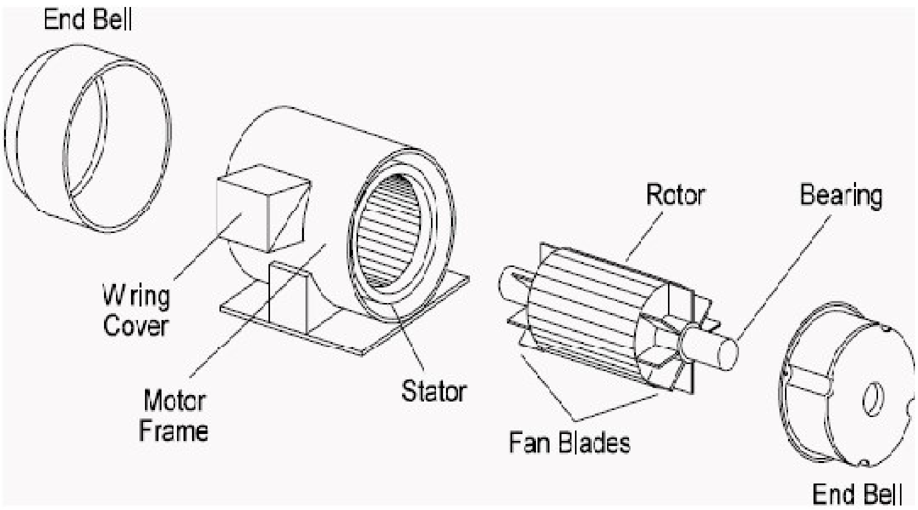

Figure 2: Three phase induction motor diagram (Nanoty & Chudasama, 2013, p. 732)

2.2 Types of EVs

Not all EVs work solely on the principle of an electric motor. There are also EVs which operate on a combination of an electric motor and a combustion engine. These type of EVs are called hybrids. Hybrids have a small battery which allows them to drive on electric power for a limited number of kilometres. When the battery is empty, the car can switch to the combustion engine and continue by running on fossil fuel. A further distinction of hybrids can be made between Hybrid

Electric Vehicles (HEV) and Plug-in Hybrid Electric Vehicles (PHEV). HEVs charge their battery through regenerative breaking and while driving (TU Delft, 2019). In the end, their battery is still partly charged using fossil fuels. PHEVs, on the other hand, can be plugged into a charging station. Hence, their battery is charged using the regular charging infrastructure for EVs. When the battery is depleted, the car will change automatically to the combustion engine. A Battery Electric Vehicle (BEV) only has an electric motor and no combustion engine. Therefore, it exclusively runs on electricity and not on any fossil fuels. Table 1 provides an overview of all the different types of EVs.

Table 1 - Different types of EVs (TU Delft, 2019)

Type of vehicle	Energy + driving source
ICE	Gasoline / Diesel through combustion engine
HEV	Gasoline / Diesel through combustion engine / electric motor
PHEV	Gasoline / Diesel / Electricity through combustion engine / electric motor
BEV	Electricity through electric motor
FCEV[1]	Energy from hydrogen through electric motor
SEV[1]	Energy from solar power through electric motor

[1] Not considered in this thesis.

2.3 The various charging options

There are several different charging options. To provide a good understanding of the different options, they are explained in table 2.

Table 2 - Explanation of the various charging options (RVO, 2019)

Charging option	Explanation
Private	Private charging points are only available to the owner of the charging point and need to be purchased individually. They can only be located on own premises, like a driveway.
Public	Public charging points can be accessed by everyone. An EV user can ask permission from the municipality for the placement of a charging station. However, this charging station is not exclusive, but will be available to any EV user. Public charging points can be found in urban neighbourhoods, at car parks, near shops, and supermarkets. The public charging station needs to be accessible 24 hours a day to everyone.
Semi-public	Semi-public charging stations are available to everyone but may not be accessible 24 hours a day due to parking- or opening restrictions of the facilities at which they are located.
Work	Charging at the workplace is sometimes seen as private parking, since the charging station is only accessible for their own employees. However, the offered charging stations can also be public in which case every EV user may use them.

2.4 Regular vs. Fast charging

There are two main options to charge an EV: the ‘regular’ way and the ‘fast’ way. Most destination charging stations, which include charging stations at home, work, or public places, deliver regular charging or so-called Alternative Current (AC) charging (TU Delft, 2019). The electricity grid delivers AC, while all worldwide batteries, including the batteries in EVs, use Direct Current (DC). Therefore, the mechanics of an EV include an AC/DC converter. These 'regular' charging points deliver power of 3.7 – 11 kW, depending on whether the EV charges on a special 3-phase connection or not. The charging time for 'regular' charging varies significantly, depending on the size of the battery and whether a 3-phase connection is present. (TU Delft, 2019) To illustrate, a Tesla Model 2 Long Range has a battery capacity of 74 kWh. When charged with 3.7 kWh, it will take 20 hours before the car is fully charged. However, with 11 kWh, the charging time will be reduced to approximately 7 hours. (Elektrische Voertuigen Database, 2019) In addition, the charging rate heavily decreases after the EV is 80% charged to protect the battery's life (TU Delft, 2019). This makes the last 20%, until a full battery is achieved, take extra-long when charging with a regular charger.

Fast charging is readily available in the Netherlands and targets EV users who want to charge their EV in a short amount of time to cover longer distances. In 2019, 1,262 fast charging points were present, distributed over 339 fast charging locations (RVO, 2020). A fast charging station can deliver power of 50 kW, which provides an EV with an additional range of 100 km within just 24 min (TU Delft, 2019). However, fast charging requires a stronger AC/DC converter which adds weight to the vehicle and takes up more space; not the type of converter any EV manufacturer prefers in his EV. Therefore, fast charging utilizes an external AC/DC converter which is located inside the charging station. This way, the converter can be bigger, and the charging station can charge at greater power. (TU Delft, 2019) Fastned is the market leader of highway fast charging in the Netherlands. They employ over 200 stations at highway locations with the attempt to relief EV users from their range anxiety (TU Delft, 2019). Nowadays, Fastned has already charging stations in place that charge up to 175 kW (Fastned, 2020), providing an additional range of 100 km within just 7 minutes.

Chapter 3. Theoretical background

In this chapter, an overview of the current literature regarding EVs and their charging infrastructure will be provided. Even though the concept of EVs was only reintroduced in 1997 with the introduction of the Toyota Prius, the first EV was already produced in the 1800s (Energy.gov, 2014). Nowadays, EVs are becoming increasingly popular. Car manufacturers actively responded to this increase in demand but were also obligated by political institutions to develop more electric models. By 2020, 5% of their annual sales need to originate from selling EVs. This percentage needs to increase to 10% in 2021, or otherwise they will face fines (Transport & Environment, 2020). Consequently, this increase in sales drew attention from the academic world. In the last decade, a substantial amount of papers has been written on the topic of EVs. The most relevant papers related to the topic and research question will be discussed in this chapter.

3.1 EV adoption barriers

The adoption of EVs can be viewed as a chicken-and-egg problem. The development of an adequate charging infrastructure has relied on the number of EVs being purchased, and the other way around. Furthermore, the relative high price of EVs plays an important role in its uptake. The Council of the European Union explained the adoption problem as follows: "*In this vicious circle, refuelling stations are not being built because there are not enough vehicles. Vehicles are not sold at competitive prices because there is not enough demand. Consumers do not buy the vehicles because they are expensive, and the stations are not there."* (Council of the European Union, 2014, p. 3). In this light, Achtnicht, Bühler, & Hermeling (2012) assessed what effect fuel availability has on the uptake of alternative-fuel vehicles like the EV. On the one hand, their results indicated that advancement of the charging infrastructure has a greater impact on the adoption of EVs than on other types of vehicles. This suggests a barrier for the EV in becoming mainstream. On the other hand, Achtnicht et al. (2012) concluded that the marginal willingness to pay for an expansion of the fuel infrastructure decreases with its availability. Overall, their results imply that the presence of a basic charging infrastructure is highly valued, but an expansion of the network is irrelevant. Hence, the chicken-and-egg problem might not be the main barrier holding back the adoption of EVs.

This leaves the questions open of what hinders consumers from buying an EV. Egbue & Long (2012) examined this issue by asking 500 persons in a survey about their perceptions regarding EV attributes. Respondents perceived the decrease or elimination of fossil fuels as the most appealing factor, followed by a decline in maintenance costs. Comfort and the look of the EV, on the other hand, received the lowest rankings (Egbue & Long, 2012). Furthermore, the main concern of their respondents withholding them from purchasing an EV was the battery range and the initial purchase price. More than half of their respondents indicated one of them as their biggest concern (Egbue & Long, 2012). Admittedly, there is some controversy about the first comment, as a battery of 100 kWh already allows an EV to drive up to 500 km (TU Delft, 2019). A fair number of the new EV models are being equipped with a battery of this size. The limited range of EVs may currently be an obstacle in the adoption of EVs, but according to Hoekstra & Refa (2017) a range of 250-500 km would be sufficient for market diffusion in the future.

The aforementioned controversy around range anxiety lies in the fact that research has shown that EV users almost never drive more than the average battery capacity (Dong, Liu, & Lin, 2014; Franke & Krems, 2013). Dong et al. (2014) stated that in the U.S., where travel distances are often large, BEV users practically never drove more than the 80-120 miles (equal to 130-200 km) available range at that time. Correspondingly, Franke & Krems (2013) concluded that German EV users drove on average 37 km per day. Based on a field study of 6 months, analysing 79 EV users, they found that charging occurred approximately three times per week with a large battery surplus upon charging (Franke & Krems, 2013). Nowadays, BEVs have ranges exceeding up to 400 or 500 km. This increase in available range should let the anxiety of consumers disappear, and over time this is expected to happen.

Moreover, charger availability is not a barrier for the current group of EV users. Research has shown that most EV users have a definite preference for charging at home in the evening (Franke & Krems, 2013; Morrissey et al., 2016; Sun et al., 2015; Xu et al., 2017). As a result, the availability of a charger is no longer an issue. EV users with private charging stations are guaranteed a full battery in the morning upon recharge, reducing the problem of range anxiety. According to Hoekstra & Refa (2017), who researched the typical Dutch EV user based on a survey of 286 EV users with multiple years of EV experience, this makes sense. 63% of the EV users have their own private parking place and therefore the opportunity to install a private charging station (Hoekstra & Refa, 2017). Contrastingly, the national Dutch average is only 25%, indicating that 75% of the population does not have a private parking place (Hoekstra & Refa, 2017). Hence, the (prospective) urban EV user is presumed not to have the opportunity of private charging. This leaves him dependent on the public charging network. As a result, charging availability is expected to be an issue for the prospective urban EV user.

3.2 The current EV user

Before being able to research (prospective) urban EV users, it is important to understand the demographical and social characteristics of the current EV user. To illustrate, the typical Dutch EV user is well-educated and has a high income (Hoekstra & Refa, 2017). Likewise, Vassileva & Campillo (2017) described the same characteristics for EV users in Sweden and argued that the majority of EV users live outside the larger cities. Only 15 respondents out of a total of 247 EV owners stated to be living in an apartment (Vassileva & Campillo, 2017). This observation can be attributed to the lack of charging infrastructure in cities. Similarly, Hardman, Shiu, & Steinberger-Wilckens (2016) concluded the same findings for early EV adopters worldwide but added the existence of two different types: high-end and low-end early adopters; based on their type of EV. Using t-tests, their results showed that there is a significant difference between high- and low-end early adopters in terms of age, education, and income (Hardman et al., 2016). Additionally, Hardman et al. (2016) confirmed that low-end early adopters were less likely to purchase a BEV in the future than high-end early adopters. This unwillingness to repurchase an EV in the future, poses a challenge on the market diffusion of the BEV. To combat this, the construction of more charging stations can help in overcoming this reluctance.

Instead of analysing just two EV adopter groups, de Rubens (2019) created six consumer segments of both current and prospective EV users. His results put three consumer segments in the spotlight: Status Seekers, Blue-collar Moderates and Greens. Together they accounted for 68% of the sample and their groups could be targeted when attempting to move to a mainstream EV adoption (de Rubens, 2019). Like Hoekstra & Refa (2017), de Rubens (2019) concluded that nowadays Status Seekers have the highest EV adoption, accounting for 70% of the current EV users. Moreover, they displayed the previous described characteristics. Interestingly, the Greens reveal the highest EV interest but only 1% of them actually owns an EV putting this segment in second-least position regarding EV ownership (de Rubens, 2019). Consequently, the consumer segment with the highest environmental awareness is not able to purchase an EV due to the high purchase price. This signals the importance of government incentives until the point where the (battery) technology allows EVs to become less expensive.

3.3 The decision to charge

As aforementioned, if the EV were to become mainstream, a substantial percentage of the prospective EV users would live in a city, as generally high levels of urbanisation are expected (Ritchie & Roser, 2018). These prospective EV users will have to rely on the public charging infrastructure, due to their lack of a private parking place. Given the above, a developed public and semi-public charging infrastructure is required. An adequate charging infrastructure can accelerate and support the transition of electrification.

In order to construct a suitable public charging infrastructure, it is important to understand what drives consumer's charging decisions. Even though the general preference is targeted towards private charging due to availability and cost issues, this thesis focuses on the public charging infrastructure and the corresponding preferences of consumers. Studies like Yang, Yao, Yang, & Zhang (2016) investigated public charging behaviour using various route choice scenarios. In these scenarios, the state of charge (SOC) level, specifying the current battery level in percentages, was displayed at four different levels. These different SOCs were combined with three different routes including and excluding charging stations. Their results indicated that initial SOC at the origin was the most important factor for choosing a route with or without charging opportunity (Yang et al., 2016). When the users had selected a route with a charging station, they were inclined to charge as soon as possible (Yang et al., 2016). Moreover, Yang et al. (2016) concluded that the initial SOC values increase proportionally with an increase in travel distance, suggesting that BEV users have a certain base level of comfortable SOC.

In line with this, Sun et al. (2015) argued that SOC next to 'interval in days before the next travel day' and 'vehicle-kilometres to be travelled on the next travel day' are the key predictors in the general choice of charging. However not only the general choice of charging is important, but also the following selection of a specific charging station. Charging prices can range from 0.29 EUR to 0.69 EUR per kWh, as they are highly dependent on the charging speed. Nonetheless, the charging price also depends on the charge point operator (CPO) and mobility service provider (MSP) responsible for the charging service (E-flux, n.d.). According to Jabeen et al. (2013), factors like the cost of a charging session and its duration have a negative impact on the selection of a charging location. Pan, Yao, & MacKenzie (2019) similarly showed that next to SOC, other variables like charging price, parking price, and excess range were significant in the selection of a charging station. Relating this price-sensitivity to the conclusions from Egbue & Long (2012), it can be implied that EV users want to earn back their initial investment of the EV through lower (alternative) fuel costs. This leads to the first hypothesis:

(H1): Price of charging has a negative effect on the selection of a public charging station.

Another important variable is availability. This thesis focuses on the urban EV user and the public charging infrastructure in his own neighbourhood. As aforementioned, charger availability is not an issue for the current EV user, as most current EV users have private parking places (Hoekstra & Refa, 2017). However, this is not the case for (prospective) EV users living in urban areas. Hence, it can be implied that availability will affect the selection of a public charging station for this group of EV users. In addition, literature showed that SOC is a key predictor of the general choice of charging (Pan et al., 2019; Sun et al., 2015; Yang et al., 2016). Interesting for the urban charging case is to combine the SOC with the availability of a public charging station. It can be argued that availability of a public charging station is of higher importance when the SOC decreases. This way, the SOC would serve as a moderator in the association between availability and selection of a public charging station. To investigate this relationship, this thesis will cover the following additional hypotheses:

(H2): Charger availability has a positive effect on the selection of a public charging station.

(H3A): The SOC has a negative effect on the general choice of charging.

(H3B): The SOC negatively affects the association between charger availability and the selection of a public charging station.

3.4 Location of charging stations

Besides price and availability, a third important variable influencing the general choice of charging is location. The location of public charging stations should be convenient in order to stimulate their usage. However, parking space is already scarce in contemporary cities, and specially designated parking places for e.g. handicapped people or EVs have a lower utilization rate than regular parking places (TU Delft, 2019). Therefore, municipalities should carefully consider where to locate charging stations. A high level of heterogeneity is present for the circumstances in which the different types of public charging points are preferred (Morrissey et al., 2016). For example, car parks were the most popular charging location for regular charging according to Morrissey et al. (2016), compared to on-street parking, a petrol station, or a multi-modal mobility centre. The usage frequencies for car park locations were the highest, but with a maximum of two charging sessions per day (Morrissey et al., 2016) this is still far from a commercially viable solution (Madina et al., 2015).

Additional to the location of public charging stations, policies can help to increase the occupancy rate of these parking places (Wolbertus et al., 2018). In their research, Wolbertus et al. (2018) analysed the effect of three different types of policies on EV adoption. The policies included a daytime charging policy, a placement policy, and a parking fee policy. Especially, the placement policy of constructing a new public charging station per 1, 2 or 4 new EVs had the largest impact on EV purchase (Wolbertus et al., 2018). Parking fee and daytime charging policy were far less important for consumers, when considering the purchase of an EV. Hence, the placement policy had a definite positive effect on EV adoption, but the effect of the other policies was more doubtful. For instance, offering free parking for EVs at parking places with a charging station could have a positive effect on EV adoption. Nevertheless, EV users might be less inclined to move their car after full charge, causing inefficient use of charging stations. Ultimately, Wolbertus et al. (2018) showed that different policies can influence the occupancy rate of public charging places.

One specific concept of public charging which is becoming increasingly popular within the urban development sector is the so-called 'charging plaza' or 'laadplein' in Dutch. The charging plaza is a plaza with multiple charging stations for EVs where the charging stations have one mutual connection to the general electricity grid (NKL, 2019). Hence, a charging plaza is not a concentration of multiple charging stations where all stations have a separate connection. The charging stations must share the same connection to the energy grid. The development of these charging places is a highly debated topic for regional governments, since the utilization rate of these parking places is likely to be below average, causing an inefficient use of already scarce urban space. In addition, their financial business case is difficult to assess as comparable usage cases are scarce. To get an understanding of their advantage over regular charging stations, a business case was developed which can be read later in this thesis in chapter 7.

As aforementioned, usage cases from these charging plazas are very scarce and academic research specifically on their application is almost non-existent. One interesting paper was written by Frade et al. (2011), in which the neighbourhood Avenidas Novas in Lisbon, Portugal was analysed on potential public charging station locations. This neighbourhood is an interesting case, since it is located in central Lisbon and has residential housing as well as offices. Due to its urban nature, most buildings do not have private parking places and are dependent on on-street parking, parking lots, and parking garages. In order to differentiate between the demand of residential inhabitants and office employees, Frade et al. (2011) divided the overall demand into night-time demand accounting for residential demand, and daytime demand accounting for office demand. Even though the results are based on data from 2001 and their reliability in current times can therefore be questioned, the results do provide a first impression of the optimal charging infrastructure in an urban neighbourhood. According to Frade et al. (2011), the best scenario included 29 charging stations which gave access to 6.2 charging points per station. All dwellings were preferably within a 400-metres range of a charging station, and maximally within 600-metres walking distance (Frade et al., 2011).

For an urban EV user without private parking, a public charging plaza can be a substitute for private charging. However, their distance should not be too far from the EV user's home. Interesting is to see how important the walkable distance to a public charging station is for the selection of a charging station. To analyse this, the following hypothesis can be formulated:

(H4): Distance from home to a public charging station has a negative effect on the selection of a public charging station.

3.5 Role of risk in charging behaviour

Egbue & Long (2012) stated that range anxiety was a main barrier for the adoption of the EV and, even though gasoline cars need to be refuelled as well, electric cars are perceived to be riskier in this regard. However, the basic economic concept of risk aversity shows that people handle risk differently. In a research by Pan et al. (2019), risk was added as a latent variable which proved to be a determinant of EV users charging choices. Comparing two latent class logit models, Pan et al. (2019) concluded that EV users could be divided into two clusters. Both clusters displayed different focus points during the general choice of charging. The risk seeking cluster cared for the SOC, the charging price, and the parking price when deciding to charge (Pan et al., 2019). This cluster would make a trade-off between the available range to drive and the total price of charging at a specific charging station. Afterwards, a balanced decision would be made. On the contrary, the risk aversion cluster only focused on excess range (measured by subtracting the next trip in km from the SOC) in their general choice of charging (Pan et al., 2019). Their choices were led by range anxiety, with little attention for price or SOC.

For the reason that urban EV users have no private parking place, charging anxiety may play a greater role in their decision process than that of other EV users. Hypothesis 2 and 3 analyse the role of charger availability and SOC, on the selection of a public charging station for the full sample of (prospective) EV users. In addition, hypothesis 5 will analyse whether risk attitude influences these charging decisions. The sample of Pan et al. (2019) showed a high percentage of EV owners without private charging stations (61%). Together with the land scarcity in urban cities and the generally low occupation rate of public chargers, this shows an important opportunity for future research. For instance, the effect of risk aversion on charging decisions for urban EV users. Therefore, this study explores the following hypothesis:

(H5): Risk aversion has a positive effect on the general choice of charging.

3.6 Fast charging

In the final part of this literature review, fast charging will be discussed. Even though this thesis will not focus on fast charging, the views and perspectives on fast charging are important for the usage of the public charging infrastructure in a neighbourhood. When fast charging starts to become the 'normal' way of charging, the regular public charging infrastructure becomes obsolete. To understand these dynamics, a comprehensive theoretical background is provided. Furthermore, a basic knowledge of fast charging is needed to understand the decisions and assumptions made further on in this research.

In general, there are more regular chargers than fast chargers in the Netherlands. According to the 'Nationale Agenda Laadinfrastructuur', the Dutch government prognosed to have an 85%/15% division between regular and fast chargers, respectively. (Rijksoverheid, 2019). Most of the current fast chargers are located at highway gas stations, but they are not exploited by these gas stations. As a result, gas stations are now standing at a crossroad and need to decide which role they want to play in the charging industry. The EV sector has adopted three different scenarios (Berenschot, 2019). In the first scenario, fast charging is used solely for emergencies when the distance is longer than a full battery can provide. The second scenario implies that only EV users with a private parking facility charge at home, and all other EV users engage in fast charging at gas stations. This way, gas stations are transformed into 'energy stations'. The final scenario proposes a mixed view in which both home charging, charging plazas, and fast charging represent the full charging infrastructure (Berenschot, 2019). Besides the EV sector, the global academic world has also reflected on the concept of fast charging. Interestingly, the academic's views on the future of fast charging are quite contradicting. Hence, the different perspectives of various papers will be discussed.

Morrissey et al. (2016) analysed the usage of both regular chargers and fast chargers and found a significant difference between regular and fast chargers in terms of duration and consumed kWh per charging session. Their results implied that EV users charge longer at fast chargers located at car parks, but the total consumption of kWh is significantly higher at gas stations (Morrissey et al., 2016). Ultimately, they believe that fast charging stations will become commercially viable in the short to medium-term and they advocate the development of a large fast charging network (Morrissey et al., 2016).

While the study by Morrissey et al. (2016) collected data through data loggers at various charging stations, Xu et al. (2017) followed 500 private and commercial Japanese EV users for a period of 2 years analysing their charging choices. Japan is an interesting country regarding fast charging as it held the largest number of fast chargers worldwide in 2012 with 1400 points, and the government has planned on having 5000 fast chargers by 2020 (Xu et al., 2017). Hence, Japan can be seen as the most mature market in the world when it comes to fast charging. In their research, Xu et al. (2017) concluded that personal familiarity to fast charging is a key indicator for the usage of fast charging stations. In line with this, Sun et al. (2015) argued that the number of previous fast charging events had a negative effect on the given charging choices, which all included regular charging. This indicates that fast charging becomes the preferred option when an individual has had experience with it. The experienced speed and short duration of fast charging may persuade EV users to prefer fast charging over regular charging.

On the contrary, Hoekstra & Refa (2017) claim that fast charging may seem like the perfect solution, but it is not expected to fully replace destination charging. Motoaki & Shirk (2017) agree with them, and in their research, they highlight two important drawbacks of the current fast charging technology. First, the speed of charging is not only dependent on the charging rate of the charging station but also on the acceptance rate of the EV's battery (Motoaki & Shirk, 2017). For example, when the battery has an acceptance rate of 50 kWh, the charging station may have the ability to charge at 100 kWh but the EV will limit the charging rate to his personal maximum of 50 kWh. Therefore, the benefit of fast charging depends both on the charging technology and the battery innovation. Second, the charging rate of an EV is not constant over time (Motoaki & Shirk, 2017; TU Delft, 2019). According to Motoaki & Shirk (2017), the charging rate is 0.72 kWh per minute at a SOC of 30% and decreases to 0.16 kWh per minute at a SOC of 80%. The introductory EV course by TU Delft (2019) confirms this threshold of 80%. As a result, the duration of staying plugged in at a fast charging spot depends on the SOC at the start of charging (Motoaki & Shirk, 2017).

Together with the relatively high initial SOC levels found in the literature; Sun et al. (2015) recorded an average SOC of 63.2% for private vehicles and 69.3% for commercial vehicles, and Xu et al. (2017) documented respectively 52.1% and 67.4%, a misalignment is formed between the potential power of fast charging and the charging behaviour of EV users. More research towards the dynamics of fast charging is needed to create sound policies for the future public charging infrastructure. Therefore, besides regular charging preferences, this thesis will also exploratory investigate the perspectives of the industry on fast charging through the following hypothesis.

> **(H6):** Fast charging will not be the preferred charging option for the daily commute of urban EV users.

3.7 Summary

To summarize this literature review, it seems that the current EV user has a high income and education level, and has the preference to charge at home with the decision to charge mainly depending on the SOC. Some individuals that are risk-seeking will try to make a balanced decision between the SOC, and the speed and price of charging. Nevertheless, for (potential) EV users without private parking, other variables will be of importance. For them, the public charging infrastructure will play an important role. Therefore, availability of a charging station, and its distance from home are expected to be important choice characteristics. The possibilities for exploiting public charging stations are great. Charging stations can be located on the street, at parking places, at gas stations, or even sometimes at the workplace. Especially combining multiple charging stations on one grid connection, more regularly known as a charging plaza, seems interesting. As a final component, the contrasting academic views on fast charging were explored. On the one hand, fast charging is expected to fully replace destination charging and become the new 'normal' way of charging. On the other hand, fast charging is expected to be solely used for emergencies when the entire trip cannot be completed with a full battery.

This literature review has led to the development of six hypotheses. Figure 3 shows the various hypotheses in one conceptual framework except for hypothesis 6. Hypotheses 1 till 5 will be answered using the data from the discrete choice experiment (DCE). Hypothesis 6 will be answered through interviews with stakeholders.

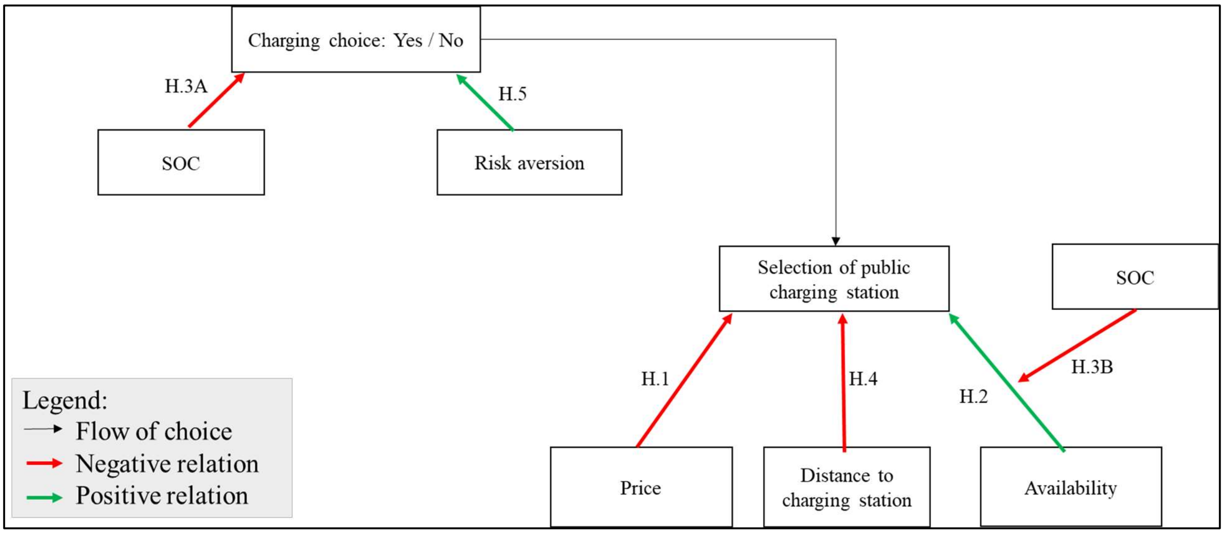

Figure 3: Conceptual framework of hypotheses answered through the DCE.

Through the wide scope of this literature review a good knowledge base was achieved to correctly analyse the research question. The following section will discuss the methods of this thesis to gain an impression of the future public charging infrastructure in urban cities.

Chapter 4. Methods

This research examines the reasons behind the public charging preferences of an urban citizen that is driving or will drive an EV in the future. Including both prospective EV users, and current EV users who own a private charging station enlarges the sample size and gives the research a futuristic orientation. Both groups are familiar with the topic of EV charging, and therefore are well able to define their preferences. Individuals with no affinity towards electric driving were excluded from this research, as data could become invalid. Overall, the research topic will be analysed both from the consumer's perspective and the industry's perspective. In the first part, the consumer's perspective will be measured through a survey. In the second part, the industry's perspective will be analysed through interviews with stakeholders. Afterwards, policy recommendations will be provided on the future urban charging infrastructure.

4.1 Consumer perspective

In the first part, the consumer's preferences for charging at public charging stations in an urban neighbourhood are investigated. Since the necessary future investments in the charging infrastructure and the energy grid are substantially large, it is crucial to know the preferences of EV users regarding the attributes characterizing a public charging station in an urban neighbourhood. In general, discrete choice experiments (DCE) are used to analyse these preferences. Differences in behaviour can be explained by either revealed preference or stated preference (Louviere, Hensher, & Swait, 2000). For this thesis, stated preference will be used to explain individual differences due to the future focus. A revealed preference experiment would be difficult to achieve, as most current EV users have the opportunity of private charging (Hoekstra & Refa, 2017). With stated preference, (prospective) EV users are requested to answer as if they did not have a private charging station.

According to Ben-Akiva & Bierlaire (1999), travel behaviour is a great example of a research subject to analyse with a DCE. Travel behaviour is a demand driven activity in which the sum of individual choices leads to the aggregate demand. The same holds for charging. The general choice of charging can be seen as a demand driven activity, since the sum of all individual charging sessions makes the aggregate demand of charging. The DCE designed for this thesis was constructed following the general DCE modelling principles of Ben-Akiva & Bierlaire (1999). In total, there are four general modelling assumptions: decision maker, alternatives, attributes, decision rule (Ben-Akiva & Bierlaire, 1999). In addition to these assumptions, the design of the various choice sets is explained.

4.1.1 Decision maker

As mentioned in the previous paragraph, the model is defined as a disaggregate model in which every individual taking part in the experiment is seen as the decision maker (Ben-Akiva & Bierlaire, 1999). In this choice experiment, the decision maker, being the (prospective) EV user, is an individual who only represents him or herself. As known from daily life, people have various preferences. However, this heterogeneity will not influence the model when it can be explained by other factors than the attributes measured in the choice experiment. Examples of these factors are socio-economic variables like education, age, gender, and income (Ben-Akiva & Bierlaire, 1999). These factors are measured through asking demographical questions in the survey (see appendix A.1).

In addition to these standard socio-economic variables, other factors specifically interesting for EV users are included in the first part of the survey (see appendix A.1). For instance, choice preferences may differ for either current EV users or prospective EV users. Further, a difference in preferences can be expected between full electric vehicle users (e.g. BEV) or partial electric vehicles users (e.g. PHEV, HEV). For example, an attitudinal difference could be expected regarding price of charging. The battery capacity of a BEV is much larger than of a PHEV, signalling a greater perceived importance for the first group. Another difference is expected between business EV users who have a company leased EV, and individual EV users who own a private EV. All these individual differences are considered in the first part of the survey. This way, a good overview of the type of respondents can be formed.

4.1.2 Alternatives

The second modelling assumption entails the alternatives which define the options available to the decision maker (Ben-Akiva & Bierlaire, 1999). The set of alternatives presented to an individual in a choice experiment is called the choice set. Within transport related research, this choice set is often composed of various travel mode options like walking, biking, public transport, or the car. The same can be applied to charging options. In general, there are private, public, and semi-public charging stations. However, categories have again their own sub-categories. For example, the public charging infrastructure includes both public charging stations with multiple charging points (e.g. charging plazas), and fast charging stations often located next to highways. Important is to select the various alternatives based on their availability and their awareness to the decision maker (Ben-Akiva & Bierlaire, 1999).

With regard to availability, the topic of this thesis focuses on the charging infrastructure in an urban neighbourhood where an EV user is not expected to have a private parking spot. For this reason, the alternative of a private charging station is withdrawn from the survey. In addition, fast charging is at this moment generally not available in urban neighbourhoods. In the future, there might be fast charging stations available for visitors, but for now they are excluded from the survey.

Concerning awareness, it is rather difficult to predict every individual's knowledge regarding the precise location of charging stations. Nonetheless, the location of most charging stations can be easily found online or in special apps. Therefore, awareness does not seem to be a key issue for the specification of alternatives. For availability, on the other hand, this is not the case. EV users may have access to different charging alternatives. Some EV users may have the ability to charge at work, while others might not have this opportunity. This will influence their choice behaviour regarding the alternatives. By asking at the start of the survey for the availability of charging facilities at work, this issue is solved. Furthermore, EV users always have the choice not to charge at a charging station. To account for this and to keep the survey as practical as possible, an opt-out option was created. In the survey, the opt-out option was displayed as: 'I do not want to charge'. The use of opt-out option is a discussion point when creating a DCE, since the decision to choose opt-out gives no further information about the analysed attributes for this specific decision maker. Nevertheless, in this survey it was included to maintain the real-life experience.

Finally, the last option of a charging plaza does not differ in terms of charging experience from a regular public charging point. Therefore, no differentiation was made in the survey whether the charging station was part of a regular charging point or a charging plaza. The choice for either option is more a discussion of available space and financial benefit. These considerations are discussed in chapter 7 of this thesis.

In conclusion, the alternatives in this survey displayed regular public charging facilities in an urban neighbourhood. They were not labelled, as this was not necessary, and were named: charging station A / B / C. Additionally, an opt-out option was created to present real-life choice sets.

4.1.3 Attributes

The attributes in a DCM reflect the characteristics defining the various alternatives from which the decision maker can choose in each choice set (Ben-Akiva & Bierlaire, 1999). These characteristics can be general, applying to all alternatives, or alternative-specific. In this survey, the generic attributes are price, distance from home to a public charging station, and availability. First, these generic attributes will be discussed.

From the previous literature review, it was concluded that price, distance, and availability display best the various characteristics of a public charging station. Speed or duration of charging was also often mentioned in the literature as a significant variable (Jabeen et al., 2013). However, to limit the number of attributes, only regular charging stations of 11kWh were applied in this choice experiment. This type of charging station is most common in an urban neighbourhood.

Regarding price, fast charging is on average more expensive per kWh than regular charging, but for this research only regular charging will be applied. E-flux, a business specialised in charge cards and charging software, publishes all the different charging tariffs of the various charge point operators and mobility service providers (E-Flux, n.d.). All these parties charge slightly different rates and the lack of transparency regarding these prices has been perceived as a drawback within the EV industry. To set a representative range of prices for the different choice sets, data were taken from the overview of E-flux, and an average price for regular charging was calculated. The average price for regular charging at a public charging station is 0.34 EUR, rounded to 0.35 EUR. Charging at a private charging station at home is generally cheaper, at 0.25 EUR. This resembles the average electricity price. The three price levels in the choice sets are based on these prices. The lowest level resembles the average electricity price of 0.25 EUR. The highest level is composed of the price difference between level 1 and 2 serving as a mark-up on the average price (see table 3).

Next, the levels of distance and availability were determined, based on the previous literature and the results from the stakeholder's interviews. Frade et al. (2011) researched the preferred public charging infrastructure in urban Lisbon and set the preferred distance at 400 metres. Moreover, according to one interviewee, the Dutch public service maintains a maximum distance of 350 metres. Consequently, the maximum distance was set at 400 metres and the other levels were based on this maximum with the lowest level set at 100 metres (see table 3). For availability, levels were based on the chance that a charging station was available expressed in percentages. Since none of the alternatives includes a private charging station, 100% availability cannot be guaranteed. Therefore, availability levels were set at 30% for the lowest level, and 90% for the highest level.

Besides these generic characteristics, other scenario-specific characteristics are considered. As aforementioned in the literature review, the SOC plays an important role in the charging behaviour of individuals (Sun et al., 2015; Yang et al., 2016). Yang et al. (2016) found an average SOC of 52.1% for private EV users and Sun et al. (2015) found for the same group an average SOC of 63.2%. Taking these averages into account, the SOC in the choice sets was determined to be 20% or 40%. Both percentages reflect a battery which is lower than the average battery level observed in literature. Hence, charging is expected to be the preferred option instead of choosing the opt-out option. Preferably, decision makers receive scenarios with both SOC levels. However, this would have resulted in too many scenarios per decision maker. As a solution, half of the decision makers were shown a SOC of 40% and the other half a SOC of 20%. This way, the influence of the SOC could still be determined.

Table 3 - Generic attributes with corresponding levels

Attribute	Levels		
Price	0.25 EUR	0.35 EUR	0.45 EUR
Distance home ↔ public charging station	100 m	250 m	400 m
Availability	30%	60%	90%

Table 4 - Respondent specific attribute with corresponding levels

Attribute	Levels	
SOC	20%	40%

SOC = state of charge.

4.1.4 Choice set design

After defining the attributes, the various choice sets are generated. These choice sets together form the experimental design. Choice experiments have been used extensively in disciplines like engineering or physical and biological sciences (Louviere et al., 2000). In the earlier stages of experimental design, the experiment was created using a factorial design. In factorial design, each level of each attribute is combined with every other level of all other attributes (Louviere et al., 2000). This is possible when for instance only 2 attributes with each 2 levels are included, giving 2 x 2 possible combinations of a choice set. However, experimental designs became more complex making this method rather impracticable. As a result, a solution was created in the form of fractional factorial designs. Within fractional factorial design, only a part of the full factorial design is presented towards a respondent. Nonetheless, this comes at a price. The practicality of it causes an inevitable loss of statistical information, resulting in a trade-off (Louviere et al., 2000).

Due to the complexity of this survey, the fractional factorial design was used. With the use of Stata, a balanced decision was made about the number of scenario's while keeping the D-efficiency high (D-efficiency = 1.221). This resulted in nine different choice sets with each four alternatives of which one alternative represented an opt-out option[2]. The opt-out option could be chosen when an individual did not want to charge given the circumstances.

4.1.5 Decision rule

The final assumption concerns the decision rule. The decision rule is explained by the process a decision maker undergoes when choosing one of the alternatives within a choice set (Ben-Akiva & Bierlaire, 1999). Often this process consists of two steps. In the first step, the decision maker values each alternative, and in the second step the decision maker chooses one alternative based on the perceived value. Within transport research, it is very common to view this perceived value as utility (Ben-Akiva & Bierlaire, 1999). The model assumes that an individual will try to maximize his utility when considering the different options with various observed (and unobserved) attributes. In general, there are two different views on individual choice theory: the deterministic choice perspective and the probabilistic choice perspective (Ben-Akiva & Bierlaire, 1999). The first one assumes that a decision maker will always choose the same alternative when being in an identical situation. The second perspective argues that a decision maker does not always choose the same alternative in identical situations. Within the probabilistic choice perspective, a degree of probability is always present. The probability can lay in either one of the two aforementioned steps of a decision process. Luce & Suppes (1965) classified this as, respectively, constant utility and random utility. Constant utility assumes that the probability lies in the second step of the decision process. A decision maker is expected to assign similar values to an alternative under identical circumstances, but his definite choice will vary (Tversky, 1972). Random utility, on the other hand, assumes that the valuation of each alternative can fluctuate, but that the alternative with the highest utility is always selected (Tversky, 1972). This way, the probability lies in the first step of the decision process.

For this model, the random utility theory will be used to explain individual's choices. It is expected that in the process of this survey, a decision maker will not have complete information. Hence, a degree of uncertainty needs to be considered (Ben-Akiva & Bierlaire, 1999). This uncertainty can originate from unobserved alternative attributes, unobserved individual

[2] Appendix A, section A.1 displays the entire survey with the nine choice sets.

characteristics, measurement errors or instrumental variables (Manski, 1977). The random utility model can be specified as

[Eq.1] $$U_{nj} = V_{nj} + \varepsilon_{nj}$$

where utility U_{nj} is estimated using the deterministic part V_{nj} plus a degree of uncertainty captured by ε_{nj}. The deterministic part V_{nj} is composed of the attributes of alternative j. Any alternative can be chosen by decision maker *n*. Alternative *i* will be chosen by decision maker *n* only when the utility U_{ni} is greater than the utility U_{nj} of alternative j. However, the researcher does not know ε_{ni}. As a result, an alternative with a higher deterministic part V_{ni} may not have the highest U_{ni} and therefore not be the preferred option. This is reflected as

[Eq.2] $$P_{ni} = Prob(U_{ni} > U_{nj} \,\forall\, j \neq i)$$

$$P_{ni} = Prob(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj} \,\forall\, j \neq i)$$

$$P_{ni} = Prob(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj} \,\forall\, j \neq i)$$

However, the distribution of ε_{nj} remains undetermined. The different assumptions regarding this unobserved part define the various choice models as explained by Train (2009). These models and their fit for this choice experiment will be explained in the next section.

4.1.6 Data analysis

When judging the random utility model of Equation 1, it seems to be a normal linear probability model. However, the dependent variable of utility or choice is neither multinomial, ordinal nor countable. The value characterizing this choice is binary. A binary dependent variable is an example of a limited dependent variable (LDV) (Wooldridge, 2013). When looking at the various alternatives, their possible values are limited as an individual either chooses an option or not. Hence, their only possible values are zero or one.

According to Wooldridge (2013) there are two major drawbacks of limited probability models (LPM). First, the predicated probabilities are unbounded, meaning they can be less than zero or greater than one (Wooldridge, 2013). This does not support the statement that the possible values of LDVs can only be zero or one. Secondly, the model assumes that probabilities are linearly related to the explanatory variable for all levels (Wooldridge, 2013). To illustrate it for this specific choice experiment, a level reduction in charging price would increase the probability of selecting a public charging station linearly. However, it would be expected that the effect of an initial price drop is greater than additional price drops, demonstrating the law of diminishing marginal utility. These two arguments are the main disadvantages of LDVs, but another violation can be concluded from the binary nature of the LDV. The LPM violates the fifth Gauss-Markov assumption of homoscedasticity. (Wooldridge, 2013) For the reason that the dependent variable has to be a binary response of either zero or one, the probability of 'success' is equal to the mean. Nevertheless, the variance is dependent on the mean. Thus, the variance is dependent on the underlying probability of 'success'. Since the probability depends on the independent variables within the model, the variance of the error term can never be a constant. This serves as an indication of heteroskedasticity.

This issue of heteroskedasticity can be easily solved by a link function which is bounded between zero and one (Wang, 2019). There are two popular link function, the logit and the probit model. For simplicity reasons, the logit model will be applied in this thesis. The deterministic part of the utility model is explained by the attributes of alternative j faced by decision maker *n* and some characteristics of the decision maker (Train, 2009). This can be written as

[Eq.3] $$V_{nj} = x_{nj} s_n$$

A further specification of the alternatives can be made with p for price of alternative j, *d* for distance of alternative *j* and v for availability of alternative *j*. This results in

[Eq.4] $$x_{nj} = p_{nj} + d_{nj} + v_{nj}$$

which leads to the final basic utility function of

[Eq.5] $$U_{nj} = (p_{nj} + d_{nj} + v_{nj}) s_n + \varepsilon_{nj}$$

After specifying the appropriate utility function, the aforementioned link function of the logit model can be implemented. One starting point of basic-utility theory is the irrelevance of the scale of utility (Train, 2009). As explained before, an alternative is preferred over another alternative when the difference in uncertainty is smaller than the difference in the deterministic part of utility. Therefore, scale does not matter, and the deterministic part of the utility function can be divided by the standard deviation of σ. This leads to

[Eq.6] $$U_{nj} = V_{nj}/\sigma + \varepsilon_{nj}$$

which can be rewritten to

[Eq.7] $$U_{nj} = x_{nj}(\frac{\beta^*}{\sigma}) + \varepsilon_{nj}$$

At last, with equation 7 the link function can be implemented. Equation 8 shows the implemented link function with $\beta = \beta^*/\sigma$, and displays the aggregated probability that alternative *i* is chosen from choice set C_k. This is the conditional logit function in a scaled form, which is most often found in statistical textbooks.

[Eq.8] $$P_{ni} = \frac{\exp(\beta' x_{ni})}{\sum_j exp(\beta' x_{nj})}$$

As previously discussed, the discrete choice model measures utility. To maximize this utility, a logit model is required. In equation 8, the pure conditional logit model (CLM) is displayed. This logit model assumes that the unobserved term ε_{nj} is independent and identically distributed (Train, 2009). Consequently, Train (2009) explains that the unobserved factors are not correlated over the various alternatives and the logit displays only observable taste variation. Random taste variation, which cannot be explained by the deterministic part of the equation is not accounted for.

Another implication of the CLM, due to its mathematical specification, is the Independence of Irrelevant Alternatives (IIA). This restriction implies that a change in any characteristic of one specific alternative has the same impact on the probabilities of all other alternatives. (Greene, 2009)

For example, when the price of a specific car like a Tesla increases, the probability of individuals buying this car decreases. However, the IIA principle implies that all alternatives are independent. As a result, the loss of market share created with this price increase is equally distributed over all other car brands in the choice set. Meaning that a car manufacturer like BMW would earn the same extra market share as a brand like Opel. Clearly, there are some car brands that are more identical to a Tesla like other luxury car brands as BMW or Porsche. Hence, it would be expected that these brands earn a higher market share increase from this rise in Tesla prices, than a lower-segment brand as Opel. This implies that the alternatives are dependent on each other.

In this experiment, this restriction may be less problematic as the alternatives are unlabelled and all alternatives illustrate public charging stations. Nevertheless, the IIA principle is an important drawback of the conditional logit model and therefore should be analysed. Other more advanced models allow for both unobserved taste variations and for the dependence between alternatives (Train, 2009).

4.1.7 Mixed logit

One of the more advanced logit models is the mixed logit model (MLM). The MLM can be applied to any random utility model (McFadden & Train, 2000). It assumes that some taste variation per decision maker is present in the choice of alternatives which is represented by β_n. This can be illustrated in the CLM as

[Eq.9] $$P_{ni}(\beta_n) = \frac{\exp(V_{ni}(\beta_n))}{\sum_j exp(V_{nj}(\beta_n))}$$

However, this β_n is not known by the researcher (Train, 2009). Had the β_n been known to the researcher, the β_n could have been filled out and the basic logit function of equation 6 would have appeared. Nonetheless, this is not the case and $P_{ni}(\beta_n)$ needs to be observed over all possible values of β_n (Train, 2009), which leads to

[Eq.10] $$P_{ni} = \int \frac{\exp(\beta' x_{ni})}{\sum_j exp(\beta' x_{nj})} f(\beta)\, d\beta$$

which shows the mixed logit probability with the assumption that utility is linear in β (Train, 2009).

The MLM assumes that the probability of choosing alternative i is a weighted average of the general logit formula, but analysed at different values of β (Train, 2009). Hence, it assumes that the personal tastes of decision makers differ, and therefore their choice may differ. When no taste variation is present and all taste variation can be related to observable variables, it will transform back into a simple logit function (Train, 2009). This makes the MLM appropriate for all choice analyses (McFaddden & Train, 2000).

Moreover, the specification of the MLM allows for the violation of the IIA principle. Train (2009) explains that when taking the ratio of two mixed logit probabilities, for example P_{ni}/P_{nj}, the formula depends not only on these two alternatives but on all other alternatives as well. The denominators of the logit function do not cancel out in the division, since they are inside the integral (Train, 2009). In a CLM, the denominators do cancel out and the IIA principle holds.

In conclusion, the MLM is appropriate for all choice analyses (Train, 2009). It is especially interesting in this thesis to witness the differences between the MLM and the basic logit model, as the unlabelled alternatives make the chance on violation of IIA less obvious. To analyse this, the MLM will be used as an extension for the CLM.

4.1.8 Endogeneity

Even though statistics can explain a large degree of variation in a relationship, endogeneity remains an issue in almost all cases. Especially in the research topic of electric driving, which is a relative new topic, the problem of endogeneity remains fairly undiscussed. In general, endogeneity appears when an explanatory variable is correlated with the error term. Several common sources of endogeneity are reverse causality, omitted variable bias and measurement error. Since endogeneity in the EV research paradigm has not been discussed extensively, drawing strong conclusions is difficult but still some inferences can be made.

From the literature review, it was concluded that the choice of when to charge and where to charge is dependent on many factors. In fact, it is dependent on too many factors to consider in a DCE. A decision maker can only take in a considerable amount of information. Therefore, it can be interfered that endogeneity in the form of omitted variable bias is expected to be present in the model.

Moreover, a degree of measurement error is difficult to fully exclude when working with surveys. Measurement errors can occur in the design of the survey with regard to the measurement of variables, but also on the side of the respondent when filling out the survey. In this survey, the target group consists of both EV users and prospective EV users. Hence the response of the prospective EV users can be biased as they have not got the real experience of driving and charging an EV in daily life. Still, the benefit of having more respondents outweighs this problem. In addition, the survey is designed to analyse stated preferences rather than revealed preferences. Again, an inconsistency can be found between the actual behaviour and the stated behaviour. Due to the objective of the thesis, a stated choice model was preferred.

4.2 Industry perspective

In the second part of the research design, the industry's perspective is analysed by conducting interviews with industry stakeholders. One characteristic of the EV industry is its great landscape of different actors. When constructing a new charging station, a long list of actors appears, including the local government, the national government, the energy operator, the charging point operator and the mobility service provider. This list can be elaborated with car manufacturers, knowledge platforms and consulting agencies. Within the various interviews, the central question revolved around what the future charging infrastructure would look like and which types of charging stations would take the upper hand[3]. The goal of conducting the interviews was to receive input for the survey design and to have the ability to put the results into perspective. In the results section, a summary will be provided of the interviews[4].

[3] Appendix A.2 provides an overview of the different interview questions.
[4] Appendix A.3 provides a short summary of each interview.

Chapter 5. Data

The data was collected anonymously through a web-based questionnaire with the use of Qualtrics. The survey was distributed through various channels. In order to reach the target group of EV users, the Dutch Association of Electric Vehicle Users (VER) was contacted for support with the distribution of the survey. With their assistance, the survey was distributed on social media in various EV user groups. In addition, the survey was distributed within Rebel Netherlands and Belgium and sent to all interviewees with the request of further distribution within their own organizations.

After ten days of response collection, a total of 224 individuals filled in the survey completely. Of these 224 respondents, 8 individuals were not interested in buying an EV in the future. For them, the survey stopped after the question regarding future EV ownership. Furthermore, 6 respondents were in the possession of a HEV which does not allow for charging at a charging station. Hence, they were removed from the sample. Finally, 4 respondents who stated they were interested in driving an EV in the future, were especially interested in buying a HEV. These respondents were removed from the sample for the same reason previously stated. In the end, 206 usable responses were collected. The rest of this chapter is devoted to describing the data and characteristics of the respondents. In the first paragraph, the general characteristics of the sample will be described. In the second paragraph, the focus will be on analysing the level of risk aversion of the respondents.

5.1 Sample characteristics

In total, 206 usable responses were collected. Within this sample, 66.67% of the respondents owned an EV. This high stake of EV users was extremely beneficial for the validity of the researched scenario's in the latter part of the survey. Their experience with the activity of charging makes the data collected in the DCE part of the survey more trustworthy, when drawing conclusions from it. Regarding general characteristics, males were overly represented in the current EV user group; 86.96% of the current EV users was male. In the prospective EV user group, the gender ratio was exactly 50/50. The average EV user was 41-50 years old with a WO or HBO education, and an above average income. This is in line with the typical EV user described in the literature (Hoekstra & Refa, 2017; Vassileva & Campillo, 2017). For the prospective EV user group, younger individuals of 18-30 years old were strongly represented with 52.94%. This can be explained by the effect of convenience sampling when distributing the survey across personal contacts.

Regarding type of EV ownership, 94.20% of the current EV users owned a BEV, contrasted to only 4.35% that owned a PHEV. This high percentage of BEV owners is striking, since range anxiety is perceived to be a large adoption problem from literature. Often PHEVs are seen as a logical EV alternative for persons with range anxiety. Nonetheless, almost 70% of the prospective EV users also displayed the preference for a BEV. Interesting was to see that almost half of the current EV users did not own a private charging station. This characteristic is striking, as literature showed that most EV users have a private charging station on own premises (Hoekstra & Refa, 2017; Wolbertus et al., 2018). However, with regard to the research question of this thesis, this is beneficial. This thesis investigates the preferred public charging infrastructure of an EV user with no opportunity of private charging. Consequently, many of the respondents were able to imagine these circumstances, as they experience the dependency on the public charging infrastructure in their daily life. On average, the respondents were willing to walk a maximum of 360 metres from their home to a charging station. This is in line with the maximum preferred distance found in literature from Frade et al. (2011) of 400 metres.

In accordance with the unavailability of private charging infrastructure, it was noticed that most respondents lived around the larger cities of Amsterdam, Rotterdam, and Utrecht. An overview of the living location of the respondents based on postcode can be found in figure 4. In addition, 70.29% of the respondents who owned an EV were able to charge at work. This implies that there is an active demand for charging infrastructure at work. In conclusion, the sample is judged to be adequate for analysis.

Figure 4: Overview of respondent's living location, based on postcode

A summary of all the general characteristics of the sample can be found on the next page in the various tables.

Table 5 - General characteristics of the sample

	Freq.	% in Total
Gender		
Current		
Female	18	13.04
Male	120	86.96
Total	138	100.00
Future		
Female	34	50.00
Male	34	50.00
Total	68	100.00
Age		
Current		
18-30	11	7.97
31-40	29	21.01
41-50	50	36.23
51-60	38	27.54
61-70	9	6.52
71-80	1	0.72
>80	0	0
Total	138	100.00
Future		
18-30	36	52.94
31-40	7	10.29
41-50	12	17.65
51-60	10	14.71
61-70	3	4.41
71-80	0	0.00
>80	0	0.00
Total	68	100.00
Education		
Current		
WO	44	31.88
HBO	65	47.10
MBO	21	15.22
Other	8	5.80
Total	138	100.00
Future		
WO	48	70.59
HBO	13	19.12
MBO	3	4.41
Other	4	5.88
Total	68	100.00
Salary		
Current		
Above average	103	74.64
Average	19	13.77
Below average	2	1.45
I prefer not to say	14	10.14
Total	138	100.00
Future		
Above average	31	45.59
Average	13	19.12
Below average	22	32.35
I prefer not to say	2	2.94
Total	68	49.28

Table 6 - EV ownership

	Freq.	% in Total
Yes	138	66.67
No	68	32.85
Total	206	100.00

Table 7 - Type of EV in possession or desired

	Freq.	% of Total
Current		
BEV	130	94.20
PHEV	6	4.35
Other	2	1.45
Total	138	100.00
Future		
BEV	47	69.12
PHEV	11	16.18
I do not know	10	14.71
Total	68	100.00

Table 8 - Possession of private charging station

	Freq.	% in Total
Current		
Yes	75	54.35
No	63	45.65
Total	138	100.00

Table 9 - Possession of charging station at work

	Freq.	% in Total
Current		
Yes	97	70.29
No	41	29.71
Total	138	100.00

Table 10 - Construction used to drive an EV

	Freq.	% in Total
Current		
Business lease - employee	57	41.30
Business lease - ZZP/DGA	15	10.87
Business purchase - employee	7	5.07
Business purchase - ZZP/DGA	23	16.67
Private lease	9	6.52
Private purchase	27	19.57
Total	138	100.00

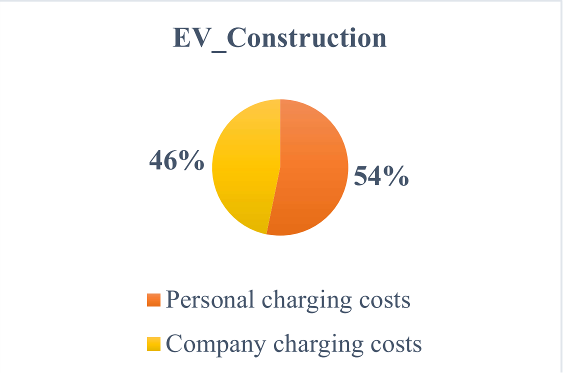

Figure 5: Construction used to drive an EV indicating whether charging costs are paid by the respondent him/herself, or the company

5.2 Risk aversion

In the survey, several questions were asked to judge the risk aversion of respondents (see table 11). The respondents were requested to judge a lottery situation in which they needed to choose one out of two options. Either they had a 100% chance to win an amount of money (option 1), or they had 50% chance to receive a higher amount of money (option 2). This way, the risk aversion of the respondents was measured. In addition to this analysis, it was researched whether the risk aversion differed across the sample. From previous literature, it was concluded that EV users make different types of trade-offs when charging, caused by different levels of risk aversion.

In lottery 1, the respondent had either 100% chance on winning 100 EUR or 50% chance on winning 250 EUR. Analysing the answers of the respondents based on gender, it was observed that females were more inclined to choose the certainty of option 1 than males. Males were quite indifferent between option 1 or option 2 in lottery 1 as can be seen from figure 6. The results were different for lottery 2. In lottery 2, both females and males chose the less risky option 1. All in all, respondents were more risk averse, as option 1 was the most chosen option in both lotteries.

Table 11 - Risk aversion questions displayed in the survey

1.	Imagine you are playing in a lottery. Which option would you prefer?	Option 1: 100% change to win 100 EUR Option 2: 50% change to win 250 EUR
2.	Imagine you are playing in a lottery. Which option would you prefer?	Option 1: 100% change to win 175 EUR Option 2: 50% change to win 300 EUR
3.	Imagine you are leaving with your (future) EV for your daily trip. What is your minimal preferred battery level?	Answer in %

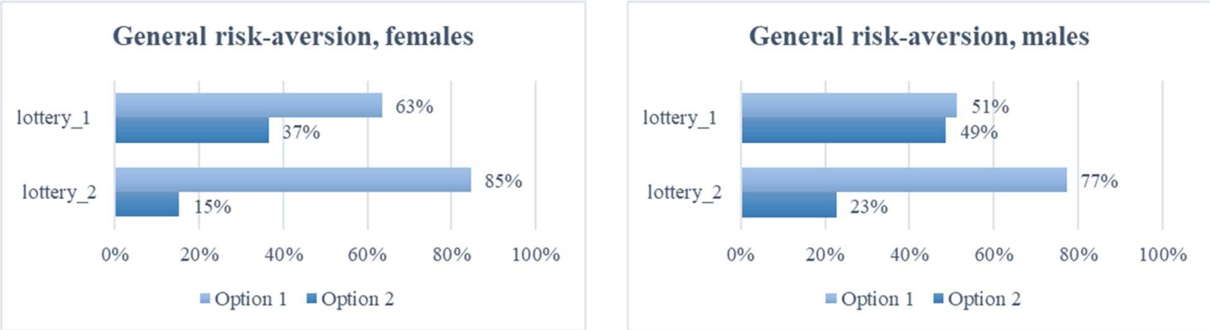

Figure 6: Results from the lottery questions, based on gender

Another interesting question in the survey analysed the minimal preferred SOC before someone's daily trip to either work, studies, etc. Based on previous literature, it was expected that this minimal SOC would be higher for prospective EV users than for current EV users, as prospective EV users might be more influenced by range anxiety. The opposite was through. The average SOC from the sample for current EV users was 61.20%, while the average SOC for prospective EV users was 57.96%. Hence, current EV users had a slightly higher minimal SOC. Nonetheless, the difference is only 3.24%, which is quite small. Both SOC levels are similar to SOC levels found in the literature of 63.2% (Sun et al., 2015) and 52.1% (Xu et al., 2017) for private vehicles. When distributing the SOC across gender, age, and education the observed differences were relatively small. Only for education, individuals with a university degree had a lower minimal SOC of 55.72% than individuals with a vocational education who showed a minimal SOC of 69.13%. Moreover, for age, some outliers were present in the data which caused the average SOC to be a bit misaligned over age groups. Appendix B.1 displays more detailed information regarding the various distributions.

Chapter 6. Results

In this chapter, charging behaviour is analysed using the previously explained models from the methods chapter. The results from these models will be used to answer the hypotheses of this thesis, and the final research question.

6.1 Results from data analysis

The data were analysed using the conditional logit model with the statistical software program Stata. Before the data could be analysed, the dataset had to be reshaped from a wide to a long distribution. This is required for performing logit analyses. In appendix B.2, the tabulation output of the data is shown. From this, it was concluded that the data were balanced with all four alternatives being present in each choice set. An important aspect of the survey was the displayed SOC. The SOC shown per respondent was randomized. Unfortunately, since not all respondents finished the full survey, the SOC was not evenly distributed across the respondents in the final dataset. 46.1% of the respondents received a SOC of 40% and 53.9% of the respondents received a SOC of 20%. Nevertheless, the effect of the SOC could still be interpreted in the following analyses.

6.1.1 Conditional logit model

With the introduction of version 16 of Stata, analysing choice models became incredibly simpler. In this Stata version, data could be specified to be coded choice data with the use of the cmset command. This means each case has a specific case id and a specific set of alternatives. Next, each alternative per case is rated with either a one or a zero, depending on whether the alternative was chosen by the decision maker. Furthermore, an extension of the pure conditional logit model, called the conditional logit choice model (CLCM), allowed for the specification of alternative-specific variables and case-specific variables. As a result, a simple division between variables that altered over the alternatives, and variables that remained constant per decision maker could be made. Especially in this thesis, it is important to analyse these alternative-specific variables as they represent a large part of the researched hypotheses. In the dataset, price, distance, and availability change over the alternatives per choice set. Furthermore, an alternative-specific constant (ASC) was added for the opt-out option. The ASC was one for alternative 4 and zero for all other alternatives. This way, the effect of the opt-out option could be extracted from the main effect of price, distance, and availability. The SOC that was shown to each decision maker in the various choice sets, remained constant. Hence, it was not categorised as an alternative-specific variable. Besides these four alternative-specific variables, other variables that described characteristics of the decision maker were included. For example, whether the decision maker was a current or a prospective EV user, and the maximum distance he was willing to walk to a charging station. Only characteristics that were observable for all respondents could be included in the logit model. The results of the CLCM can be found in table 12.

From table 12, it is concluded that price, distance, and availability are all significant at the 1% significance level and play a significant role when selecting a charging station in the scenarios of the survey. For price and distance, the coefficient is negative, while for availability the coefficient is positive. These signs are in line with previous expectations. The low standard deviations of all three variables show that the variance of the coefficient is very low, and that the data points are highly centred around the mean. Therefore, hypothesis 1, 2, and 4 can be accepted.

According to basic utility theory, only differences in utility matter for choice models (Train, 2009). Hence, a base alternative to which all outcomes are contrasted needs to be chosen. Stata automatically chooses the alternative that is chosen most often. However, in this case the opt-out option (alternative 4) was chosen as the base scenario. This was done intentionally, so that the effect of the case-specific variables on the general choice of charging could be explored. As a consequence, all case-specific variables are contrasted per alternative to the base scenario

The SOC is significant at the 1% significance level in all three charging alternatives and displays a positive coefficient in table 12. Since the SOC was dummy coded, with the value of one describing a SOC of 20% and 40% otherwise, a decision maker that was shown a SOC of 20% is expected to choose alternative 1, 2, or 3 rather than alternative 4. This implies that when shown a SOC of 20%, a decision maker is expected to prefer charging over not charging. Hence, the SOC is of significant importance in the general choice of charging, and hypothesis 3A can be accepted. Next, EV ownership displays a negative coefficient significant for all charging alternatives at different significance levels. Consequently, decision makers who currently own an EV were more likely to choose the opt-out option than prospective EV users. This could be explained by the experience that current EV users have with the battery's duration. Both SOC levels that were shown to respondents were rather low SOC levels as to discourage choosing the opt-out option. Nonetheless, as seen from the significance of EV ownership, current EV owners were not afraid to choose the opt-out option for both SOC levels of 20% and 40%.

Regarding risk-aversion, the variable min_battery indicates the minimal preferred battery level, in percentages, at the start of a respondent's daily trip to, e.g., work. This variable is significant for all three alternatives at the 5% or 10% significance level and shows a positive coefficient. Therefore, there is a positive association between minimal preferred battery level and the decision to charge. This phenomenon is known as range anxiety in which decision makers are inclined to avoid lower battery levels. Furthermore, risk-aversion was measured with two general lottery questions: lottery 1 and lottery 2. Both were coded as dummy variables, with one indicating that option 1 was chosen by the decision maker. Option 1 displayed the less risky option of a 100% chance on winning a certain amount of money. Interestingly, lottery 1 is not significant but lottery 2 is significant for all alternatives at the 5% or 10% significance level. The coefficient of lottery 2 is negative, indicating that decision makers who chose the 100% option were more inclined to choose not to charge. This is contradicting to what was expected, as risk-averse people were expected to prefer charging over not charging. Since the minimal battery coefficient and the lottery coefficients contradict each other, hypothesis 5 can neither be accepted nor rejected.

For the variable considering the maximum distance decision makers were inclined to walk from home to a public charging station, only the final category of 500 metres is significant for the three alternatives. It shows a positive coefficient, meaning that people who were willing to walk 500 metres to the public charging station preferred charging over not charging. This seems logical as these people do not mind walking, so they would not perceive any of the public charging stations to be located too far, and therefore choose not to charge. All other variables regarding demographical characteristics such as age, education, and income were not significant in the CLCM.

Table 12 - The coefficients of the conditional logit model based on the full sample

VARIABLES	(general)	(alt1)	(alt2)	(alt3)
price	-0.982***			
	(0.063)			
distance	-0.671***			
	(0.055)			
availability	0.729***			
	(0.063)			
ASC	-0.130			
	(1.347)			
SOC		2.513***	2.185***	2.282***
		(0.440)	(0.454)	(0.447)
EV_ownership		-0.947***	-0.682*	-0.919**
		(0.364)	(0.372)	(0.363)
min_battery		0.017**	0.015*	0.019**
		(0.008)	(0.008)	(0.008)
lottery_1		0.425	0.677	0.428
		(0.406)	(0.441)	(0.411)
lottery_2		-1.147*	-1.432**	-1.223*
		(0.626)	(0.682)	(0.656)
2.max_distance_station		0.688	1.065	0.807
		(0.719)	(0.848)	(0.833)
3.max_distance_station		0.763	1.247	1.035
		(0.767)	(0.895)	(0.878)
4.max_distance_station		1.558*	1.562	1.480
		(0.884)	(0.976)	(0.982)
5.max_distance_station		2.422***	1.810**	2.135**
		(0.744)	(0.862)	(0.858)
age		-0.106	-0.013	-0.070
		(0.152)	(0.161)	(0.157)
education		0.201	0.149	0.211
		(0.155)	(0.161)	(0.156)
salary		-0.273	-0.231	-0.246
		(0.195)	(0.202)	(0.205)
Observations	7,416	7,416	7,416	7,416

alt1 = alternative 1; alt2 = alternative 2; alt3 = alternative 3; ASC = alternative-specific constant; SOC = state of charge; EV = electric vehicle; min_battery = minimal battery capacity.

Robust standard errors in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

6.1.2 Margins alternative-specific variables

So far only positive or negative associations between either alternative-specific variables and the alternatives, or case-specific variables and the alternatives are concluded. For an understanding of the strength of the relationship, margins need to be applied. When using solely the margins command without any other options, Stata delivers the probability that an alternative will be chosen. In general, the probability of choosing to charge at a public charging station, either alternative 1, 2, or 3, is 79.8%, while 20.2% of the individuals is expected not to charge given the circumstances (see appendix B.2). The predicted probabilities for the alternatives 1 till 3 differ. Even though they all display a regular public charging station, they vary in their attribute levels per choice set. As a consequence, their expected probabilities differ. However, the public charging station alternatives were not labelled and therefore their expected probabilities can be summed up to one general probability of choosing to charge.

Next, the effect of price, distance, and availability will be analysed. These three attributes were composed of three different levels. In this case, the margins command can be specified to analyse the effect of a one unit, in this case level, increase per attribute. Interesting is to see whether decision makers moved to the opt-out option, when the attribute was increased, or chose another charging station. All margin estimates were significant at a 1% significance level for all alternative-specific variables.

From table 13, the margins result of the variable price can be seen. These results show the effect of a one- and two-level increase in price for alternative 1, in comparison with the other alternatives. For the reason that the coefficient of price in the CLCM was negative, the marginal coefficient of price in alternative 1 is negative. When price is increased from 0.25 EUR (level 1) to 0.35 EUR (level 2), the probability of choosing alternative 1 decreases by 19.3 percentage points. However, this decline needs to be offset by an increase in probability of choosing the other alternatives. In other words, the pie cannot get any bigger. Decision makers have to choose another option and cannot choose two options within one scenario. Most of the increase in expected probability is moved to option 2 and 3, respectively 5.7 and 8.7 percentage points. The opt-out option increases with 4.8 percentage points. Hence, when price increases from 0.25 EUR to 0.35 EUR for alternative 1, the expected probability of choosing another public charging station (alternative 2 & 3) increases more than the expected probability of choosing not to charge. When price increased more rigorous from 0.25 EUR (level 1) to 0.45 EUR (level 3), the decrease in probability of choosing alternative 1 is 34.7 percentage points. This is slightly less than two times the decrease in probability of a one-level increase in price. Hence, the price effect is somewhat stronger when moving from 0.25 EUR to 0.35 EUR. Still, most individuals are expected to follow the same substitution pattern as before: the opt-out option increases only by 8.2 percentage points, the rest of the decrease in probability of choosing alternative 1 is moved to the other charging alternatives.

Table 13 - The marginal coefficients of the alternative-specific variables

VARIABLES	(1) price	(2) distance	(3) availability
level 2 vs level 1_alternative 1	-0.193***	-0.112***	0.094***
	(0.013)	(0.011)	(0.006)
level 2 vs level 1_alternative 2	0.057***	0.032***	-0.025***
	(0.004)	(0.003)	(0.002)
level 2 vs level 1_alternative 3	0.087***	0.050***	-0.047***
	(0.006)	(0.005)	(0.004)
level 2 vs level 1_alternative 4	0.048***	0.030***	-0.022***
	(0.006)	(0.004)	(0.003)
level 3 vs level 1_alternative 1	-0.347***	-0.212***	0.210***
	(0.020)	(0.019)	(0.016)
level 3 vs level 1_alternative 2	0.105***	0.060***	-0.058***
	(0.007)	(0.006)	(0.005)
level 3 vs level 1_alternative 3	0.161***	0.096***	-0.100***
	(0.011)	(0.009)	(0.008)
level 3 vs level 1_alternative 4	0.082***	0.056***	-0.052***
	(0.009)	(0.007)	(0.007)
Observations	7,416	7,416	7,416

Price (level 1 = 0.25 EUR, level 2 = 0.35 EUR, level 3 = 0.45 EUR), distance (level 1 = 100 m, level 2 = 250 m, level 3 = 400 m), availability (level 1 = 30%, level 2 = 60%, level 3 = 90%).
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The same process can be applied to both attributes of distance and availability. For distance, the drop in probability after a one-level decrease was smaller than for price with respectively 11.2 percentage points against 19.3 percentage points (see table 13). Here, a one-level increase implies an expansion from 100 metres distance to 250 metres distance. The effect of a two-level increase in distance (from 100 metres to 400 metres distance) is a decrease in the expected probability of choosing alternative 1 of 21.2 percentage points. This is roughly double the decrease in probability of a one-level change in distance. Hence, the marginal effect of a one-level increase in distance at 100 metres, or 250 metres is highly comparable. Moreover, the decline in probability is again, like with the attribute price, primarily shifted towards the other public charging station options (alternative 2 & 3). In total, 8.2 percentage points of the 11.2 percentage points, associated with a one-level decline, is shifted to other charging options, while a 3.0 percentage points increase in the probability of choosing the opt-out option is present. When increasing the distance from 100 metres to 400 metres, the probability of choosing another charging station increases by 15.6 percentage points and the probability of not charging at all increases by 5.6 percentage points. As a result, when distance increases, individuals are tempted to prefer charging at other public charging stations than not charging at all.

The final alternative-specific variable is availability. From table 12, it was concluded that availability was the only alternative-specific variable which had a positive association with the selection of a public charging station. This positive coefficient can also be seen in table 13 when analysing the margins of the attribute availability. When the level of availability is increased from 30% (level 1) to 60% (level 2) for alternative 1, the expected probability of choosing alternative 1 increases with 9.4 percentage points. This is predominately at the expense of alternative 3, whose expected probability decreases by 4.7 percentage points. In total, most of the expected shift towards alternative 1 originates from individuals who had already chosen another public charging station (alternative 2 or 3), accounting for 7.2 percentage points. Only 2.2 percentage points of the increased probability of choosing alternative 1, comes from the opt-out option. The same applies for a two-level increase in availability. If availability in alternative 1 would increase from 30% (level 1) to 90% (level 3), the expected probability of choosing alternative 1 increases by 21.0 percentage points. This is slightly more than double the rise in expected probability of choosing alternative 1 in a one-level increase. Again, most of the increment of alternative 1 comes at the expense of other public charging stations, rather than the opt-out option. Hence, most individuals who switch to alternative 1 already made the decision to charge. Only 23.4% and 24.8% of the individuals that change towards alternative 1 are expected to come from the opt-out option, for a respectively one-level and two-level increase in availability.

In conclusion, the alternative-specific variable price has the biggest effect on the choice process of individuals when price is increased either by one-level, or two-levels. Distance and availability show comparable margins. Strikingly, the increase of price, distance, or availability primarily shifts expected probabilities from other public charging stations (alternative 2 & 3) towards or from alternative 1, rather than influencing an individual's choice to change from not charging to charging. This implies that most people who chose not to charge decided this despite differences in price, availability, or distance. One potential reason is the presence of other charging opportunities at work or other locations. Unfortunately, investigating other charging locations, e.g., at work, or at a shop is outside the scope of this thesis. However, other case-specific variables were used to examine what drives this choice of not charging. This question will be analysed in the next section.

6.1.3 Margins case-specific variables

To gain more insights into the reasons for choosing the 'I do not want to charge' option, two case-specific variables were investigated. Case-specific variables are variables that do not vary over the alternatives. These variables are person specific. Examples are the age or income of a person, but also the presented SOC level is a case-specific variable. In the CLCM of table 12, the coefficients of SOC and EV ownership were significant over all alternatives. Therefore, these variables will be analysed using the margins command.

First the case-specific variable SOC, representing the specified battery level, will be explored. The SOC was dummy coded with a value of zero belonging to a SOC of 40%, and a value of one belonging to a SOC of 20%. In table 14, this is represented respectively by 0 and 1. All coefficients for SOC are significant at a 1% significance level, signalling the importance of SOC when choosing an alternative. From table 14, it can be concluded that the predicted probability of choosing the opt-out option (alternative 4) decreases from 34.8% to 6.6% depending on the SOC. This implies that the probability an individual chooses the opt-out option significantly decreases when the SOC changes from 40% to 20%. Logically, this makes sense as the scenarios were formulated in such a way that the SOC of 20% was precisely enough to make the next trip. However, the EV would not be able to drive any more kilometres after this specific trip. Hence, in the case of a SOC of 20%, the predicted probability of charging is 100% minus 6.6% resulting in

93.4 percentage points. For a SOC of 40%, this probability is different. In this scenario, the predicted probability of charging decreases to 65.2 percentage points. Therefore, the SOC had a significant effect on the general choice of charging.

Following the SOC, the case-specific variable EV ownership was analysed. This variable was also dummy coded. In table 14, not being an EV owner is described by 0 and owning an EV is described by 1. It can be interfered from table 14 that when the person is a current EV user, the person is more likely to choose the opt-out option than a person who is not an EV user. The same was concluded from the coefficients in table 12. However, with the margins command we can retrieve some insights about the marginal effect of being an EV user. The difference in percentage points for the opt-out option regarding EV ownership is 9.6 percentage points. Implying that the probability an individual chooses the opt-out option increases by 9.6 percentage points to 23.4 %, when the individual owns an EV. For the other alternatives, the effect is the opposite. Owning an EV reduces the probability of choosing alternative 1 and 3, however for alternative 2 the probability increases slightly by 1.0 percentage point. This can be attributed to the design of the choice sets in which alternative 2 was the least chosen alternative. Hence, its combinations of attribute levels were least attractive. For alternatives 1 and 3, when a person owns an EV the predicted probability decreases by 5.3 percentage points and 4.5 percentage points to a probability of respectively 31.3% and 26.6%.

To sum up, the variables of SOC and EV ownership are important factors to consider when trying to understand the underlying decision process of charging. The effect of SOC is much bigger than the effect of EV ownership on the opt-out option. This can be attributed to the almost inevitable need for charging in the scenario of a SOC of 20%. Nonetheless, the margins of EV ownership show that range anxiety is less present for current EV users than for prospective EV users. Prospective EV users favour the opt-out option less than current EV users.

Table 14 - The marginal coefficients of the case-specific variables, SOC and EV ownership

VARIABLES	(1) SOC	(2) EV_ownership
0_alternative 1	0.254***	0.366***
	(0.018)	(0.019)
1_alternative 1	0.399***	0.313***
	(0.013)	(0.013)
0_alternative 2	0.159***	0.186***
	(0.015)	(0.018)
1_alternative 2	0.215***	0.187***
	(0.014)	(0.012)
0_alternative 3	0.239***	0.311***
	(0.016)	(0.016)
1_alternative 3	0.321***	0.266***
	(0.012)	(0.011)
0_alternative 4	0.348***	0.138***
	(0.037)	(0.029)
1_alternative 4	0.066***	0.234***
	(0.021)	(0.025)
Observations	7,416	7,416

SOC = state of charge; EV = electric vehicle.
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.1.4 Moderating effect of SOC on availability

The final analysis examines the moderating effect of SOC on availability in the choice sets. Unfortunately, it is not possible to create an interaction effect between a dummy case-specific variable and an alternative-specific variable. In this analysis, the alternative-specific variable is availability, and the case-specific variable is the SOC. A value of zero for SOC would make the interaction case-specific, as a multiplication by zero is always zero. A value of one for SOC would make the interaction differ per alternative due to the different levels of availability. Thus, the interaction would be neither fully alternative-specific nor case-specific. A solution was provided by creating subsamples. One subsample contained all the cases with a SOC of 20%, and another subsample contained all cases with a SOC of 40%. Afterwards, the margins regarding availability were calculated for both subsamples.

From table 15, it is concluded that the margin of availability for a SOC of 20% is greater than for a SOC of 40%. The expected increase in probability of choosing alternative 1, when availability increases by one level for alternative 1, is 12.9% for a SOC of 20% and 5.7% for a SOC of 40%. The same conclusion can be drawn for a two-level increase in availability for alternative 1. In conclusion, hypothesis 3B is accepted. The level of SOC has a negative moderating effect on the relationship between availability and the selection of a charging station.

Table 15 - The marginal coefficients of availability per SOC level

VARIABLES	(1) SOC_20%	(2) SOC_40%
2 vs 1_alternative 1	0.129***	0.057***
	(0.009)	(0.009)
2 vs 1_alternative 2	-0.043***	-0.010***
	(0.004)	(0.002)
2 vs 1_alternative 3	-0.074***	-0.021***
	(0.005)	(0.004)
2 vs 1_alternative 4	-0.011***	-0.026***
	(0.003)	(0.005)
3 vs 1_alternative 1	0.282***	0.126***
	(0.024)	(0.023)
3 vs 1_alternative 2	-0.098***	-0.023***
	(0.011)	(0.005)
3 vs 1_alternative 3	-0.158***	-0.045***
	(0.013)	(0.009)
3 vs 1_alternative 4	-0.026***	-0.057***
	(0.007)	(0.012)
Observations	3,996	3,420

SOC = state of charge.
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.1.5 Hausman-McFadden test

In the previous part, the CLCM was used to estimate the coefficients of the choice experiment. CLCM is an upgrade of the regular CLM analysis, specifically designed for choice sets. However, as mentioned in chapter 4 on methods, in the CLM the IIA principle holds. The choice set design of this thesis includes unlabelled alternatives, therefore the IIA principle is expected to hold. There is no suspicion why the choice of one alternative would depend on another alternative. All alternatives, excluding the opt-out option, include a regular public charging station. No ASCs were specified for these alternatives.

Nevertheless, the IIA principle needs to be checked. One way of checking this principle is the Hausman-McFadden test. Essentially, the Hausman-McFadden test compares two estimators of the same parameters. Both estimators need to be consistent, but not efficient for the null hypothesis to be rejected, meaning the IIA holds. For the CLM, which is based on the maximum likelihood estimator (Wang, 2019), this means that the model needs to be based on a limited set of alternatives. If the IIA principle holds and the alternatives are independent of each other, dropping one alternative should be irrelevant for the estimates of the parameters. For this thesis, alternative 4 could not be dropped as alternative 4 serves as the opt-out option, which is the base alternative. In appendix B.3, the results from the Hausman-McFadden test are presented. When dropping for instance alternative 1 or alternative 2, the null hypothesis: “difference in coefficients is not systematic”, could be rejected at a 5% significance level. This indicates that the IIA principle does not hold. Nonetheless when dropping alternative 3, the null hypothesis was not rejected which indicates that the IIA principle holds. This shows the inconsistency of the Hausman-McFadden test which is also the conclusion of Cheng & Long (2007). There is no systematic difference between alternatives 1, 2, and 3, and therefore no suspicion for one alternative to be different than another alternative. In addition, no suspicion for taste variation regarding the various public charging stations is expected. Still, the MLM would have been adopted to account for the IIA principle, as MLM is an appropriate analysis for all utility models. Unfortunately, convergence could not be achieved even after trying different seed numbers and integer points. As a result, the data have been interpreted using the CLCM.

6.2 Summary of conducted interviews

As mentioned in the methods sections, this research consists of two research strategies. In the first part, the perspective of the consumer was examined by analysing their choice data. In this second part, the perspective of the industry on the current and future charging infrastructure will be presented through a summary of the interviews. These interviews are used to answer hypothesis 6.

Overall, the interviewees perceived the current charging infrastructure in the Netherlands as adequate. Nonetheless, they expect an increase in the number of charging stations. Looking specifically at the charging infrastructure for urban EV users, the general opinion is that charging plazas will play a large role in these urban neighbourhoods. Their convenience with regard to the bundling of charging points is seen as a big advantage by the industry. Especially the network operator perceived the stronger grid connection for charging plazas as positive since this allows an easier expansion if necessary. When an existing charging station with a weak grid connection needs to be expanded, this results in higher investment costs. The network operator advocated to combine connection investments with other projects, like a renovation of the sewerage. This way, projects could be combined and the hassle of breaking a street open would occur only once.

The concept of charging at work was welcomed by all stakeholders. It is expected that an increasing number of employers will offer charging to their employees. One reason is the low energy tariffs combined with higher demands. An interviewee explained that the energy tariff for companies decreases per kWh when demand grows. Therefore, companies might require their lease users to charge solely at work. This fixed demand offers the company a better position in a bargain with the CPO. Another interviewee mentioned the reason of social profiling. Some companies advocate the use of green energy and support sustainable mobility. Hence, these companies should also accommodate their employees with EVs and stimulate leasing EVs. Exactly how charging at work will develop is still vague, but a positive scenario is expected by the interviewees.

The development of fast charging was a more debated topic. On one hand, the interviewees perceived fast charging as only necessary when occasionally driving larger distances, which exceed the battery capacity. Consequently, fast charging is only used for emergencies. One interviewee explained that the waiting time for fast charging is longer than the waiting time for regular charging. With this statement, not the actual waiting time in minutes or hours is intended, but the perceived waiting time. According to the interviewee, when charging at home or at work an individual does not feel like he is waiting. This is different when an individual needs to wait twenty minutes at a gas station for fast charging. Only when the location with fast charging offers a service, then the individual might be willing to wait.

On the other hand, a share of the interviewees thinks fast charging can play an important role due to the dominant character of gas stations. Two reasons are causing this. First, gas stations generate most of their income from the shops/restaurants located at the gas stations, not from their gas sales. Hence, a price war is expected between gas stations and other CPOs. Since the current gas station operators are almost all large industry players, a price war could be a very interesting development for fast charging. The second reason is that people are used to go to gas stations to fill up their tank with gasoline. Hence, this behavioural pattern might be partly sustained even when people switch to EVs.

As a result, hypothesis 6 can neither be accepted nor rejected. The perspectives of the industry on fast charging vary from player to player. The same was concluded from the literature review that many contradictory views on the future outlook of fast charging are present. From the interviews, two main requirements were formulated for fast charging to become a viable charging option for daily trips. Firstly, charging prices need to decrease. Secondly, services need to be offered to the EV user at the fast charging station to reduce the cognitive waiting time. Nevertheless, only the future can tell whether fast charging will become a popular charging option. In figure 7, an outcome summary of the various charging locations is provided.

LOCATION	**FUTURE OUTLOOK**
Charging at work	
Charging plaza	
Fast charging	 

Figure 7: Future outlook according to interviewees.

6.3 Overview of hypotheses

In this section an overview of the hypotheses is provided. Per hypothesis, it is determined whether the hypothesis can be accepted or rejected.

(H1): Price of charging has a negative effect on the selection of a public charging station.	*Accepted*
(H2): Charger availability has a positive effect on the selection of a public charging station.	*Accepted*
(H3A): The SOC has a negative effect on the general choice of charging.	*Accepted*
(H3B): The SOC negatively affects the association between charger availability and the selection of a public charging station.	*Accepted*
(H4): Distance from home to a public charging station has a negative effect on the selection of a public charging station.	*Accepted*
(H5): Risk aversion has a positive effect on the general choice of charging.	*Neither accepted nor rejected*
(H6): Fast charging will not be the preferred charging option for the daily commute of urban EV users.	*Neither accepted nor rejected*

Chapter 7. Business Case

7.1 Public charging station

From the previous sections, a thorough theoretical perspective on the charging preferences of (prospective) EV users was achieved. Nonetheless, theory remains theory unless some form of practicality is combined with it. The business case of public charging stations is not the most prosperous one. In the research of Madina et al. (2015), it was concluded that a public charging stations needs 3.16 charging sessions per day of 10 kWh each to be profitable. Adding up to approximately 11,500 kWh per year for one charging station. In comparison, the total charged kWh per station in Amsterdam was only 8,179 in 2019 (G4+MRA elektrisch, 2019). Moreover, the average for the three provinces Noord-Holland, Flevoland and Utrecht was even slightly below 5,000 (G4+MRA elektrisch, 2019). Hence, based on the research of Madina et al. (2015), the business case for a charging station in the Netherlands is not very strong. For simulation reasons, the business case was recreated. Initial data were retrieved from the Public Charging Benchmarking Report of NKL Nederland. Their benchmark report consists of a detailed cost/benefit overview considering a regular public charging station with two charging points (NKL, 2018). The cost items for initial investment were slightly altered, as NKL was perceived to be too optimistic about this. Based on desk research and the conducted interviews, a new investment price was formed.

Figure 8 shows that the business case for a regular charging station with two sockets is not strong. Within the target ten-year deprecation period, the break-even point cannot be achieved. The average expected daily demand in kWh was set at 14 kWh and the price without VAT at 0.25 EUR (NKL, 2018). The average daily demand in kWh was retrieved from the yearly demand of the three aforementioned provinces, which was just below 5,000 kWh (G4+MRA elektrisch, 2019). Regarding demand, it was assumed that demand would grow 5% per year starting from 2021. This percentage is based on the charging data of G4+MRA elektrisch (2019) of the previous years.

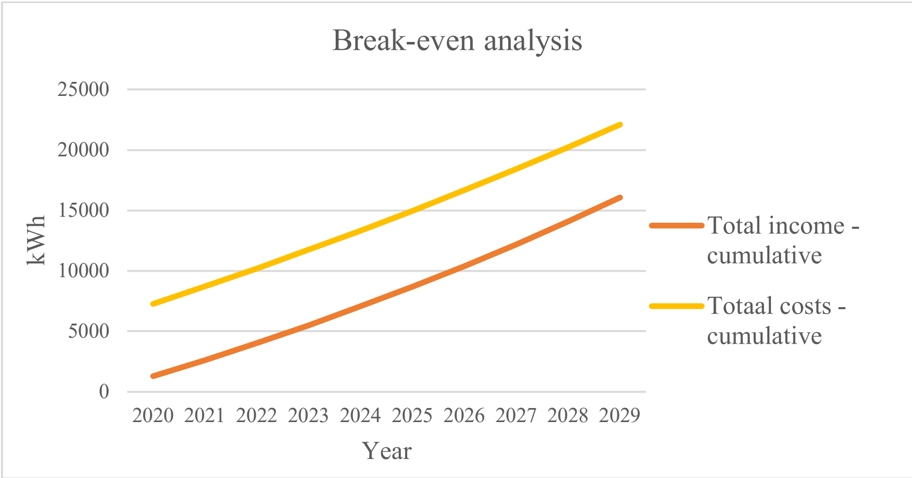

Figure 8: Display of income versus costs, calculated cumulatively, of a regular charging point[5]

To check the price sensitivity of the model, a price scenario analysis was created. As displayed in figure 9, if the price per kWh is increased by 25%, the break-even point is almost achieved within ten years. However, the price needs to be increased by 50% before the business case becomes really profitable. Unfortunately, given the current market conditions this is not likely to happen. At this moment, EVs are partially preferred due to their low alternative fuel costs. Increasing the charging price works counterintuitive when trying to promote the adoption of EVs.

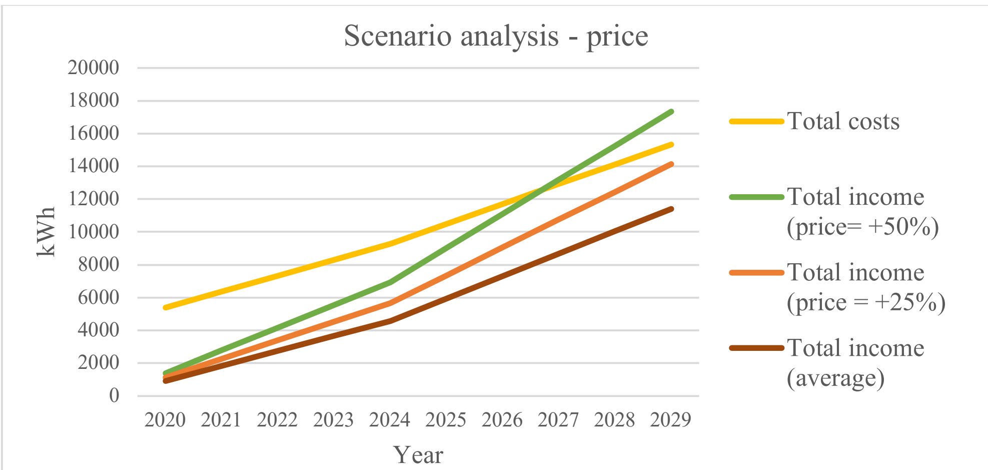

Figure 9: Scenario analysis of a regular charging point with regard to price

[5] See appendix C.1 for further specification

Instead of increasing the charging price per kWh, the expected demand can also be increased to analyse the potential break-even point. When the demand per day is increased to 25 kWh from 14 kWh in 2020 and demand is expected to grow 5% per year (see scenario 3 in figure 10), the break-even point is achieved in the year 2027[6]. This is in line with the findings of Madina et al. (2015), they concluded that a demand of approximately 30 kWh per day is needed for profitability. Nevertheless, it must be noted that the current demand is far from 30 kWh per day. From the interviews, it was concluded that the current charging infrastructure in the Netherlands is very good and the number of charging stations is more than adequate for the current demand. Consequently, supply is higher than demand which partly explains the previous numbers of low yearly demand per public charging station.

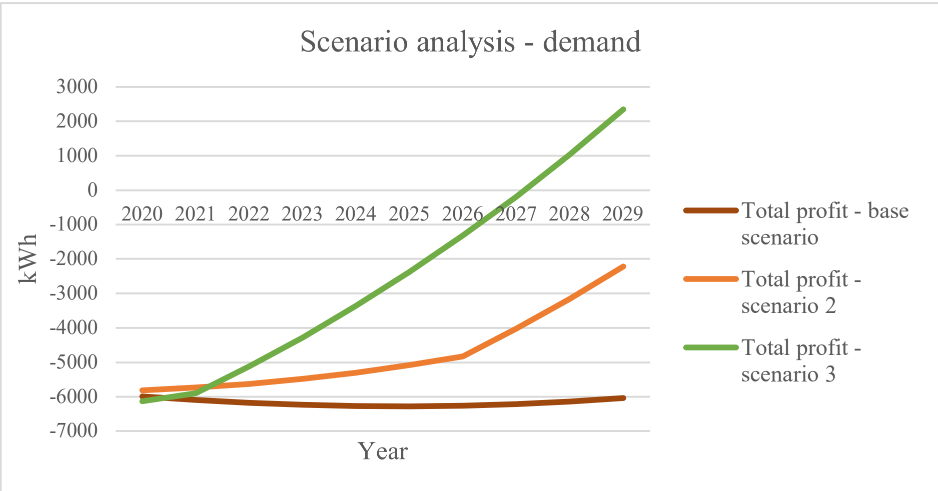

Figure 10: Scenario analysis of a regular charging point with regard to demand

All in all, the business case for a regular public charging station is not yet profitable at this moment. Either an increase in charging demand, hence EV adoption, or increasing government incentives are needed for an improvement of the business case.

[6] See appendix C.1 for further specification

7.2 Public charging plaza

In addition to the individual charging stations, this thesis also provides some insights into the business case of a charging plaza. A public charging plaza is a charging option with high potential for urban cities where most inhabitants do not have private parking. However, there are still some hurdles to overcome before charging plazas can serve as an adequate charging option. The business case of a charging plaza is more difficult to comprehend compared to that of a single charging station. The difficulty lies in the fact that the range of options for a charging plaza, with regard to network connection, is greater. To understand this, a short technical description of a charging plaza is provided.

According to NKL (2019) a charging plaza consists of more than two charging points for EVs which share the same grid connection. This way, the charging points do not have separate grid connections, but share one grid connection. In general, two types of charging plazas connections are explained by NKL (2019). The first type is a master-slave configuration in which one charging station is the master and the other charging stations are the slaves. The master has the full grid connection together with a back-office connection, while the slaves are only connected to the master. As a result, the master has the capability to determine the charging speed for each slave. The second type is a system street unit in which a separate unit provides the grid connection, and all other charging stations are connected to this separate unit. In the second type, both AC (<22 kWh) and DC (>50 kWh) charging can be provided on the charging plaza. However, more space is required to install this separate grid connector. This is for example possible at large car parks near shopping centres or mobility hubs.

In the business case of this thesis, the master slave construction was used, as this type of charging plaza connection is expected to be most common in urban neighbourhoods. One benefit regarding a charging plaza is the opportunity of smart charging. With smart charging, the load of charging can be balanced efficiently over the different outputs (NKL, 2019). Consequently, it is possible to charge faster when only one car is connected and slower when multiple cars are connected.

Financially, a charging plaza is an attractive option as the investment only concerns one grid connection. This way, the costs per charging point can be reduced. However, the total costs for the investment remain higher for a charging plaza than for a single charging station. Therefore, most CPOs are not very fond of the idea of charging plazas. The low demand per charging station makes it difficult to regain the initial investment plus the yearly operating costs. Hence, it is more logical to spread single charging points rather than concentrating them in one place.

To illustrate, an example is provided of the different connection costs. These costs are based on online cost data provided by network operator Liander and their cost level is regulated by the Dutch Authority Consumer & Market. This institution decides the maximal connection costs per year. The connection costs for the 3x50Ampere (A) connection of the master are 916.00 EUR. To this master, 4 slaves can be connected (Liander, 2020). In comparison, the investment costs of a regular connection of 3x25A are 657.00 EUR for one charging station (Liander, 2020). In order to exploit five individual charging stations, the connections costs of 657.00 EUR need to be multiplied by five. The first option seems to be better. However, the periodic connection costs are much higher for the 3x50A connection (Liander, 2020), which makes the business case for a charging plaza doubtful again. From figure 11, it is concluded that the cumulative total costs of a charging plaza are slightly lower than of five individual charging stations[7]. Nonetheless, the business case of both remains unattractive when demand is only 14 kWh per day with 5% growth per year. Due to the high initial investment costs and low charging demand, a charging plaza is often not the preferred option by CPOs. Individual charging stations are preferred to spread the locational risk.

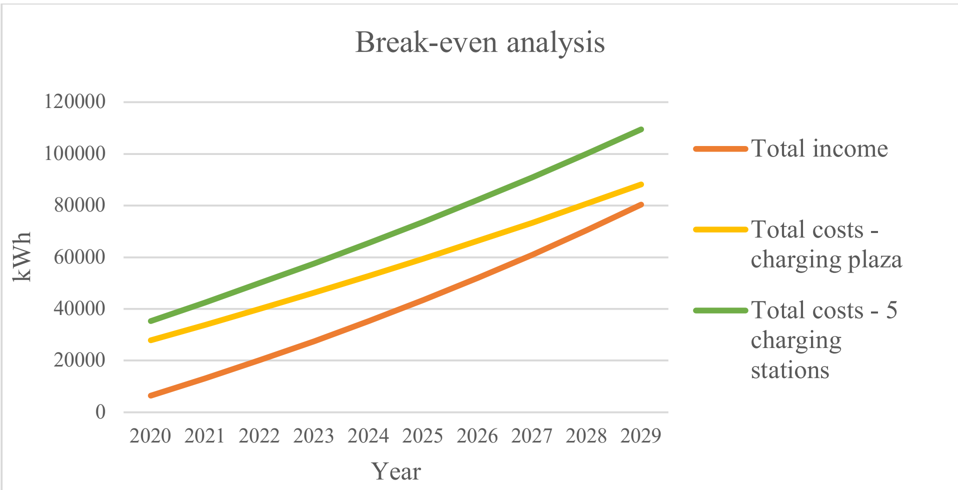

Figure 11: Break-even analysis of a charging plaza compared to five individual charging stations

[7] See appendix C.2 for further specification

A large charging plaza only becomes the preferred option when the investment is spread out over time. A scenario was created in which the charging plaza starts with five charging stations on one 3x50A connection. After three years, the connection is expanded, and three charging stations are added. Finally, in year 7 the charging plaza extends to ten charging stations, and the connection is expanded to a 3x80A connection. With the assumption that the average charging demand per station of 14 kWh increases yearly by 5%, the break-even point is achieved in year 2028 (See figure 12)[8]. For a CPO, the business case might be positive, but it remains relatively weak. Only when charging demand increases in the upcoming years, charging plazas can become a popular investment option.

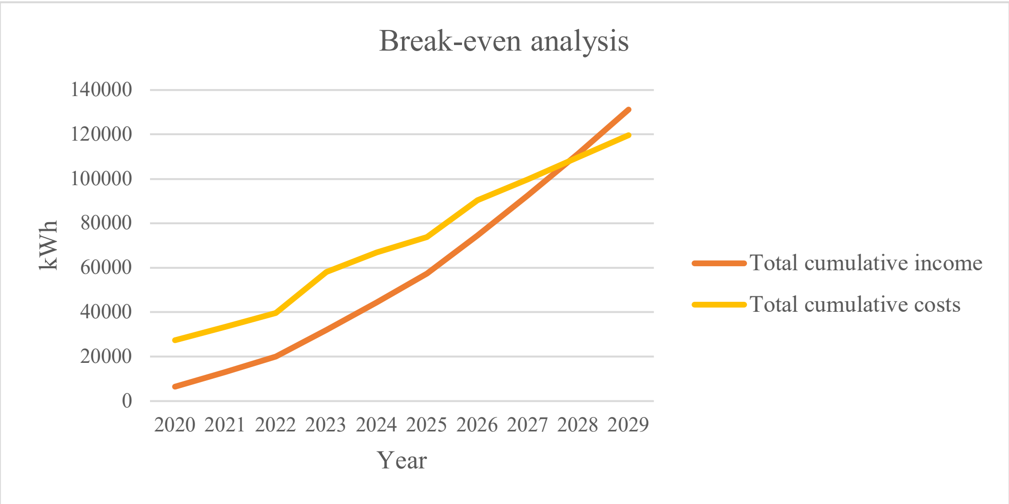

Figure 12: Break-even analysis of a charging plaza with aggravation

However, this demand may be difficult to achieve with the current EV adoption. Especially since the charging plaza centralizes charging points. As a consequence, the location is extremely important for a charging plaza and a well-considered decision for this is needed.

In conclusion, the business case for a charging plaza with five charging stations, or five individual charging stations is not very good. The business case for the charging plaza is slightly better, but in both situations the break-even point is not achieved within the target ten-year exploitation period. However, when the investment of the charging plaza is spread out over time,

[8] See appendix C.3 for further specification

the business case becomes positive. Hence, some advice for future policy makers would be to start with a weaker grid connection and when the location seems profitable, further invest in a stronger grid connection and more charging stations.

Chapter 8. Discussion

8.1 Summary

The research objective of this thesis is to answer the following research question: "*What are the charging preferences of (prospective) EV users living in an urban residential neighbourhood with no opportunity of private parking?"*. Until now most literature has analysed charging data of current EV users who prefer charging at home in the evening. However, these researches do not take into account the general population who has no private parking place, and for whom EVs should become available in the next decade. The urge for research into the dynamics of public charging in urban areas is substantial. This thesis has provided insights into the decision process of (prospective) EV users when selecting a public charging station.

To model the choice of charging, a survey was designed with nine choice sets which was distributed across both current EV users and prospective EV users. About two-third of the respondents of the survey owned an EV. This substantial percentage underpins the validity of the results, as electric driving and charging are concepts difficult to comprehend for non-EV users. In addition, 46% of the current EV users did not own a private charging station. This group of users was the main target group of this thesis. However, an inadequate response rate was expected when targeting this main group only. Therefore, the decision was made to expand the target group to all current EV users and prospective EV users.

Despite the broader-oriented target group, the collected data showed interesting results. From the CLCM, it was concluded that all alternative-specific variables: price, distance, and availability, were significant in the decision process of charging. For price and distance, this relationship proved to be negative. For availability, a positive relationship was shown. Overall, price is the most important parameter when selecting a charging station. For distance and availability, the marginal effects were comparable to each other. Even though their effects may be smaller than the effect of price, these variables are important to consider when planning a new public charging location. Individuals prefer a charging station which is as close to home as possible. Nonetheless, the respondents are willing to walk a maximum of 360 metres (weighted average) to a public charging station in their neighbourhood.

An interesting question is to which charging option respondents would switch, if an attribute like price was increased. From the marginal analyses, it was concluded that when the price at one charging station increased, most respondents would switch to another charging station. Few respondents would move to the no-charge alternative when either price or distance increased, or availability decreased. Thus, when respondents chose the opt-out option, they tended to stick to this option.

Besides the alternative-specific variables, other case-specific variables were also of interest. For instance, SOC proved to be an important variable in the choice of charging even at lower battery levels. From literature, it was already concluded that SOC plays an important role in the general choice of charging (Sun et al., 2015; Yang et al., 2016). To make the opt-out option unattractive, the SOC levels were set below the average SOC levels stated in literature. Surprisingly, even at these already low SOC levels, the SOC had a significant negative effect on the general choice of charging. Especially the opt-out option was much more often chosen when the respondent was shown a SOC of 40%, than with a SOC of 20%. This implies that the current high levels of SOC before charging stated in literature could be due to ease of charging, rather than a need for charging. With the increasing pressure put on the electricity network, it is important to make a division between these different reasons for charging. At this moment, the current literature does not take this into account.

Another case-specific variable of interest was EV ownership. As aforementioned, this thesis targets both current and prospective EV users. Hence, the real experience of driving electric and charging is expected to have an effect on the decision process of a respondent. Being a current EV user had a significant positive effect on choosing the opt-out option. Consequently, prospective EV users were less likely to choose the no-charge alternative and would predominately choose to charge at a public charging station. This observation can potentially be explained by range anxiety. According to literature, range anxiety is one of the most important reasons for consumers to withdraw from buying an EV (Egbue & Long, 2012). The results of this thesis confirm this.

To make this research more practical, the business case of a public charging station has been investigated. In general, the business case of a public charging station is not very prosperous. Only when the demand doubles to approximately 30 kW per day, the business case will become interesting for companies. Although the business case might not be profitable yet, it is still important to develop the current public charging infrastructure to increase the visibility of charging stations. When this visibility is strengthened, adoption barriers like range anxiety are expected to be overcome. Furthermore, a business case was developed that takes into account the comparison between multiple individual charging stations and a charging plaza. Even though a public charging plaza does not achieve the break-even point within the target ten-year exploitation period, its total costs are lower than for installing individual charging stations. As a result, a public charging plaza is an attractive option for clustering charging stations but should be reviewed with great attention.

In conclusion, all three alternative-specific variables of price, distance, and availability played a significant role in the selection of a public charging station. The (prospective) EV users prefers a public charging station that has a low charging price, high availability, and is less than 360 metres away located from his home. Moreover, the general decision of charging is influenced by the SOC, and whether the person is a current EV user. This shows that experience with electric driving affects the preferences of (prospective) EV users. In addition, some practicality was combined with theory in the form of a business case. In the end, the business case of a public charging station is far from profitable, and demand is the main causer of this unprofitability.

8.2 Recommendations

From the previous stated results, certain recommendations can be made to add to the discussion on the public charging infrastructure. Due to the current poor business case of a charging station, it is important to find ways to increase the future demand for charging. This together with cost reduction is the only way to improve the business case, as increasing charging prices reduces the attractivity of buying an EV.

It was concluded from the analyses, that price had the largest marginal effect on the expected probability of selecting a public charging station. Therefore, finding ways to increase profitability while decreasing charging prices would help strengthening the business case. In order to be cost-competitive, smart charging is required. One ‘smart’ idea is to look at the duration of charging. In the literature, the duration of a charging session was assessed to have a negative effect on the selection of a charging station (Jabeen et al., 2013). However, not necessarily the duration of a charging session, but the relative waiting time is important to consider. For example, with fast charging your absolute waiting time is approximately 30 minutes. This absolute waiting time is rather short, but relatively it may feel like you are waiting for a long time since you have no other planned activity at this location. This is different for charging at home or at work. Even though the absolute waiting time may rise to multiple hours, your relative waiting time is far shorter. At this destination, either at home or at work, you have other activities which you can do whether your EV is charging or not. Performing your job is not dependent on whether your EV is connected to the energy grid. Consequently, the relative waiting time of fast charging is longer than the relative waiting time of regular charging at home or work. This example serves as the base for the following recommendation.

It is recommended to explore smart charging concepts with dynamic pricing in which the charging price can fluctuate according to the offered regular charging speed. For instance, in urban neighbourhoods where private parking is rare, many EV users will connect their car at the end of a working day and let the EV charge for the entire night. For them, it does not matter whether the car takes 6 hours or 10 hours to be fully charged. Their absolute waiting time is unimportant. Hence, in their case, the charging speed can be reduced below the regular charging speed of 11 kWh. When charging speed is reduced, more charging points can make use of a weaker grid connection. This suggestion decreases both initial investment costs and yearly costs. From this point of view, small charging plazas of approximately two or three charging stations with each two charging points can be developed. Due to the weaker grid connection, one of the larger expenses like the initial and yearly grid connection fee can be minimized. As a result, a lower charging price can be specified and demand at these charging stations is expected to rise, improving the business case of the public charging station.

Naturally, this concept of combining lower charging speed and weaker grid connection with lower charging prices is not the right solution for every charging location. When a charging location is used mostly by visitors who are staying for a short period of time, this solution is not appropriate. For them, the absolute waiting time is of uttermost importance. Nevertheless, the idea that charging needs to become faster in the future is not correct. Most important is to look from the EV users' perspective to understand their needs, and which type of charging they value most at each location.

8.3 Limitations & future research

While writing this thesis, limitations were mostly present in the research design. To analyse the preferences of current and prospective EV users, a DCE was developed in which stated preferences were measured. The restriction on stated preferences can be explained by the following question: Will your respondents display the same behaviour as they have stated? In this regard, a stated choice does not reflect actual reality, and some uncertainty in future behaviour will remain present.

Two other limitations can be identified considering the target group of the DCE. Both current and prospective EV users were asked to fill out the survey. For prospective EV users, it might be hard to fill in charging preferences, as they have never had the real experience of electric driving and charging. Nevertheless, they stated to be interested in buying an EV in the near future. Moreover, it might be difficult for current EV users as well as prospective EV users to imagine not owning a private charging station. As seen from the literature and the collected data, most of the EV users own a private charging station. For that reason, being in the position in which an individual is fully dependent on the public charging infrastructure can be hard to envision. An improvement of the model would be to include urban EV users without a private charging station only.

Furthermore, the reason for respondents to choose the opt-out option remained unclear. Many respondents who chose the opt-out option tended to stick to this option. Future research could offer more insights into the underlying reasons for this choice. It would be interesting to analyse whether these respondents preferred to charge their car elsewhere (e.g. at work or at shops) or that they did not feel the need to charge due to adequate SOC levels.

All these limitations show that research on the use of the public charging infrastructure is far from sufficient. More research is needed to develop a resilient public charging infrastructure, in order to prepare ourselves for the future.

Appendix

Table of contents

Appendix A – Used methods

A.1 Survey

Survey – Master Thesis

Start of Block: Intro

Intro 1
Beste deelnemer,

Bedankt voor uw deelname aan dit onderzoek. Voor mijn afstudeeropdracht aan de Erasmus Universiteit Rotterdam onderzoek ik de laadvoorkeuren van (toekomstige) elektrische rijders. Om inzicht hierin te krijgen is bijgaande survey ontworpen. Het onderzoek zal ongeveer 10 minuten duren.

Lees a.u.b. iedere vraag aandachtig en neem de tijd om de vraag eerlijk te beantwoorden. Met de pijl rechtsonder in uw beeldscherm kunt u naar de volgende vraag klikken.

Indien u de resultaten van dit onderzoek wilt ontvangen, laat dan uw e-mailadres achter aan het einde van de survey. Als u vragen heeft, stuur dan een e-mail naar 421971jr@student.eur.nl

Met vriendelijke groet,
Jamila

Let op: de medewerking in dit experiment is vrijwillig en de antwoorden zullen anoniem worden geregistreerd. U bent vrij om te stoppen met het onderzoek op ieder moment gedurende de vragenlijst. De uitkomst van deze survey wordt alleen gebruikt voor wetenschappelijke doelen.

End of Block: Intro

Start of Block: EV bezit

Q1
Bent u in het bezit van een elektrische auto (bv. volledig elektrisch, plug-in hybride, hybride)?

- ◯ Ja
- ◯ Nee

End of Block: EV bezit

Start of Block: EV geïnteresseerd

Q2 Als u in de komende 3-5 jaar een (nieuwe) auto zou aanschaffen, zou u geïnteresseerd zijn in het kopen van een elektrische auto?

- ◯ Ja
- ◯ Nee

End of Block: EV geïnteresseerd

Start of Block: EV eigenschappen

Q3 Welk type elektrische auto bezit u?

○ Volledig elektrisch *(alleen batterij)*

○ Plug-in hybride *(batterij + verbrandingsmotor)*

○ Hybride *(batterij + verbrandingsmotor)*

○ Anders ____

Q4 Via welke constructie rijdt u uw elektrische auto?

○ Zakelijke lease - werknemer

○ Zakelijke lease - ZZP / DGA

○ Zakelijke koop - werknemer

○ Zakelijke koop - ZZP / DGA

○ Privé koop

○ Private lease

○ Anders ____

Q5 Hoeveel maanden rijdt u al met uw elektrische auto?

- < 6 maanden
- 6-12 maanden
- 12-24 maanden
- > 24 maanden

Q6 Heeft u een laadpaal op eigen terrein/oprit?

- Ja
- Nee

Q7 Heeft u de mogelijkheid om te laden bij uw werkplek?

- Ja
- Nee

End of Block: EV eigenschappen

Start of Block: Toekomstig EV bezit

Q8 Welk type elektrische auto zou u willen bezitten?

- ○ Volledig elektrisch *(alleen batterij)*
- ○ Plug-in hybride *(batterij + verbrandingsmotor)*
- ○ Hybride *(batterij + verbrandingsmotor)*
- ○ Weet ik niet

Indien bij Q3 of Q8 hybride werd ingevuld:

Dit onderzoek is gericht op de (toekomstige) elektrische rijder met een elektrische auto die aan een laadpaal opgeladen dient te worden. Om deze reden wordt de survey voor u vroegtijdig gestopt. Bedankt voor uw tijd en moeite.

End of Block: Toekomstig EV bezit

Start of Block: Algemene risico

In het volgende gedeelte wil ik u een paar vragen stellen om uw algemene risico profiel in te schatten

Q9 Stelt u voor dat u meespeelt in een loterij. Welke optie heeft uw voorkeur?

- ○ Optie 1: 100% kans om 100 euro te winnen
- ○ Optie 2: 50% kans om 250 euro te winnen

Q10 Stelt u voor dat u meespeelt in een loterij. Welke optie heeft uw voorkeur?

- ◯ Optie 1: 100% kans om 175 euro te winnen
- ◯ Optie 2: 50% kans om 300 euro te winnen

Q11 Stel dat u vertrekt met uw (toekomstige) elektrische auto voor uw dagelijkse reis (bv. woon-werk, woon-studie, vaste vrijetijdsbesteding etc.). Met een volle batterij kunt u **300 km** rijden. Hoe vol wilt u dat uw batterij **minimaal** is?

Vul hieronder uw voorkeur in

	0 10 20 30 40 50 60 70 80 90 100
Batterij niveau in %	

Q12 Wat is de afstand (in km) van uw dagelijkse reis? (bv. woon-werk, woon-studie, vaste vrijetijdsbesteding etc.)

- ◯ < 25 km
- ◯ 25 - 50 km
- ◯ > 50 km

End of Block: Algemene risico

Start of Block: Intro scenario's

Intro3 Deze studie focust zich op de (toekomstige) stedelijke elektrische rijder, die geen privé parkeerplaats heeft (en dus **GEEN privé laadpaal** bezit). Beeldt u zich a.u.b. in dat u in een **stedelijk gebied** woont en een volledig elektrische auto bezit.

In het volgende gedeelte van het experiment gaat u 9 laadscenario's bekijken. Ieder scenario toont verschillende **publieke laadpalen in uw woonwijk** met verschillende tarieven, afstand tot uw huis, en beschikbaarheid. Het is aan u **om de laadpaal te kiezen waar uw voorkeur naar uit gaat.**

Intro4 *Lees de volgende assumpties zorgvuldig. Deze zijn van belang voor het correct kiezen van uw voorkeursscenario.*

Het is een doordeweekse werkdag en u rijdt met uw elektrische auto vanuit uw werk naar huis. U bent bijna thuis en u hoeft niet meer weg vanavond. Het huidige batterijniveau staat boven aan de vraag in %. Deze blijft gelijk bij alle scenario's.

Morgen zal uw totale reis **50 km** zijn, wat bestaat uit de autorit van huis naar werk en weer terug. Het is aan u om te kiezen of u wel of niet vandaag wilt laden en zo ja, bij welke laadpaal. De beschikbare laadpalen zijn **reguliere publieke laadpalen** (11kW).

Eigenschappen laadpaal:

- De laadprijs per kWh
- De afstand van de laadpaal tot uw huis in meters
- De beschikbaarheid van een laadpaal. 100% betekent dat de laadpaal altijd vrij is. Hoe lager dit percentage, hoe groter de kans dat de laadpaal bezet is.

Het is aan **u** om de laadlocatie te selecteren waar uw voorkeur naar uit gaat.

Sommige laadscenario's zijn GEEN correcte afspiegeling van de werkelijkheid. Dit maakt deel uit van het experiment.

End of Block: Intro scenario's

Start of Block: Scenario 1 - 40%

Example choice set

Choiceset 1

Volle batterij = 300 km

Batterij = 40%

- U bent bijna thuis.
- Morgen zal uw totale reis **50 km** zijn.
- Alle opties zijn reguliere laadpalen (11kW).

Klik hier voor herhaling van de gegeven aannames.

Selecteer de laadlocatie van uw voorkeur, als u vandaag wilt laden.

Laadpunt A

Prijs per kWh	0.35
Afstand (in m)	400
Beschikbaarheid	60%

Laadpunt B

Prijs per kWh	0.25
Afstand (in m)	250
Beschikbaarheid	30%

Laadpunt C

Prijs per kWh	0.45
Afstand (in m)	100
Beschikbaarheid	90%

Ik kies ervoor NIET te laden

Choice set 2

○ **Laadpunt A**

Prijs per kWh	0.35
Afstand (in m)	100
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.45
Afstand (in m)	400
Beschikbaarheid	60%

○ **Laadpunt C**

Prijs per kWh	0.25
Afstand (in m)	250
Beschikbaarheid	30%

○ Ik kies ervoor NIET te laden

Choice set 3

○ **Laadpunt A**

Prijs per kWh	0.45
Afstand (in m)	250
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.25
Afstand (in m)	100
Beschikbaarheid	30%

○ **Laadpunt C**

Prijs per kWh	0.35
Afstand (in m)	400
Beschikbaarheid	60%

○ Ik kies ervoor NIET te laden

Choice set 4

○ **Laadpunt A**

Prijs per kWh	0.45
Afstand (in m)	100
Beschikbaarheid	60%

○ **Laadpunt B**

Prijs per kWh	0.25
Afstand (in m)	400
Beschikbaarheid	30%

○ **Laadpunt C**

Prijs per kWh	0.35
Afstand (in m)	250
Beschikbaarheid	90%

○ Ik kies ervoor NIET te laden

Choice set 5

○ **Laadpunt A**

Prijs per kWh	0.25
Afstand (in m)	400
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.45
Afstand (in m)	250
Beschikbaarheid	60%

○ **Laadpunt C**

Prijs per kWh	0.35
Afstand (in m)	100
Beschikbaarheid	30%

○ Ik kies ervoor NIET te laden

Choice set 6

○ **Laadpunt A**

Prijs per kWh	0.25
Afstand (in m)	400
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.35
Afstand (in m)	250
Beschikbaarheid	60%

○ **Laadpunt C**

Prijs per kWh	0.45
Afstand (in m)	100
Beschikbaarheid	30%

○ Ik kies ervoor NIET te laden

Choice set 7

○ **Laadpunt A**

Prijs per kWh	0.45
Afstand (in m)	400
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.35
Afstand (in m)	250
Beschikbaarheid	30%

○ **Laadpunt C**

Prijs per kWh	0.25
Afstand (in m)	100
Beschikbaarheid	60%

○ Ik kies ervoor NIET te laden

Choice set 8

○ **Laadpunt A**

Prijs per kWh	0.25
Afstand (in m)	250
Beschikbaarheid	60%

○ **Laadpunt B**

Prijs per kWh	0.45
Afstand (in m)	100
Beschikbaarheid	30%

○ **Laadpunt C**

Prijs per kWh	0.35
Afstand (in m)	400
Beschikbaarheid	90%

○ Ik kies ervoor NIET te laden

Choice set 9

○ **Laadpunt A**

Prijs per kWh	0.45
Afstand (in m)	250
Beschikbaarheid	90%

○ **Laadpunt B**

Prijs per kWh	0.35
Afstand (in m)	100
Beschikbaarheid	60%

○ **Laadpunt C**

Prijs per kWh	0.25
Afstand (in m)	400
Beschikbaarheid	30%

○ Ik kies ervoor NIET te laden

End of Block: Scenario 2 - 20%

Start of Block: Laadplein

Q14 Hoeveel meter bent u **maximaal** bereid om te lopen naar een publiek laadpunt of laadplein dichtbij uw huis? (100 m = 1 min 10 sec wandelen)

- 100 meter
- 200 meter
- 300 meter
- 400 meter
- 500 meter

End of Block: Laadplein

Start of Block: Demografische gedeelte

Intro5 Dit waren alle laadscenario's. Nu volgen nog een paar demografische vragen.

Q15 Wat is uw leeftijd?

○ 18-30 jaar

○ 31-40 jaar

○ 41-50 jaar

○ 51-60 jaar

○ 61-70 jaar

○ 71-80 jaar

○ > 80 jaar

Q16 Met welk geslacht identificeert u zich?

○ Vrouw

○ Man

○ Gelieve ik niet te zeggen

Q17 Wat is uw hoogst behaalde onderwijsniveau?

○ WO

○ HBO

○ MBO

○ Anders ____

Q18 Wat is uw gemiddeld bruto inkomen?

- ◯ Onder modaal (
- ◯ Modaal (ongeveer 36.500 bruto per jaar)
- ◯ Boven modaal (>36.500 bruto per jaar)
- ◯ Gelieve ik niet te zeggen

Q19 Wat zijn de eerste vier cijfers van uw postcode? *(bv. 1234)*

____

Q20 Indien u de resultaten van dit onderzoek wilt ontvangen, laat dan hier uw e-mailadres achter.

____

End of survey

A.2 Interview questions

1. What is the core business of your organisation in the EV market?
2. What is your organisations strategy?
3. What is your perspective on the current charging infrastructure?
    a. What is positive?
    b. What is negative?
    c. How can it be improved?
4. How do you think the EV infrastructure should look like for urban EV users who do not have a private parking place? (e.g. laadplein, laden op het werk, snelladen)
5. What are your ideas regarding ‘laadpleinen’ and will they play a big role in the future of charging?
6. Which charging option do you think will play a frontrunner role in the future?

A.3 Summary of interviews

A.3.1 Interview with NKL

The Nationaal Kennisplatform Laadinfrastructuur (NKL) is a non-profit organisation formed in 2014. They are focused on gaining and securing knowledge. In addition, they provide their practical knowledge in the form of instruction manuals for local governments. The interviewee believes that the current charging infrastructure is sufficient for the moment. There are enough public charging stations and municipalities are working on creating planning maps for an adequate coverage. On the other hand, there is still a big gap between the CPO and MSPE regarding price transparency and information.

With regard to fast charging, the interviewee does not believe this will be the main mode of charging. There are two reasons for this. It is too expensive, and it takes too much waiting time. However, it is essential as a range extender. Providing an extensive charging infrastructure at work is especially interesting for companies with many electric cars in their vehicle fleet.

Finally, the deployment of charging plazas was discussed. The interviewee suggested this would especially be interesting in combination with mobility hubs and other services like WI-FI points. However, another current development is that parking space is being cut down and this has its consequences for constructing charging plazas. The municipality of Utrecht has the regulation that whenever the occupancy rate becomes higher than 70% for a charging point, a new charging point has to be added. This way, availability never comes below 30%.

A.3.2 Interview with VER

The VER is the Vereniging voor Elektrische Rijders and is a lobby organisation for the EV user. Their goal is to promote the usage of EVs. To achieve this, they sit together with knowledge centres, the government, but also the car manufacturers. The main problem is that the government wants to promote the adoption of EVs, but car manufacturers prefer not to promote it as they have long-term investments in e.g. new ICE vehicles. They prefer the intervention of PHEV instead of focusing straight on the BEV as the PHEV still has a combustion engine. Hence the industry does not have the intention to move as quick as the government would like. One example is Germany, where the consumer could skip the step of PHEV, but still many people buy an PHEV there. While in the Netherlands we first had a few people buying a PHEV, but now all these people tend to buy a BEV. Hence, this step could have been skipped.

The public charging infrastructure plan of municipalities is very different. The bigger municipalities have a real strategy for employing charging stations due to their goal of achieving a cleaner air. That is their incentive. According to the interviewee, they are already doing very well. However, smaller municipalities are not very keen on constructing charging stations. This is not high on their priority list, and therefore the placement can sometimes take up to nine months.

The interviewee was very enthusiastic about charging plazas, especially in newly constructed neighbourhoods. A charging plaza can consist of a square of 4 parking places and one charging station with 2 charging points. This way, not all parking places need a charger and there are enough chargers for everyone to charge. This same principle can be applied at work. People can charge and during lunchtime they can plug-out and someone else can plug their car in.

Considering the fast charging network, the interviewee did not see this as the standard for the future. So fast charging will not play the main role in the future. Charging plazas and charging at work will remain the main ways of charging for urban EV users. According to him, it will be used only when someone has to drive more than the range of the battery for work or a daytrip or when for example going on holiday. He thinks that AC charging will remain the standard charging method most people will use. For the fast charging, it is necessary to have a service at the location, like a restaurant or a cafe. People want to have a coffee or something to eat when waiting for 15/20 min. But when would people charge their car at fast stations? Before going to work probably not, but also not after work when they are going home. The extra services are very important for any fast charging station.

Price of public charging point is now quite higher than private. Of course, for public there are no investment costs for you as a consumer, but still this price should be lower. At work the price of electricity is even lower, as the base energy tariff is 6ct + btw + energy tariffs, but companies do not have to pay many of them. In the end charging there only costs 8ct. So, business users are sometimes told to charge at work instead of charging at home.

A.3.3 Interview with RVO

The Netherlands Enterprise Agency (NEA, in Dutch:RVO) is the executer of the policy on e.g. electric driving and charging infrastructure. They work on the national regulations needed in the EV sector. Their main responsibilities include execution of subsidies, secretary of the National Charging Infrastructure Agenda (Dutch: NAL), facilitating relationships between companies, knowledge platforms and the public sector, updating the database on number of EVs and number + location of charging stations.

According to the interviewee, the charging structure in the Netherlands is well spread with enough total charging points. However, some improvements can still be made regarding price transparency and a well-covered international network. With regard to charging plazas, the interviewee displayed positive thoughts. Especially since these type of charging stations allows for smart charging. Only a bandwidth of 5% is needed to fulfil this network balancing. To the interviewee's opinion, there is a good business case for this in the way that through apps and subscriptions, customers can get discount on their charging session if they allow for a variable charging speed/time. The adoption of these charging plazas is possible even in older more central neighbourhoods. The most important aspect is that space that is taken for these charging plazas, is given back to the inhabitants through green areas, playgrounds, little parks etc. For example, cars can have a diagonal parking space clustered with 4 cars at one charging station with multiple points. This is a form of centralization without the need for a completely new neighbourhood plan with large charging plazas on the side. The construction of these developments can be planned together with other work on pipelines, drains.

Next, regarding fast charging the interviewee does not expect that the price will become much cheaper. Even though, the speed of charging becomes faster, battery capacity becomes larger. In addition, certain costs like location rent remains high especially at their locations next to highways/gas stations. Finally, the energy taxes for private users are going down but for companies they are going up. Charging at work is also a very popular option. Energy taxes are much less for large scale consumers. Therefore, some companies promote their employees to charge at work for a much lower price.

A.3.4 Interview with Stedin

Stedin is the largest network operator of the Netherlands and especially active within the Randstad. The interviewee is employed at Stedin as a product manager within the EV department. In his opinion, the Netherlands is leading the way regarding the charging infrastructure. He does notice differences between municipalities in their way of planning the charging infrastructure. Some municipalities place charging stations based on direct demand while other municipalities place charging stations strategically like the municipality of Den Haag. Stedin sees large advantages in the placement of stronger networks during projects, even when this is not directly necessary. This is because the costs of a stronger network are relatively small in comparison with the costs of setting up a new construction project (soil analysis, project costs etc.). Hence, they advise municipalities to combine the construction of a charging infrastructure with other activities regarding gas or electricity in a neighbourhood. However, a CPO often has less benefit with a stronger connection since the business case is rather bad. Hence, they prefer to choose weaker connections like regular charging points instead of a fast charging plaza'. For a CPO, the break-even point is around 2.000 kWh. In comparison, the energy usage of an average household is 3.500 kWh. Nevertheless, some charging points have a demand of 16.000 kWh. Hence, the differences are large between charging points. The interviewee also told about the so-called charging hierarchy. In the first place is home charging (can be public), second comes charging at work, and on the third spot is public charging. Municipalities are working on psychological influencing people with regard to their charging behaviour.

The development of fast charging is still unpredictable. The interviewee mentioned that gas stations earn their profits on the sales of the shop/restaurant rather than the actual gas they sell. Therefore, they also try to install a charging station at their gas station, but they are rather re-active with it. It is expected that a gas station will become a energy hub with gas / electricity/ hydrogen. Since gas stations receive most of their profit through the restaurants/shops, they can significantly decrease their charging prices so that the price for fast charging even goes below 20ct. This is below the price of public charging. Especially when the eV becomes mainstream, people will keep up with their old behaviour of going to the gas station. When the charging speed goes up and the batteries become larger, this development is expected to push through. In the end, a fast charging culture will be viable, but to come to this point other tools are needed like regular public charging and charging at work.

Charging at work is also an interesting business case. At this moment, employers offer their employees charging to increase their social return on investment. This is purely good imaging. It would be interesting to see when employers make it obligatory for lease cars to charge at work since this is cheaper. This reduction in price can be accomplished through negotiations with the CPO.

A.3.5 Interview with Ecotap

Ecotap is a manufacturer of charging stations with stations installed in 14 countries in Europe, but especially present in the Netherlands and in Germany. They manufacture both AC and DC charging stations and even wireless charging stations.

When asking the interviewee about the current charging infrastructure, the interviewee thinks the current charging infrastructure is adequate enough. However, the differences between regions is extremely large. According to the interviewee, the charging infrastructure is very good in cities like The Hague and Tilburg, but poorly in Groningen and Friesland. Naturally, the adoption of EV's is lower in these regions, which plays a role in this as well. For the future charging infrastructure, the interviewee thinks that charging plazas can play a role in neighbourhoods, but the charging plaza's will only employ a couple of charging points. For a CPO it is financially not beneficial to install a heavy connection in a neighbourhood where the overall energy consumption is very low. A CPO will always stay below an 80 A connection. This is much more interesting to do at a location where energy consumption is high like a supermarket, a restaurant chain, an IKEA. Here the grid connection is already powerful and installing a charging plaza makes more sense. Especially, for fast charging these locations are interesting as people only stay there for a short amount of time. According to the interviewee, the grid operator prefers this option as well. The interviewee does not see a grand future for fast charging at gas stations for the simple reason that the energy consumption is low there at the moment. Improving these grid connections is very expensive and it is not expected to be beneficial when other locations offer fast charging as well (e.g. McDonalds/other restaurants).

Charging at work will be very promising, according to the interviewee, due to multiple reasons. First of all, regular charging is okay for charging at work since people stay longer at this location. This decreases the costs per charging station. Secondly, the employer can ask his employees to charge frequently at work which makes the business case for that type of charging station better. Thirdly, the energy consumption at a big office is already high which makes the extra connection costs doable.

The interviewee considers ease of use as the most important determinant for charging at a certain location. Price will play a role as well but is not the first determinant.

Appendix B – Data & analysis

B.1 Descriptive characteristics of risk aversion

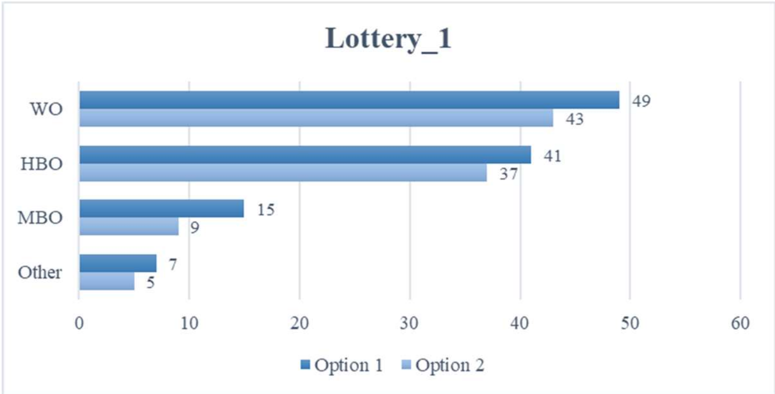

Figure B1: Results lottery 1 distributed across education level

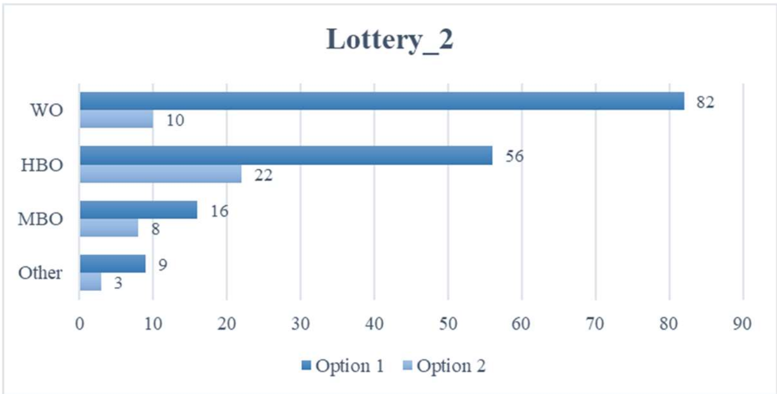

Figure B2: Results lottery 2 distributed across education level

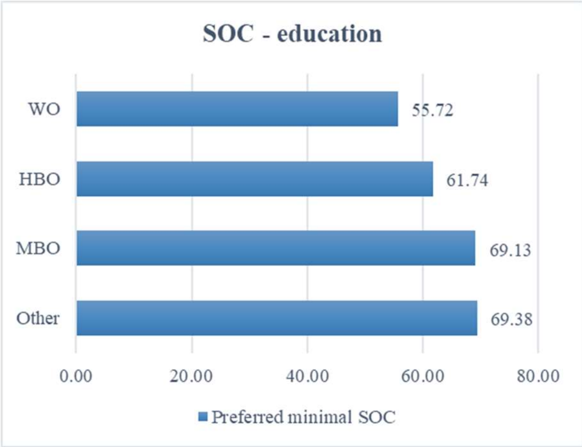

Figure B3: Results preferred minimal SOC across education level

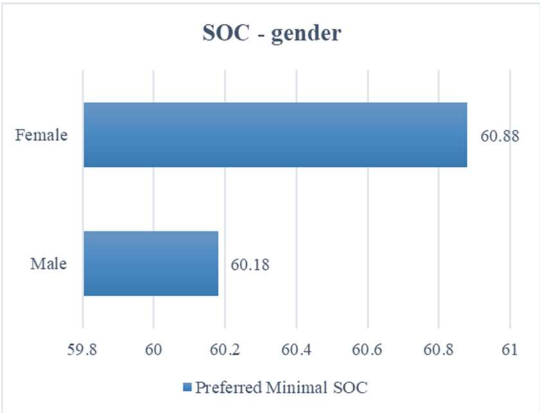

Figure B4: Results preferred minimal SOC across gender

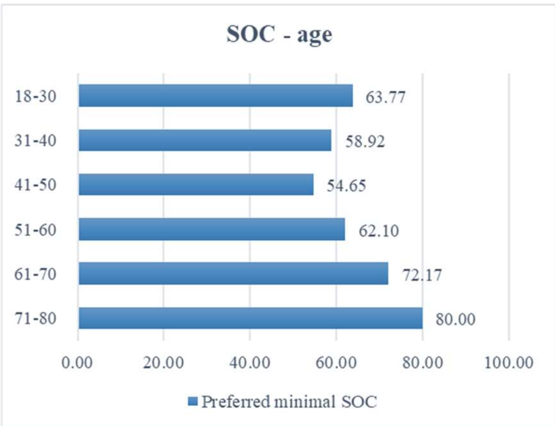

Figure B5: Results preferred minimal SOC across age

B.2 Choice-set characteristics

Table B1 - Tabulation of possible choice-sets

Tabulation of choice-set possibilities

Choice set	Freq.	Percent	Cum.
1 2 3 4	1,854	100.00	100.00
Total	1,854	100.00	

Total is number of cases.

Table B2 - Tabulation of all observations

Tabulation of choice-set possibilities

Choice set	Freq.	Percent	Cum.
1 2 3 4	7,416	100.00	100.00
Total	7,416	100.00	

Total is number of observations.

Table B3 - Tabulation of chosen alternatives

Tabulation of chosen alternatives (**choice = 1**)

alt	Freq.	Percent	Cum.
1	608	32.79	32.79
2	350	18.88	51.67
3	522	28.16	79.83
4	374	20.17	100.00
Total	1,854	100.00	

B.3 Hausman-McFadden test

Table B4 - Hausman-McFadden test for dropping alternative 1

	Coefficients (b) .	(B) full	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
price	-.9130648	-.9821494	.0690846	.0630507
distance	-.707325	-.6714826	-.0358424	.0400454
availability	.6722092	.7289652	-.056756	.0540122
asc	-.7310328	-.1298555	-.6011773	.2372398

b = consistent under Ho and Ha; obtained from cmclogit
B = inconsistent under Ha, efficient under Ho; obtained from cmclogit

Test: Ho: difference in coefficients not systematic

chi2(4) = (b-B)'[(V_b-V_B)^(-1)](b-B)
= 9.91
Prob>chi2 = 0.0420

Table B5 - Hausman-McFadden test for dropping alternative 2

	Coefficients (b) .	(B) full	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
price	-.9683401	-.9821494	.0138093	.0420952
distance	-.614764	-.6714826	.0567186	.0342168
availability	.6681639	.7289652	-.0608013	.0247368
asc	.4301703	-.1298555	.5600258	.2457025

b = consistent under Ho and Ha; obtained from cmclogit
B = inconsistent under Ha, efficient under Ho; obtained from cmclogit

Test: Ho: difference in coefficients not systematic

chi2(4) = (b-B)'[(V_b-V_B)^(-1)](b-B)
= 15.01
Prob>chi2 = 0.0047

Table B6 - Hausman-McFadden test for dropping alternative 3

	Coefficients (b) .	(B) full	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
price	-.975436	-.9821494	.0067134	.0416577
distance	-.771431	-.6714826	-.0999484	.0636976
availability	.8247253	.7289652	.0957601	.131543
asc	.2882652	-.1298555	.4181207	.358468

b = consistent under Ho and Ha; obtained from cmclogit
B = inconsistent under Ha, efficient under Ho; obtained from cmclogit

Test: Ho: difference in coefficients not systematic

chi2(4) = (b-B)'[(V_b-V_B)^(-1)](b-B)
= 5.79
Prob>chi2 = 0.2155

Appendix C – Business Case

C.1 Business case of a regular charging station

Break-even analysis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Totaal investeringskosten	5873.889	0	0	0	0	0	0	0	0	0
Totaal periodieke kosten	531	531	531	531	531	531	531	531	531	531
Totaal variabele kosten	869	912	958	1006	1056	1109	1164	1222	1283	1348
Totaal kosten	7273	1443	1488	1536	1587	1639	1695	1753	1814	1878
Totaal inkomsten	1277.5	1341.375	1408.444	1478.866	1552.809	1630.45	1711.972	1797.571	1887.449	1981.822
Totaal inkomsten - cumulatief	1278	2619	4027	5506	7059	8689	10401	12199	14086	16068
Totaal kosten - cumulatief	7273	8716	10204	11741	13327	14966	16661	18414	20228	22106

Scenario analysis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Totaal investeringskosten	5873.889	0	0	0	0	0	0	0	0	0
Totaal periodieke kosten	531	531	531	531	531	531	531	531	531	531
Totaal variabele kosten	869	912	958	1006	1056	1109	1164	1222	1283	1348
Totaal winst - scenario 3	-6131	236	777	843	911	983	1059	1139	1222	1310
Totaal winst - scenario 2	-5820	83	113	145	179	215	252	805	872	942
Totaal winst - basis	-5996	-101	-80	-57	-34	-9	17	45	73	104
Cumulatief										
Totaal winst - scenario 3	-6131	-5895	-5118	-4275	-3364	-2380	-1321	-183	1039	2349
Totaal winst - scenario 2	-5820	-5738	-5625	-5479	-5300	-5085	-4833	-4028	-3157	-2215
Totaal winst - basis	-5996	-6097	-6177	-6234	-6268	-6277	-6260	-6215	-6142	-6038

C.2 Business case of a charging plaza vs. five charging stations

Break-even analysis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Laadplein										
Totaal investeringskosten	22056	0	0	0	0	0	0	0	0	0
Totaal periodieke kosten	2758	2758	2758	2758	2758	2758	2758	2758	2758	2758
Totaal variabele kosten	3066	3219	3380	3549	3727	3913	4109	4314	4530	4756
Totaal kosten	27880	5977	6138	6307	6485	6671	6867	7072	7288	7514
Totaal inkomsten	6388	6707	7042	7394	7764	8152	8560	8988	9437	9909
Totaal winst	**-21492**	**730**	**904**	**1087**	**1279**	**1481**	**1693**	**1916**	**2149**	**2395**
Totaal kosten - cumulatief	27880	33857	39995	46303	52787	59458	66325	73397	80685	88200
Totaal inkomsten - cumulatief	6388	13094	20137	27531	35295	43447	52007	60995	70432	80341
Totaal winst- cumulatief	**-21492**	**-20763**	**-19859**	**-18772**	**-17492**	**-16011**	**-14318**	**-12402**	**-10253**	**-7858**

Break-even analysis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
5 laadpalen										
Totaal investeringskosten	28256	0	0	0	0	0	0	0	0	0
Totaal periodieke kosten	2660	2660	2660	2660	2660	2660	2660	2660	2660	2660
Totaal variabele kosten	4344	4561	4789	5028	5280	5544	5821	6112	6417	6738
Totaal kosten	35259	7221	7449	7688	7940	8204	8481	8772	9077	9398
Totaal inkomsten	6388	6707	7042	7394	7764	8152	8560	8988	9437	9909
Totaal winst	-28872	-514	-406	-294	-176	-51	79	216	360	511
Totaal kosten - cumulatief	35259	42480	49928	57617	65556	73760	82240	91012	100089	109488
Totaal inkomsten - cumulatief	6388	13094	20137	27531	35295	43447	52007	60995	70432	80341
Totaal winst - cumulatief	**-28872**	**-29385**	**-29792**	**-30086**	**-30261**	**-30312**	**-30233**	**-30017**	**-29657**	**-29146**

C.3 Business case of a charging plaza with aggravation

Break-even analysis	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Laadplein										
Totaal investeringskosten	21601	0	0	10104	0	0	7270	0	0	0
Totaal periodieke kosten	2758	2758	2758	2744	2744	2744	3440	3440	3440	3440
Totaal variabele kosten	4380	4599	4829	5679	5963	6261	8217	8628	9060	9513
Totaal inkomsten	9125	9581	10060	16901	17746	18634	24457	25680	26964	28312
Totaal kosten	28739	7357	7587	18526	8707	9005	18927	12068	12500	12953
Totaal winst	**-19614**	**2224**	**2473**	**-1625**	**9040**	**9629**	**5530**	**13611**	**14464**	**15359**
Totaal inkomsten - cumulatief	9125	18706	28767	45668	63414	82048	106505	132184	159148	187460
Totaal kosten - cumulatief	28739	36096	43683	62209	70916	79920	98847	110916	123415	136368
Totaal winst- cumulatief	**-19614**	**-17390**	**-14916**	**-16541**	**-7501**	**2128**	**7657**	**21269**	**35733**	**51092**

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