Dynamics of Charging
Scaling up public charging infrastructure in uncertain times

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Dissertation

for the purpose of obtaining the degree of doctor at Delft University of Technology by the authority of the Rector Magnificus, Prof. dr. ir. T.H.J.J. van der Hagen, chair of the Board of Doctorates to be defended publicly on tuesday, 21st of January 2025 at 12:30.

by

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DYNAMICS OF CHARGING

SCALING UP PUBLIC CHARGING INFRASTRUCTURE IN UNCERTAIN TIMES

Proefschrift

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft, op gezag van de Rector Magnificus prof. Magnificus, Prof. dr. ir. T.H.J.J. van der Hagen, voorzitter van het College voor Promoties, in het openbaar te verdedigen op dinsdag 21 januari 2025 om 12:30.

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Samenvatting

Elektrische voertuigen (EVs) worden steeds meer gebruikt in Nederland. Er is een opschaling van de openbare laadinfrastructuur nodig om te kunnen voldoen aan de toekomstige laadvraag. Dit is een uitdaging voor beleidsmakers en andere belanghebbenden, omdat er nog steeds veel onzekerheden zijn rondom mobiliteit en de acceptatie van EVs. Het doel van dit onderzoek is om manieren te identificeren om de openbare EV-laadinfrastructuur in woongebieden op te schalen. Het onderzoek houdt rekening met verschillende perspectieven en uitdagingen rondom de EV-transitie, zoals mobiliteitsbeleid, laadgedrag, energie-infrastructuur en toegankelijkheid van de laadinfrastructuur. De hoofdvraag van dit proefschrift luidt:

"Hoe kan de openbare EV-laadinfrastructuur in woongebieden worden opgeschaald?"

Het proefschrift bevat vijf hoofdstukken om deze vraag te beantwoorden. Vier van deze hoofdstukken bevatten studies die zijn gepubliceerd in wetenschappelijke tijdschriften en congresverslagen. De aanpak bestaat uit literatuurstudies, data-analyse, beleidsanalyse, multiple-criteria analyse en agent-based modeling. De afzonderlijke studies dragen allemaal bij aan het begrijpen van verschillende onderdelen van het laadsysteem. De volgende paragrafen vatten elk van de vijf studies samen.

Hoofdstuk 3 beantwoord de vraag *"In welke mate zijn mobiliteitsbeleidsmaatregelen gericht op (de transitie naar) elektrische voertuigen?"*. Dit hoofdstuk bevat een literatuurstudie en beleidsanalyse, waarin mobiliteitsbeleidsdocumenten van twee Nederlandse gemeenten zijn geanalyseerd en vergeleken. Hier wordt uitgelegd welke mobiliteitsbeleidsactiviteiten er gepland zijn in deze gemeenten, welk type beleidsinstrumenten daarbij ingezet worden, op welke gebruikersgroepen het beleid van toepassing is, en hoe het beleid bijdraagt aan het elektrificeren van mobiliteit of aan modal shift. Het onderzoek richt zich ook op de effecten van dit beleid op verschillende indicatoren zoals lokale emissies (luchtkwaliteit), bezettingsgraden van laadpalen, autobezit en de elektriciteitsvraag. De resultaten laten zien dat er veel mobiliteitsbeleidsdocumenten zijn waarin beleidsmaatregelen voor EVs voorkomen. Een aanzienlijk deel van deze beleidsmaatregelen richt zich op de persoonlijke EV-bestuurder. Het onderzoek keek ook of deze beleidsmaatregelen economisch, regulerend of zacht waren. In Amsterdam waren veel van de geïdentificeerde beleidsmaatregelen zacht, terwijl in Den Haag juist veel geïdentificeerde beleidsmaatregelen van regulerende aard waren. De bijdrage van deze beleidsmaatregelen aan de doelen voor modal shift en voertuigelektrificatie wordt gerapporteerd in een tabel en samengevat in een doelenboom. De twee doelen (modal shift en mobiliteitselektrificatie) hebben overeenkomsten in hun subdoelen, hoewel een deel van de subdoelen elkaar juist kan tegenwerken. Deze studie keek ook naar hoe beleidsmaatregelen met toekomstige mobiliteitstrends en nieuwe gebruikersgroepen omgaat. De aanbeveling is dat beleidsmakers meer nadruk moeten leggen op nieuwere technologieën en de specifieke laadbehoeften van verschillende gebruikersgroepen in toekomstig beleid. Daarnaast zou de relatie tussen voertuigelektrificatie en modal shift een grotere rol moeten spelen in het uitwerken van toekomstig mobiliteitsbeleid.

Het is ook belangrijk om de impact van beleidsinterventies op laadgedrag te begrijpen. Daarom is een deel van het proefschrift gewijd aan het evalueren van de effecten van verschillende beleidsinterventies. In hoofdstuk 4 wordt de vraag *"Hoe beïnvloeden beleidsinterventies de openbare laadinfrastructuur?"* onderzocht. Dit hoofdstuk heeft als doel inzicht te geven in hoe specifieke beleidsmaatregelen de toegankelijkheid en het gebruik van openbare laadpunten kunnen beïnvloeden. Het hoofdstuk bestaat uit drie verschillende studies die de impact van beleidsinterventies op openbare laadpunten onderzoeken. Hiervoor gebruiken we open data, relevante literatuur en transactiedata van openbare laadpunten. Voor het gemak worden deze drie studies in het hele proefschrift 'casestudies' genoemd. Casestudie 1 richt zich op concurrentievraagstukken in de laadmarkt. Deze studie analyseert het aanbestedingsproces van openbare laadpunten op straat en van snelladers langs de snelweg. Hiervoor werden hoorzittingen, beleidsdocumenten en lokale grijze literatuur gebruikt. Aanbevelingen voor belanghebbenden om snelladen, slim laden en openbare laadpunten op straat te verbeteren zijn ook opgenomen in het hoofdstuk. Casestudie 2 richt zich op de effecten van de COVID-19-lockdowns en andere coronamaatregelen op het gebruik van openbare laadpunten. Deze studie analyseert de effecten van lockdowns en avondklokken op laadgedrag, met behulp van transactiedata van openbare laadpunten. Er wordt besproken in hoeverre verschillende gebruikersgroepen veranderingen in laadgedrag vertoonden. Openbare laadpunten op kantoorlocaties werden minder gebruikt en de laadactiviteiten van taxichauffeurs namen sterk af tijdens de lockdowns. Casestudie 3 analyseert het effect van het elektrificeren van Amsterdamse taxi's op de interstedelijke laadvraag, met behulp van de laadtransactiedata van de metropoolregio Amsterdam. De taxi's hadden buiten hun dienst zichtbare invloed op de laadvraag in omringende gemeenten.

Het begrijpen van de waarden en perspectieven van belanghebbenden is ook belangrijk voor de ontwikkeling van toekomstig laden. In hoofdstuk 5 worden deze belanghebbenden geïnterviewd met gebruik van multiple-criteria analyse. De vraag van dit hoofdstuk is: *"Wat vinden belanghebbenden belangrijk en hoe veranderen deze prioriteiten in de loop van de tijd?"*. Een groep besluitvormers, waaronder lokale en nationale beleidsmakers, evenals de dienstverleners van elektrische mobiliteit (EMSP's), werd gevraagd om aspecten van het laadsysteem te prioriteren. Deze besluitvormers gaven prioriteit aan verschillende indicatoren met betrekking tot het laden van elektrische voertuigen, waarbij de best-worst methode voor multiple-criteria besluitvorming werd toegepast. Een figuur in het hoofdstuk toont de prioriteitstijdlijn die uit deze studie voortkomt. De resultaten voorspellen dat de prioriteiten zullen verschuiven van de adoptie van elektrische voertuigen en de uitrol van infrastructuur naar het beheren van piekvraag, het gebruik van duurzamere laadtechnieken (zoals vehicle-to-grid (V2G)) en het gebruik van duurzame energie. Technologische vooruitgang en autonome laadtechnieken krijgen later in de tijd prioriteit, volgens de geïnterviewde belanghebbenden. Omgevingsindicatoren worden consequent laag gewaardeerd, terwijl (niet-elektrische) mobiliteitsindicatoren verschillend worden gewaardeerd door deelnemers. Beleidsmakers hebben andere prioriteiten dan EMSP's. Slim opladen word consequent hoger gewaardeerd dan andere oplaadtechnieken (zoals V2G of snelladen).

Hoofdstuk 6 bevat een conceptualisering van de besluitvorming bij openbare laadpunten in buurten. Dit hoofdstuk beantwoordt de vraag *"Welke uitrolstrategieën kunnen toegepast worden op buurten?"*. De conceptualisering stelt een manier voor om laadbronnen toe te wijzen, met behulp van de gemeten laadvraag, de voorspelde adoptiepercentages, andere buurtstatistieken en de lokale netcapaciteit. Hoofdstuk 6 bevat ook een beslisboom die de besluitvorming bij het toewijzen van deze laadbronnen illustreert. Hoofdstuk 6 introduceert ook de Amsterdamse wijk die is gebruikt als data-input voor de agent-based simulatie van hoofdstuk 7.

In hoofdstuk 7 is de onderzoeksvraag *"Hoe beïnvloed de uitrolstrategie de laaddynamiek in buurten?"*, onderzocht met een agent-based model. De conceptualisering (voorgesteld in hoofdstuk 6) werd gebruikt om een agent-based model te formaliseren dat de toewijzing van laadbronnen in negen buurten in de gemeente Amsterdam simuleert. Het model onderzoekt de impact van de toewijzing van laadbronnen op het laadgedrag en het functioneren van het laadnetwerk. Drie verschillende uitrolstrategieën voor de toewijzing van openbare laadpunten werden gesimuleerd. Deze strategieën waren:

- Vraag-gestuurde strategie (gebaseerd op de gemeten laadvraag)
- Anticiperende strategie (gebaseerd op groeivoorspellingen)
- Sociaal-economische strategie (gebaseerd op buurtdynamieken en populatiedichtheid)

Een complementaire netstrategie werd toegepast op alle drie de uitrolstrategieën om de elektriciteitsdynamieken mee te nemen. De overloop van laadvraag van de ene buurt naar de andere is ook geanalyseerd, met behulp van twee concurrentie-indicatoren. De eerste concurrentie-indicator is de concurrentie binnen de buurt, wat het aantal keren is dat gebruikers niet in hun eigen buurt konden opladen. De tweede op concurrentie gebaseerde indicator is de concurrentie tussen buurten, wat het aantal keren is dat een buurt een gebruiker uit een andere buurt moest faciliteren. De resultaten zijn als volgt: de vraag-gestuurde strategie leidde tot een hoge accumulatie van laders in veel runs (tot 1/3e van alle laders werd toegewezen aan een enkele buurt). De anticiperende strategie werd gecorreleerd met hogere concurrentie en vertoonde een lage variatie tussen runs. De sociaal-economische strategie leidde tot een bredere verdeling van laadbronnen en werd gecorreleerd met minder concurrentie, zowel binnen de buurt als tussen de buurten. De complementaire netstrategie simuleerde de installatie van een batterij om elektriciteit te bufferen en maakte het mogelijk om de laadstrategie aan te passen op basis van de netcapaciteit. De uitrol van externe batterijen zorgde ervoor dat er geladen kon worden in buurten op tijden waarin de laadvraag de netcapaciteit kon overschrijden. In de netstrategie werden laadsnelheden en laadcapaciteiten ook aangepast op basis van de lokale netcapaciteit. Hierdoor konden buurten met een hogere netcapaciteit de laadsnelheden verhogen in het model, en konden buurten met een lagere netcapaciteit slim laden inzetten.

In dit proefschrift word gekeken naar het opschalen van openbare laadinfrastructuur, met als hoofdvraag: *"Hoe kan de openbare EV-laadinfrastructuur in woongebieden worden opgeschaald?"*. De studies laten zien dat de laadvraag, de concurrentie tussen gebruikers, sociaal-economische indicatoren, indicatoren die de adoptiegraad van EV voorspellen, netinfrastructuur (en capaciteit), en indicatoren die de toegang tot particuliere laadinfrastructuur voorspellen, allemaal een belangrijke rol spelen in het toewijzen van laadinfrastructuur. De studies laten ook zien dat in sommige gebieden een aanzienlijk deel van de laadsessies wordt gestart door andere gebruikers dan de lokale bewoners [1]. Het is belangrijk om de locatie van de laadvraag te begrijpen, die kan verschillen van de gemeten laadlocatie (uit laadtransactiedata). Voor pakketbezorgers en taxichauffeurs die 's nachts in de buurt van hun huis opladen, kunnen adressen uit de database van de Kamer van Koophandel helpen bij het inschatten van de laadvraag, en voor persoonlijke EV-gebruikers kan het reguliere laadpatroon worden gebruikt om de voorkeurslocatie te bepalen. In stadsdelen waar laadpalen niet (veel) beschikbaar zijn, worden EV-autoregistraties al gebruikt bij voorspellingen van de laadvraag. Het type woning kan helpen bepalen of de gebruikers de mogelijkheid hebben om een privélader te installeren. Deze informatie is belangrijk omdat het de toewijzing van nieuwe openbare laadpalen nauwkeuriger kan maken, en het helpt bij het berekenen van het niveau van concurrentie tussen gebruikers binnen- en tussen de buurten. Het minimaliseren van concurrentie door gebruik te maken van concurrentie-gebaseerde indicatoren bij de toewijzing van laadpalen kan mobiliteitsbewegingen (spillovergedrag) verlagen. De simulatie laat ook een mogelijke toepassing zien van bi-directioneel (V2G) laden en een externe batterij, om meer laadsessies te faciliteren en de netvraag meer te verspreiden over de dag heen. Schaarste in het net komt steeds vaker voor, en woongebieden worden steeds afhankelijker van het elektriciteitssysteem. Dit maakt de diversificatie van laadpalen (slimme laadpalen en V2G-laadpalen) en het gebruik van batterijbuffers interessant voor beleidsmakers [2]. Andere hoofdstukken beschrijven ook de relatie tussen openbaar laden en mobiliteitsbeleid. De studies laten zien hoe verschillende beleidsmaatregelen het laadgedrag kunnen beïnvloeden. Dit zijn niet alleen beleidsmaatregelen met betrekking tot het opladen van elektrische voertuigen en de elektrificatie van voertuigen, maar ook andere beleidsmaatregelen met betrekking tot mobiliteit, energie, werk en levensstijl. Deze beleidsmaatregelen hebben invloed op het laadgedrag en op de ontwikkeling van openbare laadpunten. Het beleidslandschap moet in overweging worden genomen bij het voorspellen van het gebruik en de vraag naar laadpunten in een gebied. Beleidsinterventies (bijvoorbeeld de COVID-19-lockdowns uit casestudie 2 van hoofdstuk 4) kunnen namelijk van invloed zijn op de laadvraag, voorkeurslocaties, laadfrequentie, EV-acceptatie en het tijdstip van opladen. Belanghebbenden zullen beleidsontwikkelingen nauwlettend moeten blijven volgen om te kunnen anticiperen op deze veranderingen in laadgedrag.

[1] bijvoorbeeld door commerciële deelauto's of beroepsvervoer

[2] Een ander bijkomend voordeel is dat de technologieën kunnen helpen met het balanceren van vraag-en-aanbod van duurzaam opgewekte energie. Dit is niet onderzocht in het proefschrift.

Toekomstige studies zouden zich kunnen richten op de relatie tussen gedrag, beleid, modal shift, EV-acceptatie en openbaar laden. De toekomst van mobiliteit kent nog steeds onduidelijkheden, en inzichten in de onderliggende relaties kunnen bijdragen bij het anticiperen van lokale laadbehoeften. Een andere potentiële onderzoeksrichting is het verfijnen van uitrolstrategieën vanuit een multi-objective perspectief. Het voldoen aan de laadvraag is slechts een van de doelstellingen in de energietransitie van mobiliteit. Andere doelstellingen, zoals het vergroten van de toegankelijkheid van laders, of het balanceren van de netvraag in buurten, kunnen ook worden meegenomen als overweging bij de uitrol van laadpunten. Daarnaast blijft het belangrijk om onderzoek te blijven doen naar stedelijke transities en hoe verschillende transities, zoals de energietransitie, mobiliteitstransitie en andere transities, burgers en woongebieden beïnvloeden.

SUMMARY

Electric vehicle (EV) adoption in the Netherlands has been increasing, as a response to climate change and urban pollution. A scale up of the public charging infrastructure is required to satisfy the future charging demand. This is a challenge for the policy makers and stakeholders involved, as there are still many uncertainties in EV adoption and mobility. The goal of this research is to identify pathways to scale-up the public EV charging infrastructure in residential areas. The research takes into account various perspectives and challenges related to the EV transition, such as mobility policy, charging behavior, energy infrastructure, and accessibility of the charging infrastructure. The main research question is:

"How can public EV charging infrastructure in residential areas be scaled-up?"

The study contains five chapters to answer this question. Four of these chapters include studies that were published in journals and conference proceedings. The research approach consists of literature studies, data analysis, policy analysis, multiple criteria analysis, and agent-based modeling. The individual studies all contribute to understanding different parts of the charging system. The following paragraphs summarize each of the five studies.

Chapter 3 researches the question *"To what extent are mobility policies relevant to the transition towards electric vehicles?"* This chapter contains a literature study and policy analysis, in which mobility policy documents of two Dutch municipalities were analyzed and compared. The study reports which mobility policy activities are planned, what type of policy instruments are involved, which user groups the policy is addressing, and how the policy contributes to electrifying mobility or modal shift. The study also addresses the effects of these policies on various indicators such as local emissions, occupancy rates of chargers, car ownership, and electricity demand. Results illustrate that there are many mobility policy documents that contain policy measures about the electrification of mobility. A significant share of these policy measures address the personal EV driver. The study also looked at whether these policy measures were economic, regulatory or soft. In Amsterdam, many of the identified policy measures were soft, whereas in The Hague, many identified policy measures were regulatory. The contribution of these policies to modal shift and electrification goals is reported in a table (Table 3.7) and summarized in objective trees (Fig. 3.3 and 3.4). The two goals of modal shift and mobility electrification can share objectives, although some objectives contradict each other. This study also looked at how policies address future trends and user groups. It is recommended for policymakers to emphasize newer technologies, the specific charging needs of different user groups, and the relationship between electrification and modal

shift in future mobility policies.

It is also important to understand the impact of policy interventions on charging behavior. This is why a part of the study is dedicated to evaluate the effects of various policy interventions. In Chapter 4, the question *“How do policy interventions affect public charging infrastructure?”* is investigated. This chapter aims to provide insight into how specific policy measures can influence the accessibility and use of public charging points. The chapter consists of three different studies that examine the impact of policy interventions on public charging. For this aim, we use open data, relevant literature and charging transaction data. For convenience, these three studies are referred to as "case studies" troughout the dissertation. Case study 1 is focused on the challenges in competition from a charging market perspective. This study analyses the procurement process of public on-street charging and highway fast chargers, using court hearings, policy documents, and local grey literature. Recommendations for stakeholders to improve fast charging, smart charging and public on-street charging are also included. Case study 2 is focused on the effects of COVID-19 lockdowns and mandates on the use of public chargers. This study analyzes the effects of lockdowns and curfews on charging behavior, using charging transaction data. The extent to which various user groups exhibited changes in charging behavior is discussed. Public chargers at office locations were used less, and the charging activities of cab driver decreased steeply, during the lockdowns. Case study 3 analyses the effect of electrifying Amsterdam-based cab drivers on the inter-urban charging demand, using the charging transaction data of the metropole region. The cab drivers had an impact on the overnight public on-street charging demand in other municipalities, this is where their off-shift charging took place.

Understanding the values and perspectives of stakeholders is also important for the development of future charging. In Chapter 5, these stakeholders are studied using multiple criteria analysis. The question of this chapter is *“What do stakeholders find important, and how do these prioritizations change over time?”*. Stakeholders are interviewed to identify their priorities in public charging. A group of decision makers, including local and national policymakers, as well as the service providers of electric mobility (EMSPs), were asked to prioritize aspects of the charging system. These decision-makers prioritized different indicators related EV charging, using the best-worst method for multiple criteria decision making. Fig. 5.5 shows the priority timeline that resulted from this study. The results predict that priorities will shift from EV adoption and roll-out of infrastructure to managing peak demand, using more sustainable charging techniques (such as V2G), and using sustainable energy. Technological advancements and autonomous charging techniques are prioritized later in time. Environmental indicators were consistently valued low, whereas mobility indicators were valued differently across participants. Policymakers prioritized differently than EMSPs. Smart charging was consistently valued higher than other charging techniques.

The previously mentioned chapters helped identify issues, challenges and perspectives in future charging. Chapter 6 contains a conceptualization of the decision-making in public charging in neighborhoods, taking into account these findings. This chapter answers the question *"Which roll-out strategies apply to neighborhoods?"* The conceptualization proposes a way to allocate charging resources, using charging demand, predicted adoption rates, neighborhood statistics, and grid capacity. Figure 6.1 is a decision tree which illustrates the decision-making in charging and in allocating charging resources. Chapter 6 also proposes a case study environment for the simulation model (discussed in Chapter 7).

In Chapter 7, the research question *"How do roll-out strategies affect charging dynamics in neighborhoods?"* is investigated through simulations. The conceptualization (proposed in Chapter 6) is used to formalize an agent-based model that simulates the allocation of charging resources in nine neighborhoods in the municipality of Amsterdam. The model investigates the impact of charging resource allocation on charging behaviors and performance of the charging network. Three different prioritization strategies for the allocation of public chargers were simulated. These strategies were:

- Demand-based strategy (based on observations of charging)
- Anticipatory strategy (based on growth predictions)
- Socio-economic strategy (based on neighborhood dynamics)

A complementary grid strategy was applied to each of the three prioritization strategies to ensure charging under various grid circumstances. The spillover of charging demand from one neighborhood to another is also analyzed, using two competition indicators. The first competition indicator is within-neighborhood competition, which is the number of times the users could not charge in their own neighborhood. The second competition-based indicator is the between-neighborhood competition, which is the number of times a neighborhood had to facilitate a user from another neighborhood. The results are as follows: The demand-based strategy led to a high accumulation of chargers in many runs (up to 1/3rd of all chargers being allocated in one neighborhood). The anticipatory strategy was correlated with higher competition and showed low variety between runs. The socio-economic strategy led to a more widespread distribution of charging resources and was correlated with less within-neighborhood and between-neighborhood competition. The complementary grid strategy simulated the installment of a battery to buffer electricity, and made it possible to adjust charging compositions based on the grid capacity. The roll-out of external batteries helped facilitate charging sessions at neighborhoods where charging demand could exceed the reserved grid capacity. In the grid strategy, charging speeds and capabilities were also adjusted based on the grid capacity of the neighborhood. This enabled neighborhoods with higher grid capacity to increase charging speeds, and neighborhoods with lower grid capacity to employ smart chargers. The socio-economic roll-out strategy, which used spillover indicators and the number of chargers available per household to determine the allocation of chargers, led to a more widespread distribution of charging resources and was correlated with less within-neighborhood and between-neighborhood competition. The roll-out strategy that used charging demand and occupancy rates to determine the allocation of chargers led to a high accumulation of chargers in many runs (up to 1/3rd of all chargers being allocated in one neighborhood).

This dissertation looked at scaling up public charging infrastructure, with the main question *"How can public EV charging infrastructure in residential areas be scaled up?"*.
The studies reveal that the charging demand, spillover of charging demand, socio-economic indicators, indicators that predict EV adoption rates, grid dynamics, and indicators that predict the access to private charging infrastructure should be taken into account when allocating charging infrastructure. The studies also reveal that in some areas, a significant portion of charging sessions are started by other users than local residents [3]. It is important to understand the location of charging demand, which may differ from the measured charging location. For package deliverers and cab drivers who charge near their homes at night, addresses from the chamber of commerce database could help estimate the demand, and for personal EV users, the regular charging pattern can be used to determine the preferred charging location. In districts where chargers are not widely available, EV car registrations are already used in predictions of charging demand, and assessing the housing type can help determine if the users have opportunity for private charging. This information is important because it can make allocation of new public chargers more precise, and it helps to calculate the level of within-neighborhood and between-neighborhood competition for public charging resources. Minimizing competition by using competition-based indicators in the allocation of chargers can reduce mobility movements (spillover behavior). The simulation also illustrates the application of bidirectional charging and an external battery, to help facilitate charging sessions and mitigate grid demand. Grid scarcity is becoming more prevalent and residential areas are becoming more dependent on the electricity system. This makes the diversification of chargers (smart chargers and V2G chargers) and the use of battery buffers more relevant for the near future [4]. The study also revealed the relationship between public charging and policy. The studies illustrate how various policies affect charging behavior. These are not only policies related to EV charging and the electrification of vehicles, but also include other policies related to mobility, working and lifestyle. These policies have an impact on public charging development and public charging behavior. The policy landscape should be taken into account when trying to predict the use and demand of chargers in an area. Policy interventions (e.g., the COVID-19 lockdowns from case study 2) can affect charging demand, preferred charging locations, charging frequency, EV adoption and the time of charging. Stakeholders should assess policy developments regularly to anticipate on the changes in charging behavior that may take place under these policy interventions.

Future work could focus on further revealing the relationship between behavior, modal shift, EV adoption and public charging. The future of mobility is still filled with uncertainty, and understanding the underlying relationships can help in estimating the effect

[3] e.g., professional traffic, shared vehicles, visitors, workplace charging
[4] Another potential benefit of these technologies is that they can help match the supply of renewable electricity with the charging demand. This was not researched in this dissertation.

of future policies and future mobility trends on the charging network. Another potential research direction is refining roll-out strategies from a multi-objective perspective. Satisfying charging demand is only one of the objectives, and other objectives, such as increasing accessibility of chargers, or managing neighborhood grid demand, could be applied to the roll-out of chargers as well. It is also important to continue researching urban transitions, and how different transitions such as the energy transition, mobility transition and other transitions affect citizens and environment in residential areas.

LIST OF ABBREVIATIONS

ABM Agent based Models
AC Alternative Current
AV Autonomous Vehicle
BEV Battery Electric Vehicle
BWM Best-Worst Method
CBS Central Bureau of Statistics
CPO Charging Point Operator
DC Direct Current
DSO Distribution System Operator
EMSP Electric Mobility Service Provider
EV Electric Vehicle
G4 municipalities Four largest municipalities [5]
GIS Geo-information system
ICE Internal Combustion Engine
MCA Multiple Criteria Analysis
MCDM Multiple Criteria Decision Making
MRA Metropole region of Amsterdam
MRA-E Facilitator of electric charging in the MRA
MRDH Metropole region of Rotterdam & The Hague
NAL National Agenda of Charging Infrastructure
NKL National Knowledge Platform of Charging Infrastructure
OCPP Open Charge Point Protocol [6]
OEM Original Equipment Manufacturer
PHEV Plug in Hybrid Electric Vehicle
RFID Radio frequency identifier
RVO/NEA Netherlands Enterprise Agency
TSO Transmission System Operator
V2G Vehicle-to-grid
V2X Vehicle-to-everything

[5] In the Netherlands, there are four municipalities that have over 250.000 inhabitants. These municipalities are Amsterdam, Rotterdam, Utrecht and The Hague.
[6] Read more: https://openchargealliance.org/protocols/open-charge-point-protocol/

PREFACE

A dissertation is written by one, but supported by many. I would like to express my sincerest gratitude to all of those who supported me on my journey.

First, I would like to thank my promotors and supervisors. Emile, thank you so much for being my support, and making me feel like I could say or ask anything. I always left your office feeling more positive and hopeful, even in difficult times. Any PhD candidate is lucky to be supervised by you. Renée, you somehow always knew when to be my supervisor, colleague, or friend. I enjoyed our times overseas and always looked forward to your practical feedback, helping me to articulate myself better. You are a great supervisor and lector, and I can't wait to see where you will take the lectorate next. Zofia, thank you for being a role model, and for your wisdom and warm guidance. Also, thank you for motivating me to become a more confident and independent person. This is a lesson I will never forget.

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Mylène van der Koogh
Ede, July 2024

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Introduction

1.1. BACKGROUND

We need to steeply reduce the use of fossil fuels, to stay within planetary boundaries and ensure a livable planet for biodiversity and future generations. Mobility currently contributes significantly to the use of fossil fuels. The combustion of these fuels also creates harmful local emissions in densely populated areas. Mobility is responsible for almost a quarter of global emissions (Jaramillo et al., 2022), and the sector relies for 91% on oil products (IEA, 2023). Large cities across the globe have already measured dangerous levels of harmful compounds related to mobility emissions (Municipality of Amsterdam, 2019; Lyu et al., 2020; Paul and Bari, 2022). The mobility system needs to change altogether to reduce further harm to the ecosystem, and to reduce the contributions of mobility on global warming. This is why mobility is one of the four pillars in our energy and climate agreements for a climate neutral future. One of the important transitions is to make mobility independent from fossil fuels. Clean transmissions reduce harmful effects on the local air quality, and renewable energy, such as electricity generated from solar panels, can be used to charge the vehicles instead.

The transition towards an electric mobility system requires an infrastructural change from traditional petrol stations to charging points. Energy provision historically relies for a large part on gas and oil. This makes the transition to a full electric system challenging. The electricity grid is not designed for the increase in demand that is associated with this transition. This increase in demand ultimately leads to grid congestion in Europe (Hadush and Meeus, 2018), and has already led to grid congestion issues, for example in Sweden (Palm, 2021), Germany (German National Academy of Sciences Leopoldina et al., 2021) and the Netherlands (Liander, 2022a; Liander, 2022b). This is not surprising, given the fact that electrification is also a prominent solution to reduce the climate impact of other household activities, such as cooking and heating. Grid expansions are costly, disruptive and time-intensive (Liander, 2022b). EV charging infrastructure can be adapted to fit this challenge. For example, by making adjustments in charging speed, and in some cases, the EV car battery could be used as a battery buffer, and discharge into the electricity grid (V2G).

There are also still uncertainties in the exploitation of public charging. The charging market is not very profitable yet for commercial stakeholders, compared to the petrol market. Fast chargers need larger grid connections, and these connections require high investment costs. Agreements between CPOs, EMSPs and urban planners differ in length, which sometimes reduces the pay-back time of investments, and there are still uncertainties in EV adoption which affects the profitability. Rural areas with lower EV adoption and longer (smaller) grid cables are less interesting and more risky for charging investments. Commercial roll-out of charging based on business-case opportunities has already led to geographical differences in access to charging (Hardman et al., 2021). The charging market has prioritized developing charging infrastructure in areas where early adopters reside. This is why charging opportunities are currently better in areas with a higher average income (Hopkins et al., 2023). Municipalities and provinces need to ensure the development of public charging in areas with other demographics, as well. This is because future sustainability goals call for a higher adoption rate, which will include these other demographic groups. The installment of charging points is a good motivator for new adoption (Mersky et al., 2016). Therefore, the visibility of charging infrastructure could improve adoption and lead to improved charging opportunities for consumers across the country.

ROLL-OUT OF EV CHARGING INFRASTRUCTURE

The roll-out of charging infrastructure is capital intensive by its initial costs, and can be a challenging part of urban planning (Burnham et al., 2017). Cities primarily approach charging infrastructure expansions by using different roll-out strategies. During the initial roll-out, charging facilities are offered at highly visible locations to anticipate the first stages of adoptions (Schroeder and Traber, 2012). In demand-driven roll-out, resident input (usually collected through government portals with voting systems), request forms or empirical data (e.g. charging data) are considered. Lastly, there is strategic roll-out, in which the urban planning, such as parking infrastructure and surrounding facilities are considered in selecting infrastructure expansion locations (Helmus et al., 2018).

PROCUREMENT AND ALLOCATION OF PUBLIC EV CHARGING INFRASTRUCTURE IN THE NETHERLANDS

In the Dutch urban public charge case, some strategies have been used in the roll-out of charging infrastructure which roughly started around 2015. These strategies include strategic as well as demand-based placement. Historically, subsidies have been made available for municipalities to enable charging (RVO, 2015). Various municipalities have piloted with voting systems in interactive maps to include citizens in location decisions of charge points. Larger municipalities tend to work with yearly exclusive concessions. The accredited commercial stakeholders then select new charging locations: these can include strategic as well as demand-based aspects. Smaller municipalities may invest in infrastructure themselves, ask citizens who drive EVs to request a charge point using an online portal, or cooperate through regional concessions. The procurement of charging infrastructure has been criticized by commercial stakeholders in the Netherlands. Representatives of electric transport warn that the concession model is too risky for charging market parties: the price ceilings that municipalities communicate are low and static, whereas the profitability for charging point operators (CPOs) and charging service providers (EMSPs) differs across cases. Also, the offered price on charging services weighs too much in granting licenses, whereas there should be more emphasis on technical performance, customer service, and innovation, according to these representatives (Stichting Doet, 2021). Roll-out and funding strategies enabled the Dutch charging market to grow, but the development of this market differs across the country. Rural areas are more difficult to develop, and there are a few reasons for this. The adoption rates in rural areas are lower than in urban areas. Houses are more likely to include driveways, which allows for private charging infrastructure. This enables them to use excess energy from their own solar panels, if they own any. In the largest municipalities, almost half of all charging is public on-street charging, as opposed to only roughly 12% of northern (more rural) provinces (RVO, 2021a; RVO, 2021b Vereniging Nederlandse Autoleasemaatschappijen, 2021). The expectation is that public charging in rural areas will become more important over time, because of the future policy demands related to electrification. These demands will likely diversify the EV driver group, which currently consists mainly of male, high-educated, high-income lease drivers (Hardman et al., 2021; Hoekstra and Refa, 2017; Koopman, 2023; RVO, 2021b; Vereniging Nederlandse Autoleasemaatschappijen, 2021). Therefore, it is important to further study how future charging needs could differ from the charging behavior patterns that are currently observed.

WHAT DRIVES PUBLIC EV CHARGING DEMAND?

Public charging demand for electric vehicles is influenced by many aspects. A direct influence is the adoption rate of electric vehicles and the lack of private infrastructure. Other aspects that play an important role, include the charging behavior of the EV user, the distribution and composition of chargers, nearby facilities, and policy interventions. Their influence is discussed below:

- *Charging behavior:* The time, place, demand size and frequency of using charging points plays a large role in determining the demand for charging. For example, the demand for charging points could be up to five times lower, if only drivers would start charging at lower state-of-charge rates (Mashhoodi and van der Blij, 2021). The size of the battery in the EV also affects the session length and frequency (Wolbertus, R., van den Hoed, R., 2020), and charging point hogging could lead to longer wait times in areas with higher parking pressure.

- *Chargepoint distribution:* The focus on early adopters and profitability in roll-out strategies could lead to differences in charging opportunities between lower and higher income areas (Hardman et al., 2021; Hopkins et al., 2023; Xylia and Joshi, 2022).

- *Charging point technology:* Various components (e.g., charging speed and power) of the charging point itself can influence the speed and convenience of charging.

- *Facilities:* Facilities in the nearby area contribute to the demand for a potential charging location (Koopman, 2023). This facility-based demand is affected by the type of vehicle (shared, personal), type of amenity, and the time of charging (Dokka et al., 2022). This demand can be explained by user convenience (combining charging with errands), and by the fact that charging in these areas is more likely to be developed by strategic roll-out.

- *Chicken-or-egg dilemma:* Observing accessible infrastructure and neighbors with an electric vehicle, are motivators for people to adopt an electric vehicle (Mersky et al., 2016). This means that charging infrastructure could influence adoption rates. There are trade-offs in delaying infrastructure until adoption rates are high enough. For example, inadequate public charging opportunities could pose a barrier for car users to adopt an EV. This is also described in literature as the chicken-or-egg problem.

- *Policy interventions:* Mobility and electrification policies also affect the use of charging points. For example, the subsidization of electric vehicle purchases, (Sierzchula et al., 2014; Yang et al., 2019), and providing EV privileges such as free parking in cities (Langbroek et al., 2016) could improve adoption rates.

- *Constraints:* There are also other potential influences, such as the price to charge and grid and budget constraints. Grid constraints are discussed as a seperate issue (related to the energy system) and the price of charging is out of scope for the dissertation.

Stakeholders and the charging ecosystem

The *charging ecosystem* is a complex network of stakeholders, technologies, infrastructure, and the interactions that take place between them. This ecosystem connects to other systems such as the energy system, mobility system, markets, supply chains and human behavior. There are many relevant stakeholders and institutions in the charging ecosystem. The most important stakeholders for public on-street charging include:

- *Charging Point Operator (CPO):* The charging point operator operates the charging infrastructure from a technical point of view, and connects the customer with the electric mobility service provider (EMSP). In many cases they are also responsible for the hardware and installation of chargers. This dissertation makes recommendations that are relevant for the CPO.
- *Electric Mobility Service Provider (EMSP):* The service provider sells the charging service to the customer. The service provider is included as a stakeholder in the dissertation.
- *Mixed actors:* Some market parties have more than one role, for example, electricity providers who also operate charging points and/or sell mobility services.
- *Distribution System Operator (DSO):* This is the operator that is responsible for the electricity distribution, which includes expansions and maintenance. The grid challenges (relevant to the DSO) are included in the simulation part of the dissertation.
- *Policymakers:* Policymakers are decision-makers in public charging. Examples are the policymakers who grant tenders for on-street public chargers, and traffic decision makers who approve locations for charging. Policymakers are included as a stakeholder in this dissertation.
- *EV driver / User:* The EV driver, sometimes referred to as 'user (of the charging point)' is the customer of the charging service. The charging behaviour of the EV driver plays an important role in the data analysis of this dissertation.
- *Electricity Provider:* Sells the electricity to the EMSP who sells it to the customer. The electricity provider is not included in the dissertation.
- *Manufacturers:* There are different manufacturers relevant for the development of public EV charging, for example chargepoint manufacturer, original equipment manufacturers, and car manufacturers. Manufacturers are not included in the dissertation.

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1.2. PROBLEM STATEMENT AND KNOWLEDGE GAP

Roll-out strategies and initial subsidies have led to reasonably well-developed and well-covered public charging opportunities in the more urbanized parts of the Netherlands. Given the importance of scale-up to anticipate future adoption, some growing pains become more apparent. Commercial stakeholders have to strengthen the business case because tax exemptions for electricity use, and subsidies for procurement, have stopped. The DSO warns for limited grid space and wishes to avoid or delay expansions (Liander, 2022b), which also affects the development of public chargers. Interventions to manage charging demand can be disruptive for EV users, and it is unclear who should benefit from these interventions (Nationale Agenda Laadinfrastructuur, 2022). The development of the charging market also knows growing pains in the broader, societal transformation of the mobility system. Many citizens cannot afford EVs yet, which delays adoption. As a consequence, the charging behavior of these demographic groups is not clear yet. The opportunity for private infrastructure is limited to those with enough space around their house, which differs across locations. New charging infrastructure can only be provided within the local grid boundaries. There are also tensions between EV charging and other parts of the mobility transition. For example, upcoming policy goals are related to modal shift, and an important part of modal shift is lowering car ownership. The electrification goal is to adopt emission-free vehicles instead, which will not necessarily lead to a lower number of cars.

Using the current roll-out strategies to scale-up charging may exacerbate the disparities in charging opportunities[1] between residential areas. These disparities are already observed in some cases (Hardman et al., 2021; Hopkins et al., 2023; Xylia and Joshi, 2022). Grid conditions further complicate this challenge, because grid flexibility differs between areas. This makes the development of charging infrastructure more challenging for some areas than others. Policymakers need to improve charging opportunities, while taking into account grid conditions, local policies and spatial differences. The scale up of public charging infrastructure can be considered a *complex socio-technical problem:* it contains future uncertainties, affects different sub-systems, and has behavioral components as well as policy-based and technical components.

This problem can be better understood by improving our knowledge of the underlying interdependencies, which can reduce uncertainty. The roll-out of charging infrastructure is mostly steered by current demand, current grid space, and a positive business case. Scaling up this infrastructure could create issues, many of which are identified in literature already. However, it is unclear how these issues are prioritized by stakeholders, and what is the best way to address them within the charging ecosystem. The issues in charging, as well as the interest of different stakeholders, must be weighed and embedded in future roll-out strategies. This dissertation aims to fill a gap in roll-out strategies by focusing on:

- the known issues, challenges and solutions in charging[2]

[1] the extent to which chargers are available
[2] also exploring the challenges and solutions related to charging policy, stakeholders and the energy system

- the level of importance of the issues in charging
- the underlying systems in charging and their interaction
- how important issues can be embedded in the future roll-out of EV charging infrastructure.

The knowledge gap is addressed using interviews, literature, data analysis, and modeling & simulation techniques.

1.3. AIM AND SCOPE

The aim of this dissertation is to *identify pathways in which charging infrastructure can be scaled up, taking into account issues that emerge from policy changes, literature and stakeholder input*. A socio-technical perspective is applied to the research. Social and behavioral aspects of charging technology are considered in residential applications with technological limitations.

The research utilizes public charging data from Dutch municipalities to understand charging behavior and charging patterns. Policy aspects are also considered, mostly through the municipal lens, although national, regional and European policies are also considered when relevant. The research is also scoped:

- In the case of the energy system, electricity use and peak consumption are considered, but the penetration of renewables and the use of other energy sources in mobility have a limited role in the research.
- The charging and adoption of electric vehicles are considered, as well as some of the technical capabilities of chargers.
- In the policy parts of this research, modal shift trends (mostly related to sharing vehicles) are considered in scope.
- Policy research is mostly geographically scoped, and relevant urban development, such as expansions of mobility and energy infrastructure, is considered as well.
- The behavior of charging is mostly evaluated through transactional data in the geographical scope of a public charging point dataset.
- The beliefs and motivations of the EV owner that lead to this behavior cannot be determined using this type of data.
- The dataset includes larger and smaller municipalities, but is not a complete dataset of all public charging that takes place in the Netherlands.
- Semi-public charging in garages, highway charging, non-public workplace charging, fast charging, and private charging is underrepresented in the dataset that is used in this dissertation. That is why the outcomes of this research should only be generalized to public on-street charging.

1.4. RESEARCH QUESTIONS

The main question investigated in this dissertation is **"How can public EV charging infrastructure in residential areas be scaled-up?"** The research questions are as follows:

1. To what extent are mobility policies relevant to the transition towards electric vehicles?
2. How do policy interventions affect public charging infrastructure?
3. What do stakeholders find important, and how do these prioritizations change over time?
4. Which roll-out strategies apply to neighborhoods?
5. How do roll-out strategies affect the charging dynamics of the neighbourhood?

1.5. THESIS OUTLINE

The dissertation contains of 8 chapters, which report on the methods, findings and conclusion of the research. Some of the chapters have been published as a paper. Five of the chapters address one of the research questions, and these chapters contain an introduction, literature, methods, results and a conclusion. The dissertation can be read as a whole, but selective readers can choose to read a chapter individually. The dissertation is written for researchers in energy transition, with a focus on electric mobility and public chargers. The findings may also be interesting to policymakers, CPOs and EMSPs. **Chapter 2** discusses the research approach and methods of the thesis. **Chapter 3** contains a paper that reviews policy measures related to mobility and charging infrastructure. Policies are discussed and analyzed. The purpose of chapter 3 is to answer the first sub-question of the thesis *"To what extent are Dutch mobility policies relevant to the transition towards electric vehicles?"*. **Chapter 4** consists of three different sections addressing case studies of charging policies. The purpose of chapter 4 is to answer the second research question of the thesis: *"How do policy interventions affect public charging infrastructure?"*. **Chapter 5** contains a paper describing the stakeholder analysis and interviews. The purpose of chapter 5 is to answer the third research question of the thesis: *"What do stakeholders find important, and how do these prioritizations change over time?"*. In **Chapter 6**, a conceptual framework is proposed to evaluate roll-out strategies in neighbourhoods. This chapter addresses the research question *"Which roll-out strategies apply to neighborhoods?"*. **Chapter 7** discusses the simulation results of the neighbourhood roll-out strategy simulation that was made using the framework as described in Chapter 6. The purpose of chapter 7 is to answer the last research question of the thesis: *"How do these strategies affect the charging dynamics of the neighbourhood?"*. **Chapter 8** is the conclusion chapter of the thesis, in which the main question will be answered and reflected upon: *"How can public EV charging infrastructure in residential areas be scaled-up?"*.

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2

Research Approach & Methods

2

2.1. RESEARCH APPROACH

This dissertation aims to identify ways to scale-up public charging infrastructure. The main research question is *"How can public EV charging infrastructure in residential areas be scaled up?"*. To support the scale-up of public charging infrastructure, it is important to first understand the policy objectives in public charging, the allocation (roll-out) of chargers, and its effect on charging dynamics. The first three research questions of the dissertation aim to improve the understanding of these charging dynamics. From this understanding, the issues and challenges in public charging can be identified to further simulate the scale-up of public charging. RQ1 is answered in Chapter 3, and addresses the policy landscape of mobility policy and the role of EV charging policy in mobility policies. Chapter 4 (RQ2) analyzes policy effects of charging, using three case studies. Chapter 5 (RQ3) studies the prioritizations of decision-making stakeholders in public EV charging. The outcomes of Chapter 3 (RQ1) are used as scenario inputs for Chapter 5 (RQ3).

The second part of the dissertation focuses on conceptualizing and simulating the allocation process of charging resources. Various roll-out strategies for public chargers are experimented with. Chapter 6 (RQ4) summarizes the issues in public charging, which were identified through the first three studies. Chapter 6 suggests a conceptualization for allocating and evaluating chargers. Chapter 6 also explains the selection for the case study that is used in Chapter 7. RQ5 is reported in Chapter 7. Chapter 7 explains the construction of an agent-based model that simulates the allocation of charging resources. Chapter 7 also contains the results of a simulated experiment with three distinct roll-out strategies to allocate public chargers.

This dissertation uses a mixed-method approach. A diverse set of case studies is selected to study the dynamics of charging, and a variety of methods is applied to the cases, in order to answer the research questions. This includes qualitative as well as quantitative methods. The main research question is addressed at the end of the dissertation in the conclusion chapter (Chapter 8). Table 2.1 contains the research questions, methods, and output of each chapter. The research design is also illustrated in Figure 2.1. In the next sections, the methods are explained for each study. The chapters in which the studies are described explain these methods in more detail.

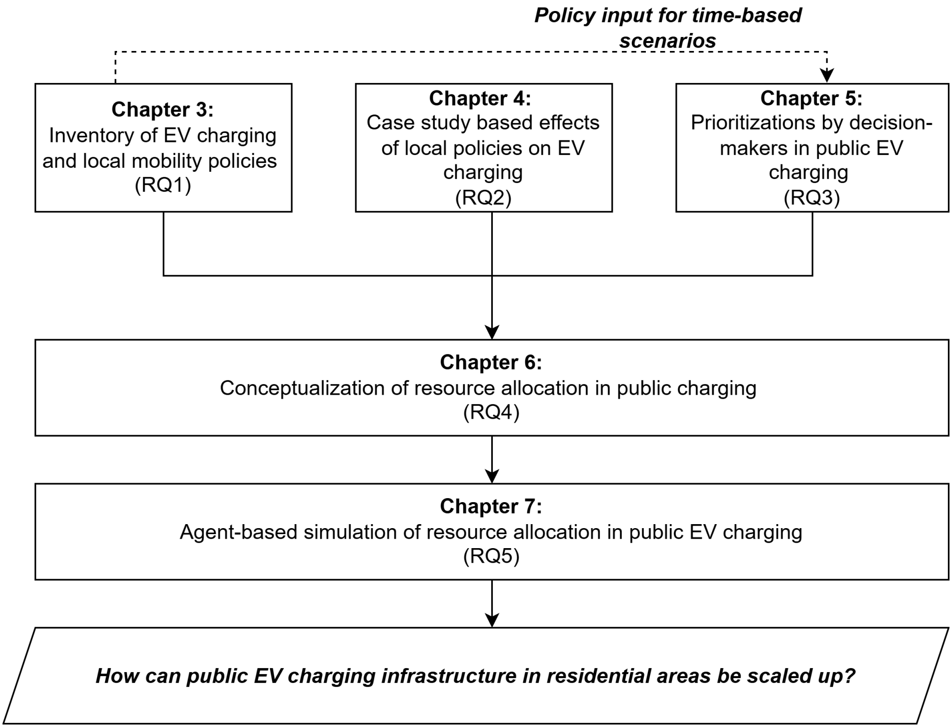

Figure 2.1: Research design

Table 2.1: Research design

Chapter	Research question	Methods	Output
3	To what extent are mobility policies relevant to the transition towards electric vehicles?	Literature review Policy analysis System analysis	Policy inventory
4	How do policy interventions affect public charging infrastructure?	Data analysis Desk research	Policy effects
5	What do stakeholders find important, and how do these prioritizations change over time?	Multiple criteria analysis	Stakeholder prioritizations
6	Which roll-out strategies apply to neighborhoods?	Conceptual modeling	Conceptual framework
7	How do roll-out strategies affect the charging dynamics of the neighbourhood?	Agent-based model	Model & Simulation results

2.2. Research Methods

The problem of the thesis was investigated using various methods. A distinction can be made of four important methods that shaped the thesis:

- Policy Analysis
- Data Analysis
- Multiple criteria decision making
- Agent-based modeling

The following sections will explain the selected methods for each study.

2.3. Research Questions

To what extent are mobility policies relevant to the transition towards electric vehicles?

Chapter 3 is designed to answer the first research question: "To what extent are mobility policies relevant to the transition towards electric vehicles?". The study analyses this question by using the following methods:

- **Desk research (government portals:)** Policy documents are identified through official government portals, using a number of search keywords.
- **Policy analysis:** Policy analysis is used to summarize and evaluate the identified policies. A policy inventory is made, and policies are categorized using the categorizations of Borras & Edquist (2013) and Mundaca et al.(2010).
- **Literature:** After the policy inventory is constructed, scientific literature is used to obtain the expected effects of the inventorized policies on important evaluation criteria.
- **System analysis:** System analysis is used to structure and summarize actions, interactions, relationships, goals and objectives of a system (Sage, 1992). Objective trees and system diagrams are selected as methods for the study.

Motivation

The decision for a policy analysis is motivated by the need to understand the policy objectives, and the policy instruments that are used to obtain these objectives. It is common in literature to analyze policies in the fields of energy, mobility and environment (Yang et al., 2023). Researchers emphasize that it is important to keep evaluating policies throughout societal transitions (Hughes and Hoffmann, 2020). The decision for using system analysis methods is motivated by the need to understand EV charging policy from a system perspective. The decision to include modal shift objectives is motivated by the relationship that both objectives (EV charging and modal shift) have to the mobility system, which means they may share common goals, path dependencies or competing goals.

OUTPUT

There are several outputs from this study:

- A policy inventory that includes the mobility and electric vehicle policies of two Dutch municipalities, and categorizes policies on user group, type of instrument and policy objective
- A matrix describing the expected effects of the categorized policy types, using literature
- An objective tree for electrification of vehicles, and an objective tree for modal shift
- A system diagram summarizing the system interactions

The outputs are used in Chapter 5 to construct the narrative of future EV policy goals for the time-based scenario's.

HOW DO POLICY INTERVENTIONS AFFECT PUBLIC CHARGING INFRASTRUCTURE?

Chapter 4 is designed to answer the second research question: "How do policy interventions affect public charging?". The study analyses this question by using the following methods:

- **Desk research:** The first case study, related to procurement and competition, is analyzed through desk research. Technical and consultancy reports, made on government request, are analyzed, and local court hearings related to procurement and competition are used. Consultative parties such as the DSO and the Nationale Agenda Laadinfrastructuur are also referred to when relevant.
- **Data analysis:** The second and third case study apply data analysis to charging transaction data. This data is used to determine how charging behavior is affected by the policy interventions of case 2 and 3. The data analysis consists of statistical summaries and is illustrated using spatial (GIS) plots, line plots, and violin plots.

MOTIVATION

The goal of this study is to understand how policy scenario's can affect public charging. The first case study is selected to understand the effect of procurement, allocation and competition policies, and to understand which issues and challenges apply to these topics. The second case study investigates the effect of COVID-19 lockdowns on charging behavior. This can provide insights to the effect of restrictive policies, such as lockdowns, work from home and curfews on public charging behavior and public charging demand. The third case study focuses on electrification of a professional traffic group. This case study can provide insights on the increase in charging demand, and some of the other challenges related to the electrification of professional traffic.

OUTPUT

There are several outputs from this study:

- Challenges and issues in public charging, related to procurement, allocation and competition

- The effects of COVID-19 lockdowns on public charging behavior
- The effect of cab driver electrification on the inter-urban charging demand, which illustrates some of the challenges of electrifying professional traffic.

The outputs are used in the conceptualization of the development of public charging (Chapter 6).

WHAT DO STAKEHOLDERS FIND IMPORTANT, AND HOW DO THESE PRIORITIZATIONS CHANGE OVER TIME?

Chapter 5 is designed to answer the third research question: "What do stakeholders find important, and how does this prioritization change over time?". The study analyses this question by using the following method:

- **Multiple criteria analysis:** Multiple criteria analysis helps to understand the decision making dynamics of stakeholders. The best-worst method (Rezaei, 2015) is selected as the method for this analysis. The survey is designed to prioritize charging criteria and activities over three time periods, for which scenarios are made using the output of Chapter 3

MOTIVATION

The goal of this study is to understand the prioritizations of the decision makers in the charging system, to understand the level of consensus between decision makers, and to understand how priorities shift over time. This helps with understanding future objectives of decision makers and the alignment between decision makers in public charging. The best-worst method is less redundant than the (classical) analytical hierarchical process, because the criteria only need to be valued twice for each scenario.

OUTPUT

There are several outputs from this study:

- Prioritizations of decision-makers for three different time periods
- The level of consensus between decision-makers
- The extent to which priorities shift over time

The outputs are used in the conceptualization of the development of public charging (Chapter 6).

WHICH ROLL-OUT STRATEGIES APPLY TO NEIGHBORHOODS?

Chapter 6 is designed to answer the fourth research question: "Which roll-out strategies apply to neighborhoods?". The study analyses this question by conceptualizing the decision-making landscape of the development of public EV charging.

MOTIVATION

A conceptual framework is an important step in the development of models. The conceptualization attempts to translate the allocation, development, grid management and intervention steps that were identified through previous studies, into a computational representation which allows for software implementation, modeling and simulation.

OUTPUT

There are several outputs from this conceptualization:

- A summary of the socio-technical concerns in neighborhood charging
- A flow diagram explaining the decision making in the allocation and management of charging infrastructure.
- A suggested case study environment based on local data

The conceptual framework is used to formalize and implement the model in Chapter 7.

HOW DO ROLL-OUT STRATEGIES AFFECT NEIGHBORHOOD DYNAMICS?

Chapter 7 is designed to answer the final research question: "How do roll-out strategies affect neighborhood dynamics?". This study simulates the allocation of charging resources in a subdistrict in Amsterdam. The following method is used for this simulation study:

- **Agent-based modeling and simulation:** Agent-based models can simulate the operations and interactions of individuals in an environment. This helps investigate the interactions between behaviour, political settings, and environmental settings. With agent-based simulations, we can study the phenomena that emerge from collective behaviours (Bonabeau, 2002).
- **Reporting of the model:** The model is also described, which includes: problem, system and actor description, input data, formalization, verification, experimentation, and data analysis of simulation results. The reporting structure that was used is from the book "Agent-based modeling of socio-technical systems" (Van Dam et al., 2013).

MOTIVATION

The modeling of EV charging knows many approaches. For example, linear and nonlinear programming, or machine learning, are often applied to optimizing problems. Time series analysis or monte carlo simulations are used to predict future charging patterns, and dynamic modeling can be used to simulate a system where the dynamics of charging play a role. In dynamic modeling, system dynamics models (SDM) can be used to investigate macro-level interactions, and agent-based modeling can be used to investigate micro-level interactions, such as the interaction between EV users and the charging network. In this study, agent-based modeling is used to simulate the allocation problem. The first reason is that roll-out and allocation of chargers touches upon different systems (public space, energy, environment, mobility, behavior) and agent-based modeling allows for the representation of parts of these systems that apply to the simulated problem. Agent-based modeling can also be applied to situations where there is still much uncertainty (Lempert, 2002). The future of EV charging is still uncertain, because public space development, grid constraints and adoption rates cannot always be predicted accurately. Charging transaction data is available in this study. In agent-based modeling, input data can be used to represent behavior that is similar to the real world

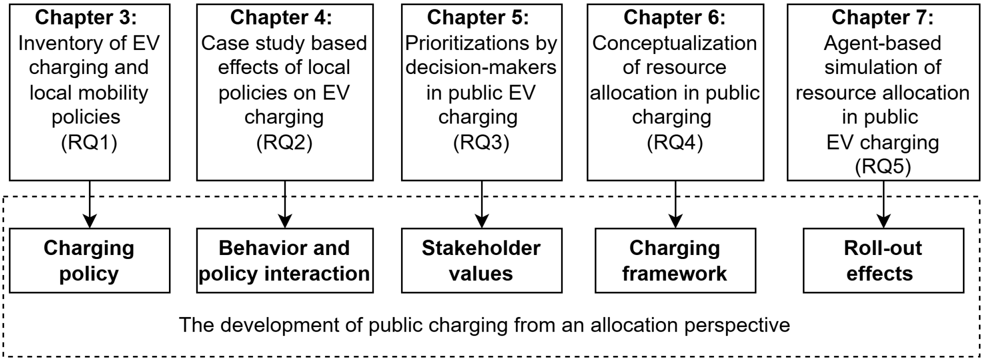

Figure 2.2: Illustration of the charging dynamics caught in the five studies

(Ward et al., 2016). Roll-out strategies are part of the allocation problem, and spatial allocation can be represented within an agent-based simulation. The charging demand, occupancy rates and the distribution of chargers should be represented spatially in the model. The simulation environment Netlogo (Wilensky, 1999) allows for such a spatial representation in an intuitive way, which is why the model was built in this software.

OUTPUT

There are several outputs from this conceptualization:

- Formalization of an agent-based model
- Agent-based allocation model
- Simulation results

DYNAMICS OF CHARGING

The dissertation catches the dynamics of charging from anallocation and roll-out perspective. Fig. 2.2 illustrates the contribution of each chapter to the understanding of public charging.

2.3.1. DATA

Open data, scientific literature, grey literature, and data with limited access is all used throughout the dissertation. The dissertation is part of the NWO RAAK-SIA Future Charging project. The results of the project can be found in Wolbertus et al. (2024). The following data were used often in the dissertation:

- **Charging transaction data:** Charging transaction data of a large sample of the Netherlands was collected through the project consortium of the Future Charging project. This data is accessed through a VPN and password-protected server. This charging data was collected using the *Open Charge Point Protocol*. The data contains the following information for each session on a public charging point in the dataset:

  - Charging location
  - Starttime and endtime
  - Charging volume
  - Anonymized identifier
  - Occupancy length (incl. non-charging)

- **Central Bureau of Statistics:** The neighborhood statistics set (similar to National Household Surveys) from the Central Bureau of Statistics is used throughout the dissertation (CBS, n.d.)[1]. For each part of the study, the latest data available at that moment was selected. The data is usually updated yearly, although not every variable is reported every year.

- **RVO (Netherlands Enterprise Agency):** The RVO is the Dutch enterprise agency. This agency provides open data about the national adoption rates of electric and plug-in hybrid vehicles. The agency also reports on the number of charging points available on a national level.

2.4. VALIDATION

The research also contains some steps to validate the outcomes of each study. In the policy analysis (Chapter 3), policymakers were asked to clarify target groups and scope, and to validate the assumptions of the researcher. Media outlets have been investigated to further explain unexpected findings, for example in Chapter 4, case 2. For the stakeholder analysis (Chapter 5), the internal consistency of participants and the consistency scores between candidates were compared and reported. Parameters of the environment in the simulations (Chapter 6 & 7) were derived from real charging transaction data, and a researcher of the Amsterdam smart charging project ('Groen et al., 2022), as well as a researcher from am Amsterdam battery pilot (Heath et al., 2024), validated the parameters.

[1]The Central Bureau of Statistics also reports on mobility and energy, these reports are also sometimes used and referred to.

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2

3

A Review and Evaluation of Dutch Urban Mobility Policies

Global climate agreements call for action and an integrated perspective on mobility, energy and overall consumption. Municipalities in dense, urban areas are challenged with facilitating this transition with limited space and energy resources. One important aspect of the transition is the adoption of electric vehicles, which includes the urban development of charging infrastructure. Another important goal is a modal shift in transportation. This study investigated over 80 urban mobility policy measures that are in the policy roadmaps of two of the largest municipalities of the Netherlands. This analysis consists of an inventory of policy measures, an evaluation of their environmental effects and conceptualizations of the policy objectives and conditions within the mobility transitions. The findings reveal that the two municipalities have similarities in means, there is still little anticipation of future technology, and policy conditions could be further satisfied by tailoring policy to specific user groups.

This chapter has been published in Sustainability **13**, 22, 25 (12736) as van der Koogh et al., 2021

3.1. Introduction

Innovations in mobility, combined with a climate crisis-fueled acceleration of policy measures, have led to a number of mobility transition strategies at the European, national and municipal levels. An important element in the mobility transition is the adoption of e-mobility. The use of electric vehicles (EVs) has high potential to reduce local emissions (Szczechowicz, E., Dederichs, T., Schnettler, A., 2012). Parked electric fleets could potentially play a role in the efficient use of energy, and in grid stabilizations (Kempton and Tomić, 2005). The Dutch Climate Agreement contains a 'Mobility' chapter (De Rijksoverheid, 2018), which includes a strategy to increase EV adoption. This strategy describes the deadlines for sales of new traditional internal combustion engine (ICE) vehicles, electrifying the fleet of specific sectors and the establishment of the National Agenda of Charging Infrastructure (RVO, 2019). Municipalities will have to work towards these national mobility goals, which include the increase in EV adoption, and the roll-out of a public charging network.

Municipalities need charging networks to satisfy the charging requirements of EV users. Although roughly 74 percent of current Dutch EV owners have their own driveway to place charging infrastructure (RVO, 2021), this percentage tends to be lower in urban areas and will decrease as adoption increases among residents who do not have access to private driveways. Dense urban areas have additional challenges, such as the allocation of charging infrastructure in a built environment with little space, and less private driveway parking compared to rural areas. EV users prefer to have their charging point close to their destination: less than 300 m from home and less than 100 m from a supermarket (Pagany et al., 2019). Therefore, it is important that the charging network is arranged carefully. The charging network should be able to provide EV users and users of adjacent systems (such as parking) with sufficient resources. Urban e-mobility users can be categorized into user groups with distinct charging behaviors and preferences. Helmus and van der Hoed (2015), observed a number of distinct user group behaviors, such as shorter connection times for cab drivers and shared vehicles (as opposed to personal vehicles), and differences in the time windows of charging across user groups. Five user groups were distinguished in total for public charging: personal (residents, commuters, visitors), shared (vehicles) and cabs. Other groups (non-public charging) include logistics and public transport.

There are also other mobility objectives that municipalities have to address in the upcoming years. Especially in dense urban areas, where streets can be crowded and street parking spots can be hard to find, additional mobility policies are necessary to safeguard the city habitability for residents, as well as for future generations. Some of these policies can be summarized as incentives to promote a modal shift (Batty et al., 2015), which aims to move residents away from the traditional 'car ownership' model of transport. Others can be summarized as smart mobility developments, which aim for a more automated and tailored experience, using new technologies. Urban mobility patterns are affected in numerous ways because of this transition. For example, car sharing affects mobility patterns (Kopp et al., 2015) and urban charging demand, while light electric vehicles (LEVs) can simply be charged from work or home (Ewert et al., 2020). Autonomous vehicles may require other charging methods altogether (e.g., inductive charging (Angrisani et al., 2014)). These developments can also affect other mobility factors such as travel times, driver comfort and road safety (Anastasiadou, 2021) and require distinct parking strategies (Ewert et al., 2020 ; Martens, 2009 ; Planbureau voor de Leefomgeving, 2020). Municipal policy makers have the challenge of implementing policy measures to address these various aspects of the mobility transition. Although systematic reviews and analyses of EV and urban mobility policies have been executed in the past (e.g., Fontoura et al., 2019 ; Guo, C. and Chan, C., 2015), and Dutch EV policies have previously been investigated (Wolbertus, 2020), these studies address the challenges in EV policies themselves, whereas the broader context needs to be considered in future policy making. This includes other aspects of the mobility transition, as well as the local context, especially in dense urban areas with limited spatial resources.

This study aims to contribute a novel, detailed mobility policy analysis of the policies in two municipalities with a relatively mature charging network. The Netherlands currently has spatial challenges, a more dedicated charging network than many other countries (Till et al., 2019 ; International energy agency, 2021), semi-accessible charging transaction data (Maasse, S., van den Hoed, R., 2019), and non-confidential municipality documents are available online. Policies and developments affecting mobility behavior in the Netherlands, such as the use of underground parking garages that aim to keep cars outside of city centers, the widespread adoption of biking and the roll-out of charging infrastructure, are frequently discussed as best practices in European policy documents (Patrick Auwerx, Robert Pressl , Ivo Cre Polis, Nazan Kocak, Tom Rye, 2019 ; Cycling Cities, 2009 ; Transport and Environment, 2018). We aim to benefit from these best practices in terms of the learning potential of the Netherlands in reviewing novel urban mobility policies. Additionally, our translated categorizations could improve the accessibility of Dutch policy documents for international stakeholders and researchers.

This study explores which policies are implemented to address the mobility transition, and how these policies contribute to the objectives of the transition. The aim of this study is to summarize and evaluate a wide variety of urban mobility policies. For this purpose, we present an overview of urban mobility policies in two Dutch municipalities: Amsterdam and The Hague. This overview contains a description of local mobility policy roadmaps, an evaluation of their effects on the local environment, and literature-based conceptualizations of the objectives and environmental interactions, using policy analysis and system analysis.. The following section describes the methods that were used in this research. Next, we present our findings, evaluations and conceptualizations of the policy and environmental interactions of urban mobility transition. The final chapter discusses future implications for the two municipalities.

3.2. MATERIALS & METHODS

The methods used in this study are discussed in the following paragraphs. This study mainly used municipal policy literature (inventory, literature evaluation) and is therefore a review of the state-of-the-art urban mobility policies in the Netherlands. An additional system analysis was used to summarize the findings and reveal the underlying conditions and challenges. The set-up, as illustrated in Figure 3.1, was derived from steps that

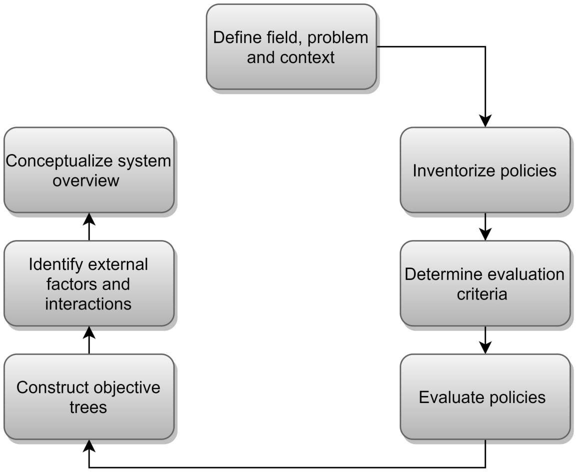

Figure 3.1: Methodological set-up

are familiar in both policy and system analysis (Patton et al., 2012 ; Enserink et al., 2010 ; Van Der Lei et al., 2011). Whereas traditional policy analysis suggests or implements a 'best alternative', our aim was to describe the mechanisms behind the policies and their expected effects on the urban environment. System analysis methods were used to summarize and conceptualize the system interactions in urban mobility policies. The criteria that were selected for policy evaluation were also used in the system analysis. Additionally, we constructed objective trees and identified external factors in the scope of the system. A conceptual diagram was made that summarizes the system interactions.

3.2.1. DECISION CONTEXT

The case study area for this study is the Netherlands, with a focus on two of the largest municipalities: Amsterdam and The Hague. These municipalities currently have a dedicated public charging network, a group of EV drivers and mobility service companies. Charging transactions were summarized to determine the decision context (see Table 3.1). The summary was formulated using a Dutch EV charging transaction database from 2020. For each municipality, the number of unique users was calculated by counting the unique identifiers (RFIDs) associated with transaction cards. The number of sessions on the public charging point, the number of charging locations (area level), the number of public charging points, the average daily occupation (users/charging point, then divided through the year) and the amount of kilowatt-hours (kWh) charged during the session (sessions with 0 kWh filtered) can also be found in 3.1.

Between 2018 and 2019, there was a growth in EV users and sessions. In Amsterdam, an increase of nearly 14,500 unique RFID cards was observed, and the amount of charging sessions also increased, with almost 180,000 extra sessions for Amsterdam and almost 100,000 extra sessions for The Hague. In 2020, the growth trends declined. The Hague had less unique RFID users than in 2019, and the growth of users and sessions in Amsterdam stagnated to roughly one third of the growth that we witnessed between 2018

Table 3.1: Descriptive statistics of the case study environments between 2018 and 2020

Stats	Amsterdam			The Hague		
	2018	2019	2020	2018	2019	2020
Users	43,518	57,987 (+14,469)	63,953 (+5966)	24,033	31,600 (+7567)	31,356 (-244)
Sessions	981,515	1,161,469 (+179,954)	1,202,222 (+40,753)	390,118	488,654 (+98,536)	547,095 (+58,441)
Occupancy	1.95	1.84	1.39	1.09	1.11	0.76
Chargeload	10.98	12.77	15.73	9.63	12.49	15.14
Connection time	9.69	9.53	12.01	10.47	10.16	11.70
Used chargers	1380	2479	2370	984	1215	2729

and 2019. Connection times increased in 2020. A smaller number of public charging points were utilized in Amsterdam. In The Hague, this number increased because of the extra infrastructure, which lowered the occupancy rates. The decline in growth could be attributed to the COVID-19 lockdown effects, when tourist attractions were closed and residents were asked to work from home. The average kWh charged also had an increasing trend, presumably because of changes in the vehicle composition in the charging network (e.g., hybrid vs. full-electric or battery improvements). This trend is likely to continue in the future.

3.2.2. POLICY INVENTORY

Policy documents were identified through online search engines. The search terms that were used to identify policies were as follows: electric vehicle (EV), mobility, car free, parking, charging infrastructure, sustainability, smart and shared mobility, traffic and transport. The search portals of the municipality of Amsterdam (Amsterdam, 2021) , municipality of The Hague (Hague, 2021), the Green Deal website (European-Commission, 2021) and the metropolitan region of Rotterdam–The Hague (MRDH, 2021) were used to gather policy documents. Table 3.2 contains descriptions of the scope that was used in selecting policy documents.

Policies were categorized into the categories described in Table 3.3, adapted from previous studies (Borrás and Edquist, 2013 ; Mundaca et al., 2010). Borras and Edquist acknowledged the relevance and widespread use of the policy typology of regulatory, economic and soft. Regulatory instruments are used to regulate aspects of the policy domain such as markets and behaviors. Economic instruments include financial resources such as cash, budgets and financial (dis)incentives. Soft instruments are voluntary and consist of agreements, recommendations and knowledge exchanges, among others. Mundaca et al. used a slightly differently named typology with similarities in the interpretation, which consists of the instrument typology of economic/financial/market, regulatory and informative/voluntary (p327).

Table 3.2: Scoping of the Policy Inventory

Scope	In scope	Out of Scope
Problem	**EV, charging, parking, public space, (smart) mobility,**	**Energy transition (not EVs), traffic, building permits**
Spatial	Amsterdam and The Hague	Highways
Sector	Personal, professional, public transport, logistics, shared mobility	Aviation, waterborne, specialized services
Temporal	after 2018 temporary measures (>2020)	Older than 2018 Permanent measures (before 2020)

3

Table 3.3: Policy Categorization

Policy Measure	Specification
Economic/Market	Subsidy, discount, tax, loans, fines, allocation
Regulatory	Permits, preferential treatment, restrictions, standards, laws
Soft	Pilots, R&D, informative, code of conduct, monitoring, evaluation

The CTO Smart Mobility of the Municipality of Amsterdam, and the Coordinator Electric Transport in the Hague were asked to validate some assumptions that were made while interpreting the policy measures. An overview of the validated assumption can be found in the Appendix (9.1).

3.2.3. EVALUATION CRITERIA

Table 3.4 contains the criteria that were selected for evaluation of the mobility policies. Effects of policies on these local criteria were determined using local reports and scientific literature. For the evaluation, we determined effect directions (decreasing, increasing or no effect). When the effect is only expected under specific circumstances, these circumstances are also mentioned.

3.2.4. SYSTEM ANALYSIS

System analysis can structure policy papers by creating a system overview of the policy problem. We selected objective trees and system diagram construction (See Sage, 1992) as methods to determine and summarize the system. The system demarcation can be derived from Table 3.2. The means were clustered from the policy measures that were identified in the policy inventory stage. Mobility goals (annotated for each user group) were also determined from policy documents and summarized in objective trees. Causal relationships were determined from the policy evaluation stage, and additional literature was consulted to determine external factors and interdependencies between evaluation criteria. This provided the necessary input to construct the system diagram. Intermediate results, such as the policy conditions table, can be found in Chapter 9.

Table 3.4: Description of evaluation criteria

Criteria	Description	Relevance
Occupancy rate	The percentage of occupied public charging points in an area.	Reveals the performance of the charging network: High occupancy increases competition and the risk of failed sessions. Low occupancy rate can lead to loss of profit and obsolete points
Parking pressure	The percentage of occupied street parking spots in an area.	Reveals the availability and necessity of street parking spots
Car ownership	The number of vehicles owned by inhabitants.	The number of owned cars will influence most of the domain indicators in some way. For example, more owned vehicles will increase the need for parking spots, and depending on vehicle types, the occupancy rates and the charging demand.
Energy consumed	The amount of kWh that is consumed by EV charging or the fuel that is consumed by ICEV.	The amount of energy that is needed at a certain time and location for users and their charging or mobility needs.
Adoption rates of EVs	The percentage of electric vehicles in the full vehicle fleet.	The adoption rate of EVs is relevant to estimate the necessary resources, such as energy demand and parking spots.
Local air pollutants	The penetration rates of air pollutants and GHG emissions (e.g., CO_2).	Municipalities want to avoid pollutants and GHG emissions as much as possible, to improve the local air quality in dense urban areas. A high percentage of local CO_2 emissions can be partly attributed to (fossil) mobility and transport.

3.3. Results

This section describes the results of this study according to the steps presented in Section 3.2. We first report on the policy inventory (Section 3.3.1), followed by our findings on evaluation criteria (Section 3.3.2), and conclude with a system overview (Section 3.3.3), which includes goals, conditions and a conceptualization of the system relationships.

3.3.1. Policy Inventory

First, the national policy context is discussed, before specifying the local policy landscape for the municipalities of Amsterdam and The Hague. We end this inventory by presenting the mobility policy measures that were associated with EVs and mobility in these municipalities.

European and National Strategy

The Paris Agreement was drafted to ensure that the post-industrial temperature does not surpass an increase of 2 degrees (Celsius), limiting the increase to a maximum of 1.5 degrees Celsius (Delbeke et al., 2019). The Netherlands ratified the Paris Agreement in 2016. The national goals for the Netherlands include a CO_2 reduction of 55 percent in 2030, and a reduction of 95 percent in 2050 (compared to 1990). Additionally, the district court of The Hague has the power to rule additional measures, which was the case for a reduction in greenhouse gas emissions between 2015 and 2020. The national strategy has been drafted in the Dutch Climate Agreement (Rijksoverheid, 2019), which includes the themes 'Built Environment', 'Mobility', 'Industry', 'Agriculture' and 'Electricity'. Goals that are related to the mobility transition and the future of e-mobility can be found in the 'Mobility' chapter. The goal is to reduce local mobility emissions, stimulate the use of renewable sources in mobility and reduce vehicle ownership by further developing mobility services in urban areas. The agreement also states that in 2030, all new vehicles sold must be emission free. The National Agenda of Charging Infrastructure (NAL) was established to determine national goals for charging infrastructure (such as the goal of 1.7 million charging points in the Netherlands by 2030) and to facilitate pilots that increase knowledge (RVO, 2019). Amsterdam and The Hague are also involved in mobility projects at the European level. For example, earlier this year, Amsterdam released its Sustainable Urban Mobility Plan (SUMP) (Vervoerregio Amsterdam, 2021), which focuses on inhabitants and environments, rather than vehicles and traffic. Amsterdam is also involved in Horizon 2020-funded mobility projects such as the digital platform of Mobility Urban Values (MUV) (MUV, n.d.) and the Atelier project (ATELIER, 2020), which contains the development of a positive energy district including electric cars. The Hague is one of the hosts of the CIVITAS living lab project (LEAD, 2020) to solve the last mile problem in logistics. This list is not exhaustive. The main focus of analysis in the upcoming sections is the municipal (and sometimes regional) level of policies.

Local Policies

We identified green deals, local policies and regional policies for the municipality of Amsterdam and The Hague, using the scoping criteria mentioned in Table 3.2. We summarized the policy measures in the categories described in Table 3.3. For both municipalities, the most commonly targeted user group is personal drivers. The city of

Table 3.5: Statistical summary of the policy measures

Policy measures	Amsterdam	The Hague
# of full policy documents	**10**	**11**
# of policy measures	**47**	**34**
Soft measures	19 (40%)	9 (27%)
Economic measures	11 (23%)	10 (30%)
Regulatory measures	10 (21%)	14 (42%)
Targeted user group	**Amsterdam**	**The Hague**
Personal drivers	18 (38%)	11 (32%)
Cab drivers	2 (4%)	2 (5%)
Logistics	2 (4%)	4 (11%)
Shared vehicles	7 (15%)	9 (26%)

Amsterdam has soft measures as the most common policy category (40 percent). The most common policy category for The Hague is regulatory (42 percent). Both municipalities have measures addressing hubs. Hubs were not categorized for one specific user group because the policy documents and assumption validation interviews (See Appendix 9.1) implied that hub access for multiple user groups (e.g., residents, logistics and/or shared vehicles). Table 3.5 contains the entire statistical summary of the identified policy measures. This table contains the number of accessed documents, the number of identified measures through these documents and the policy categorization at the measure level. The table also contains the number of measures that were introduced for each user group. The documents that were used to fill this table are: Gemeente Amsterdam, 2016 Gemeente Amsterdam, 2019b Gemeente Amsterdam, 2019a European Commission, n.d. CityDeal-gemeenten, 2018 Gemeente Amsterdam, n.d. Stadslogistiek, 2019 Gemeente Amsterdam, 2020 Vervoerregio Amsterdam, 2020 Gemeente Den Haag, 2017 Gemeente Den Haag, 2018 Gemeente Den Haag, 2020 Gemeente Den Haag, 2019b Gemeente Den Haag, 2019a Metropoolregio Rotterdam Den Haag, 2020b Metropoolregio Rotterdam Den Haag, 2020a Gemeente Amsterdam, 2011

We categorized all identified policy measures on what they intend or promote. This enabled us to categorize the measures in groups (Table 3.6). We only focused on the policy measures that could have a tangible effect on at least one of the criteria. We excluded a few subgroups such as communicative and informative measures, and car-free streets from this part of the analysis (Section 3.3.3 describes their role in the system, and Appendix 9.4 describes these measures in the context of conditions).

3.3.2. EVALUATION CRITERIA

First, the effect directions of these measure types on each domain indicator is summarized in a table. The following paragraphs describe the literature, prognoses and pilot outcomes that were used to determine these effects. Then, the way domain indicators affect each other is discussed, and in the final paragraph, we identify important external and system factors that interact with these domain effects.

3

Table 3.6: Policy measure groups

Measure Groups	Definition	Amsterdam	The Hague
New charging infrastructure	Roll-out of new charging points	8	6
New hubs	Roll-out of hubs, including clustered charging	4	3
Shared vehicles	Roll-out of the shared vehicle fleet	7	9
Mobility budgets	Budgets made available to promote modal shift (e.g. for residents)	2	1
Mobility-as-a-service (MaaS)	Roll-out of incentives to develop MaaS market	3	2
Subsidies and preferential treatment	Subsidies or benefits for EV drivers to incentivize emission-free driving	2	3
Sector electrification	Incentives to electrify a sector	4	4
Fast chargers	Roll-out of fast chargers in the urban environment	1	1
Sustainable/alternative charging methods	e.g. V2G, PV, smart charging	3	1

THE EFFECTS OF POLICY MEASURES ON EVALUATION CRITERIA

For each of the measure groups, as selected in Table 3.6, an evaluation was conducted using the literature and local pilot outcomes. Table 3.7 summarizes these evaluations. Evaluations are discussed in the paragraphs below.

Table 3.7: Evaluation of policy measures (Mersky et al., 2016 ; NKL, 2019 ; Nijland and van Meerkerk, 2017 ; Nijland et al., 2015; Mobiliteitsfabriek, 2018; Hensher, 2017; Lieven, 2015 ; Tamis and van den Hoed, 2020; Ipsos&EVbox, 2020; Bons et al., 2020)

Policy measure groups	**Occupancy rates**	**Parking pressure**	**Car ownership**	**Energy consumed**	**Adoption rate (EVs)**	**Local air (GHG)**
New infrastructure	Decreases	No direct effect	No direct effect	Increases	Increases	No local effect
Hubs	Decreases	Depends on hub parking	No direct effect	Increases (efficient use)	Increases	No direct effect
Shared vehicles	Increases temporarily	Likely to decrease	Decreases	Elec. use may increase	No direct effect	Decreases
Mobility budget	Depends on modality	Likely to decrease	Likely to decrease	Depends on modality	Depends on modality	Depends on modality
Subsidies & privileges	Likely to increase	No direct effect	No direct effect	Likely to increase	Likely to increase	No local effect
Fast chargers	Likely to decrease (shorter)	No direct effect	No direct effect	Elec. use increases (temporarily)	Increases	No local effect
Sustainable charging	No effect	No direct effect	No direct effect	Peak decreases, RES use increases	No direct effect	Likely to decrease
Mobility-as-a service	Depends on modality	Likely to decrease over time	Decreases	Depends on modality	Depends on modality	Depends on modality
Sector electrification	Likely to increase	No direct effect	No direct effect	Elec. use increases (more efficient)	Increases by definition	Decreases

(1) New charging infrastructure and new hubs

One of the main issues in the context of EV adoption is the chicken-or-egg problem (adoption first, vs. available infrastructure first). Pro-actively installing charging infrastructure in public spaces could increase EV adoption (Mersky et al., 2016). New charging infrastructure can be placed to lower occupancy rates, and to anticipate future users. Energy consumption increases with more charging transactions. Global, as well as local CO_2 emissions can be reduced when drivers give up their fossil-fuel cars to adopt EVs. CO_2 emissions are not directly affected by the placement of infrastructure. Clustered charging (hubs) could redirect pressure on charging and parking, allow for more efficient use of space, allow for more efficient use of the grid capacity and are up to 20 percent more profitable than street charging (NKL, 2019) .

(2) Shared vehicles, Mobility-as-a-Service and mobility budgets

A shared vehicle could replace four to six cars in the Netherlands, lowering both car ownership and parking pressure (Nijland and van Meerkerk, 2017). The amount of car-related CO_2 emissions for a vehicle sharer in the Netherlands is 8 to 18 percent lower compared to car owners (Nijland and van Meerkerk, 2017 ; Nijland et al., 2015). Car sharers also drive up to 20 percent less kilometers. In the ZuidAs Mobility Experience (Mobiliteitsfabriek, 2018), a local pilot in Amsterdam, participants gave up their car for a budget, which included a personal assistant for travel planning. On average, participants spent EUR 606 per month (similar to a car renting contract). At the end of the pilot, roughly 50 percent of participants indicated that they would give up their car for the budget. To summarize, car ownership could be decreased by offering drivers mobility budgets (Mobiliteitsfabriek, 2018), sharing vehicles (Nijland et al., 2015) and dedicated MaaS platforms (Mobiliteitsfabriek, 2018). Hensher (2017) stated that in MaaS ecosystems, the (reduced) fleet of vehicles is also used more extensively, leading to less vehicles that stand still, and, in the long run, lowers the need for parking spaces.

(3) Sector electrification, subsidies and charging techniques

Electrifying fleets in the Netherlands is associated with high investments costs for user groups and benefits in air quality, as well as progress in climate goals, lowered CO_2 emissions and an increased consumption of electricity per municipality. Mersky et al., (2016) did not find significant effects of preferential treatment on EV adoption; however, economic considerations were relevant, indicating a potential for subsidies. Lieven (2015) compared policy preferences in many countries including the Netherlands. Grants were more effective than tax returns, and preferential treatments (access to lanes) as well as sufficient infrastructure affected preferences in this study. Fast chargers are one of the indicated needs for Amsterdam-based cab drivers (Tamis and van den Hoed, 2020). From a global perspective, Lieven found that freeway chargers are also important for personal drivers (independent of driving distances). Another European survey found that installing fast chargers throughout Europe could lead to increased adoption (Ipsos&EVbox, 2020). Alternative sustainable charging such as solar (PV) charging, smart charging and vehicle-to-grid (V2G) charging can help control the supply and demand of electricity. This may lead to potentially higher penetration of renewable energy use by allowing charging adaptations, energy storage and/or grid support. Smart charging is an availability-based power adaptation between EVs and charging points, which

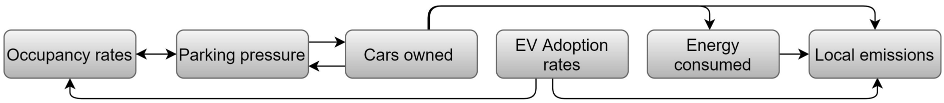

Figure 3.2: Overview of interactions between evaluation criteria

Table 3.8: Interactions between evaluation criteria

Evaluation criteria	Interactions
Occupancy rates	Correlates with parking pressure Increase in EV adoption can lead to an increase in occupancy.
Parking pressure	Correlates with occupancy rates Increase in owned cars leads to increased parking pressure.
Cars owned	Increased parking pressure can lead to a decrease in owned cars.
Energy consumed	Electricity consumption is increased by an increase in occupancy.
Adoption rates	An increase in occupancy can lead to a decrease in adoption.
Local air pollutants	A decrease in car ownership leads to lower emissions A decrease in energy consumed leads to lower emissions An increase in adoption rate leads to lower CO_2 emissions (under the assumption a previous vehicle was consuming fossil fuel).

can help in managing the electricity demand (Bons et al., 2020). An example of smart charging is the Flexpower project, where the charging of EVs was matched with the availability of locally generated renewable energy. The results of the Flexpower project, where 432 public smart chargers were placed in Amsterdam, indicate that there is no significant longer charging time for smart charging, and that the average load was reduced with 1.1 kW per charging point (leading to a 470 kW peak reduction per evening in the case study environment), leading to reduced CO_2 emissions (Bons et al., 2020).

INTERDEPENDENCIES OF EVALUATION CRITERIA

Some of the evaluation criteria also affect each other or correlate with each other. Figure 3.2 illustrates which criteria affect each other. We consulted the following literature to determine additional relationships between parking pressure (Guo, 2013), adoption rates (Bakker et al., 2014) and car sharing emissions (Nijland et al., 2015). Holding other things constant, the following interactions were expected across the criteria (see Table 3.8).

EXTERNAL FACTORS

In the previous sections, we illustrated how policies relate to the objectives, to what extend they contribute to the objectives and how criteria are affected by policy measures, as well as other criteria. However, there are also other components of the mobility system that can affect these criteria; these are the external factors. Occupancy rates of the charging network are affected by the charging preferences of users (Wang et al., 2012), the battery size and the charging speed of vehicles (Wolbertus, R., van den Hoed, R., 2020) . Parking pressure is affected by neighborhood factors such as family composition and the growth of residents in a neighborhood (Coevering et al., 2008). Similar neighborhood factors are relevant for car ownership, as well as ownership percentages of neighbors and socio-economic factors (Goetzke and Weinberger, 2012). EV adoption rates are influenced by the quality of the charging infrastructure, the battery range, the total cost of ownership and socio-economic factors (Coffman et al., 2017). The energy consumed is influenced by other modes of urban transport (e.g., fuel), and these other modes can also influence the level of local CO_2 emissions.

3.3.3. System overview

In the following section, we describe two key policy objectives, emission-free inner city and modal shift, in an objective tree to determine the subgoals, conditional settings and measures. The coding (e.g., D7) for policy measures can be found in Appendix 9.2 and 9.3. Coding that starts with a 'D' corresponds to The Hague (Den Haag, Appendix 9.3), and the coding that starts with an 'A' corresponds to Amsterdam (Appendix 9.2). An overview of policy conditions and matching policy measures can be found in Appendix 9.4

Policy objectives

The goals of the municipalities include emission-free touring cars (Amsterdam), shared vehicles, professional traffic (such as logistics and cab drivers) and, ultimately, completely emission-free traffic in the inner city (Amsterdam). Requirements for these goals are other subgoals, as well as a number of conditions that need to be satisfied. We followed the implemented measures here to define the critical success factors that were addressed through policies in Amsterdam and The Hague. Most conditions hold true for multiple user groups or mobility goals, which are annotated in the aggregated measures. Figure 3.3 is an objective tree based on the policies in Amsterdam and The Hague. An objective tree can be read from left to right. On the left, the municipality goals on electrification can be found. Before this goal can be achieved, subgoals should be met, which can be found after the goals. To meet these subgoals, the right conditions should emerge first; these can be found after the subgoals. On the right side, the necessary types of measures to create the right conditions can be found. In the following paragraphs, we discuss the objective trees for electrification as well as a modal shift and mention the applicable measures (as identified in Section 3.3.1).

The identified conditions for emission-free inner city traffic include user group requirements (clustered), voluntary agreements, transfer points, attractive options, knowledge development, information exchange and adequate charging and electricity supply (Figure 3.3). Amsterdam and The Hague addressed some user group requirements: the charging hub needs of logistics (A31, D9), as well as the fast charging needs of cab drivers (A41, D24). Amsterdam has voluntary agreements for logistics (A21) and cab drivers (A1, A20) and has announced future policies for light electric vehicles (A8). The Hague has an agreement for logistics (D7) and has plans for agreements with cab drivers (D26) and shared vehicles (D25) in 2021. There are policies addressing transfer points for visitors/personal traffic in Amsterdam (A31, A34) and for logistics in both municipalities (A5, D9). There are some attractive options for electrification of personal drivers (A10) as well as public transport (A47) in Amsterdam. The Hague offers a trade-in budget for

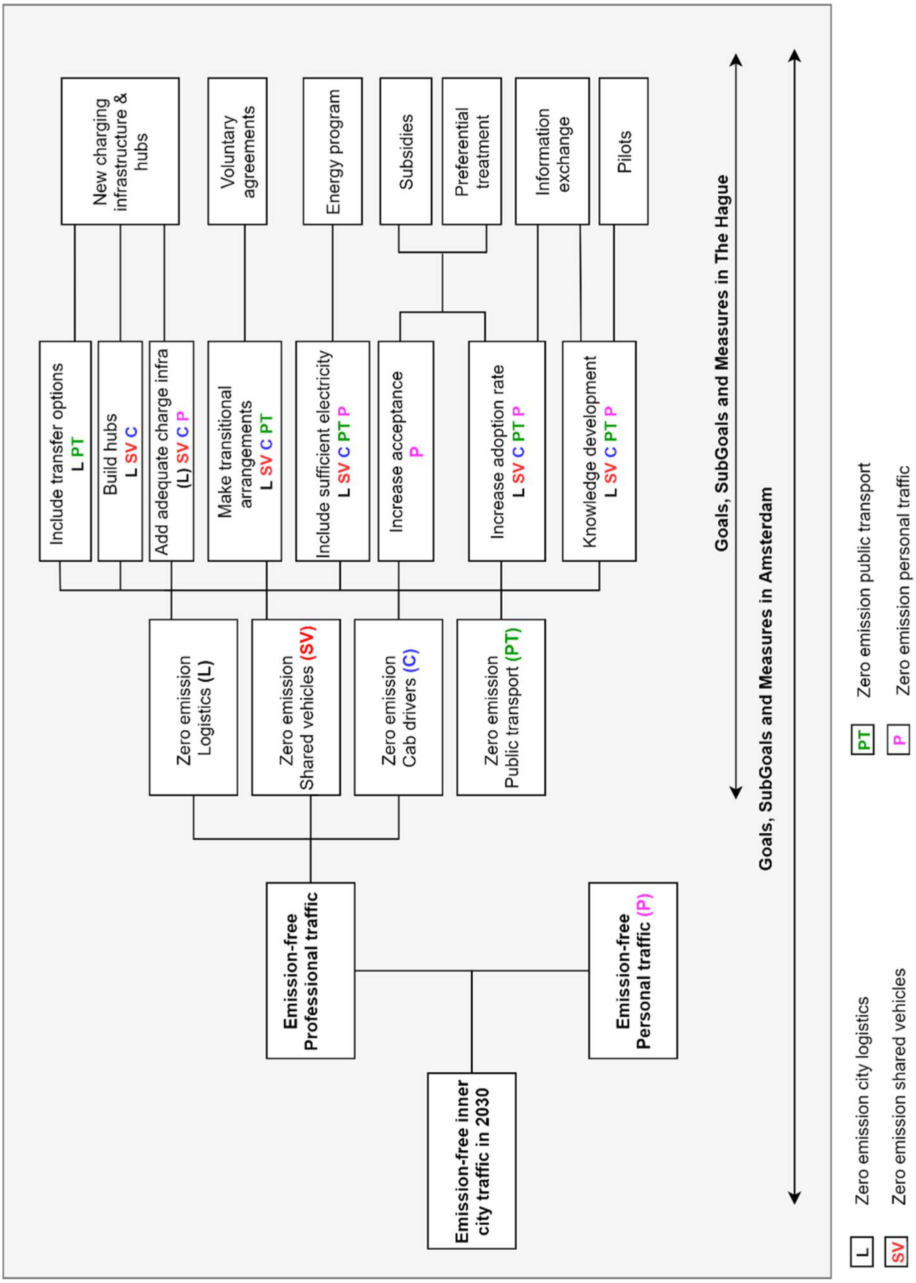

Figure 3.3: Objective Tree of Emission-Free Inner City Traffic.

old vehicles (D13) and subsidies for public transport operators who want to install PV chargers (D29). Knowledge is being developed on charging (A13, A27) in Amsterdam. An information exchange incentive was identified for decreasing CO_2 emissions in The Hague and surrounding municipalities (D30). Adequate charging is being addressed in Amsterdam for personal vehicles and logistics (A31), cab drivers (A41) and shared vehicles (A9). In The Hague, there are policies addressing charging for personal drivers (D10) as well as cab drivers and logistics (D9, D24). Electricity supply is addressed in Amsterdam with a city-wide program (A44), and in The Hague, the electricity challenge is being addressed for electrifying built hubs (D14). We identified seven conditions for logistics, six for shared vehicles and cab drivers and five for personal vehicles and public transport. Another goal that was clear from the mobility documents of both municipalities is to create a successful alternative mobility market to promote a modal shift. This would decrease the use of public spaces (such as parking spots or roads), and electrified fleets without personal owners could be used for storage. Car ownership and CO_2 emissions could decrease, as investigated in Table 3.7. In order to develop this market, policy makers have to facilitate progress by bringing providers together, work on interoperability of the MaaS market, attract users and take into account other resources that are necessary for this progress, such as mobility hubs or supply and demand platforms.

The conditions identified for a successful modal shift were attractive options, knowledge development, adequate infrastructure (parking and charging), car-free streets and public transport expansions (Figure 3.4). Attractive options were found in Amsterdam in the form of mobility budgets (A2), financial incentives for alternative transport (A7) and the roll-out of cheaper shared mobility (A33). In The Hague, shared mobility providers are attracted with parking permits (D1) and shared fleet expansions (D18). Both municipalities are developing a service mobility market by developing mobility-as-a-service platforms (A4, D27). Knowledge is being developed on shared mobility (A12, A13, D23) in both municipalities, and on living–sharing combinations (D22) in The Hague. Amsterdam has initiated pilots that anticipate drones (A18) and autonomous vehicles (A16). Information exchange takes place for shared vehicle initiatives in both municipalities (A39, D20). Adequate parking is addressed by P&R (A34) in Amsterdam, and indoor parking spaces (A24, D4) in Amsterdam and The Hague (please consult the previous paragraph for charging policies). Low-car streets are developed in the market area (A32) and by cutting the main street (A14) in Amsterdam. In The Hague, traffic is redirected (D3) with reduced maximum speeds (D21), and there is a pilot for a car-free neighborhood (D17). Public transport expansions are mentioned for The Hague (D2), and Amsterdam specified a night metro (A6) as well as a new metro line (A23). Appendix 9.4 describes the different policy measures that could be used to satisfy conditions. It also provides insight into the extent to which conditions are addressed—and for which user group.

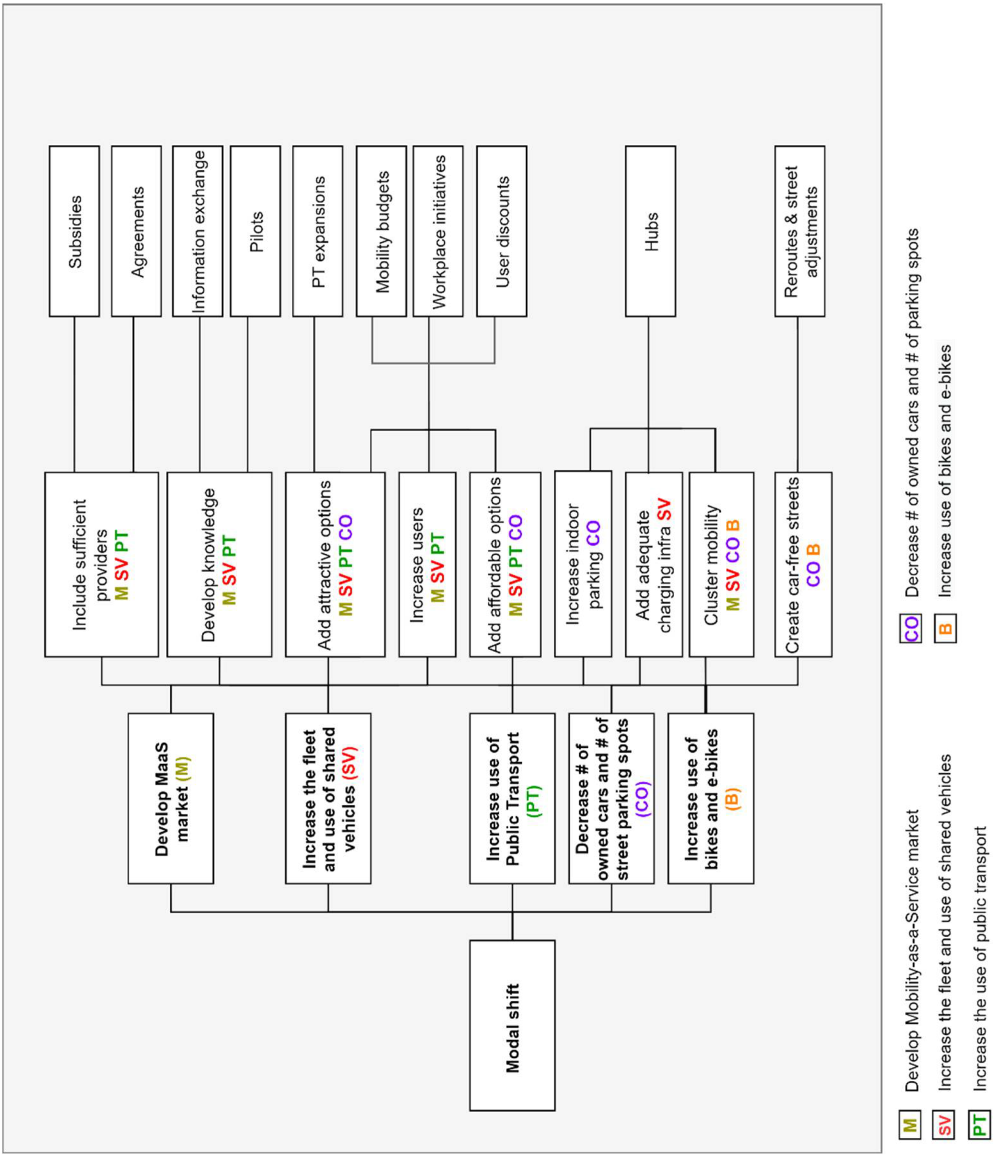

Figure 3.4: Objective Tree of Modal Shift.

SUMMARIZING MECHANISMS IN A SYSTEM DIAGRAM

The domain effects (on evaluation criteria) were combined with, external factors and policy measures of the two municipalities in a simplified system diagram (Figure 3.5). We also added some relevant system factors to explain the mechanisms behind the policy effects. Effect directions are summarized as + (will increase), +/− (both directions possible), ? (effect unknown) and − (will decrease). 'No effect' was not included in the diagram. The diagram is directed towards the evaluation criteria. The effect of these criteria on other factors is not included. On the left side, the gray boxes indicate the common measure types (aggregated). The colored boxes (middle) represent some of the system factors that are influenced by both measures, as well as external factors, and directly influence the evaluation criteria. The gray boxes on the right contain the evaluation criteria. Finally, the external factors can be found on the far right, in purple boxes.

A step-by-step description on the use of the system diagram is given below using one of the evaluation criteria (as an example): *occupancy rates*. In Table 3.7, we found that fleet compositions and adoption rates affect the influence of policy measures on the occupancy. The intermediate factors in the diagram further illustrate how occupancy takes place in the public charging system. The occupancy rate is influenced by the number of EVs, the charging network size and density, the number of and distance between charging points and by measures that influence the adoption rate (and therefore the number of EVs), such as subsidies and preferential treatment. The charging network size and density can be increased by new infrastructure, and fast chargers could increase the charging speed which can lower connection times of charging sessions. There are also factors that we do not control that influence the occupancy rates, such as the charging preferences of users and the battery size of vehicles, which can increase adoption rates (less range anxiety) but also affect connection times and the frequency of charging. Market developments, another external factor, can influence adoption rates directly by attracting more consumers, or indirectly by lowering the total cost of ownership. These influenced adoption rates also affect the occupancy rate. There are some notable relationships in Figure 3.5. The measure mobility-as-a-service draws direct as well as indirect lines to almost all evaluation criteria. This illustrates the potential of MaaS platforms to increase the use of electric mobility, decrease car ownership, and therefore parking pressure, and decrease the amount of kilometers driven, which decreases energy consumption as well as local emissions. Energy consumption and local emissions do not only correlate as criteria, but they are also affected by similar measures and the same external factors. Parking pressure and car ownership are also affected by similar external factors, measures and system factors.

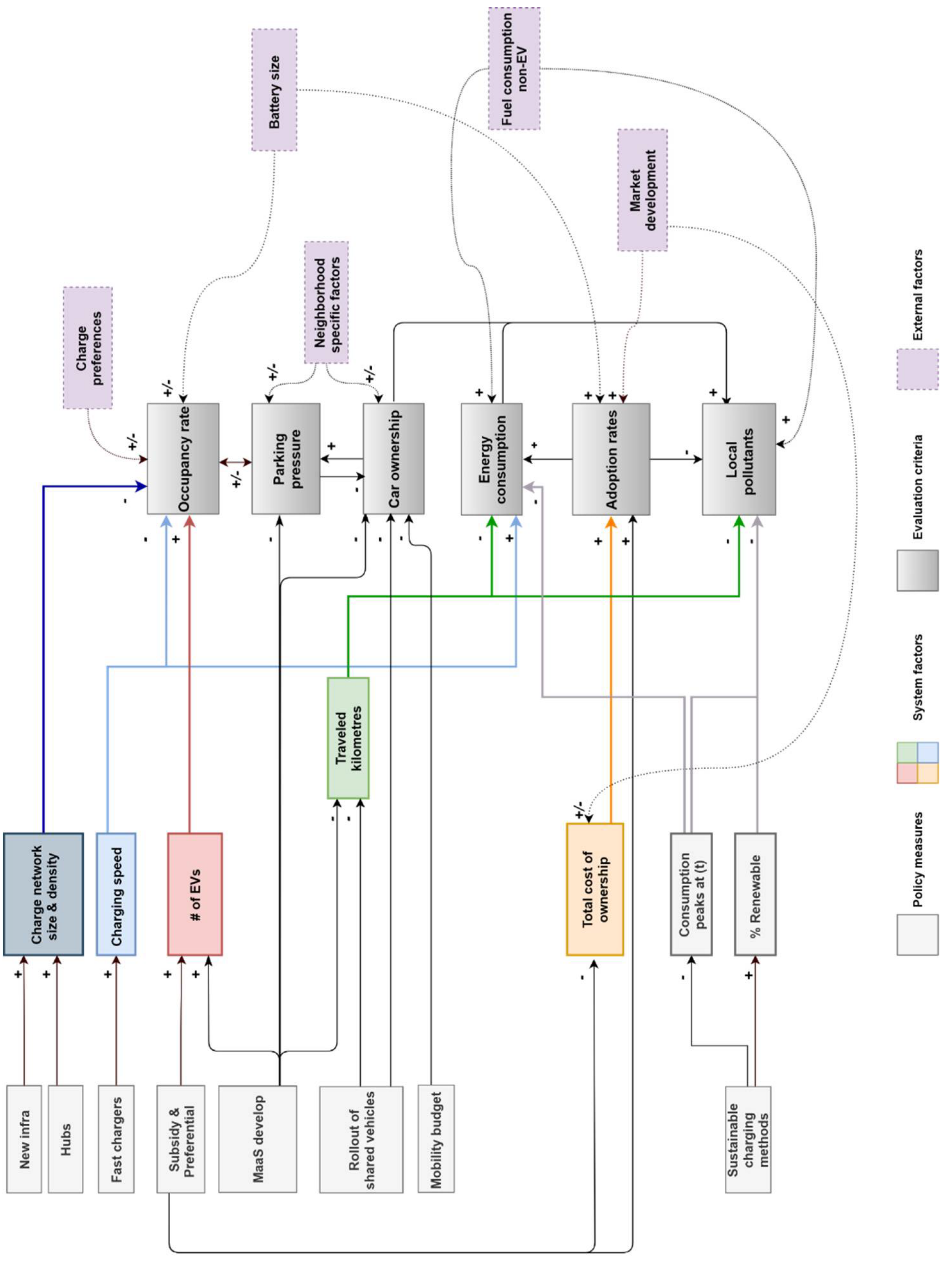

Figure 3.5: Simplified System Diagram.

3.4. Discussion

In this chapter, mobility policies of two of the largest Dutch municipalities, Amsterdam and The Hague, were analyzed. Afterwards, these policies were evaluated on relevant criteria for the municipalities. Objective trees were also constructed for two of the key mobility objectives (modal shift, and EV and infrastructure roll-out), which revealed the conditional settings for the policies to succeed. Finally, the policy mechanisms were summarized, and interactions were identified through different parts of the analysis, in a system diagram. This enabled us to illustrate the different goals of the case study environments, and the extent to which these goals have been addressed in policies. We were also able to illustrate some important interactions between the policies and goals while considering other aspects such as the local environment, external factors, interdependencies and system interactions. The results led us to a number of identified challenges, as well as recommendations. The case study outcomes are discussed first. Then, the challenges in urban mobility transitions are discussed. The chapter ends chapter with recommendations for municipalities' strategies for the mobility transition, and recommendations for future work. It is important to consider the scope (Table 3.2) and assumptions that were made (Appendix 9.1) while interpreting the results and discussion.

3.4.1. Case Study: Amsterdam and The Hague

The analysis of mobility policies was executed using two case study environments: Amsterdam and The Hague. The use of a case study environment, as opposed to a traditional literature review, enabled us to apply the findings of prior research to a case study context, while considering local challenges, data, and pilot outcomes. The case study also increased our understanding of how relationships can be strengthened or diminished by environmental factors. Using two case studies, instead of one, enabled us to compare different municipalities and explain their overlaps and differences (see next paragraphs). Similarities were found between the case study environments. The mobility strategy for Amsterdam and The Hague largely overlaps, despite differences in their policies towards electrification. We also observed an overlap in Green Deal and City Deal participation for car sharing, and both municipalities have detailed regulations for the logistic sector and public transport. The policy measures that were most common for both municipalities were measures addressing the construction of new charging infrastructure and measures addressing the roll-out of shared vehicles (Table 3.6). Both municipalities provided attractive mobility options for their citizens and made an effort to start voluntary agreements with different user groups. The municipalities both had a focus on shared mobility pilots. There are also substantial differences. The city of Amsterdam is stricter in electrification requirements and deadlines for visitors, touring cars, logistics, public transport and personal and shared mobility, whereas The Hague mainly focuses on strict zoning and deadlines for logistics and public transport, and is less strict in deadlines for other user groups. There is no 'hard' electrification requirement yet for new shared mobility providers in The Hague (Appendix 9.1). Knowledge development measures were more common in the analyzed documents of Amsterdam, and Amsterdam had more pilots addressing new technological development in these documents. Pilots addressing shared mobility in Amsterdam were focused on increasing accessibility and affordability, whereas shared mobility pilots in The Hague were more focused on the integration of shared mobility in streets, neighborhoods and living spaces. We can explain some of these differences by the environmental context. Amsterdam is a touristic hotspot that deals with a lot of visitors and touring cars, whereas The Hague had more growth in new building projects (0.6 percent vs. 1.1 percent, (CBS, 2021)) in 2020 than Amsterdam, which provides more opportunity for projects and pilots that include new streets or buildings.

3.4.2. CHALLENGES IN URBAN MOBILITY AND PUBLIC EV CHARGING INFRASTRUCTURE

We anticipate challenges in aligning the mobility policy objectives related to EV adoption and a modal shift, especially in the case of competing goals and temporal sensitivities. There is potential for synergy between the implementation of a modal shift and EV adoption. At the same time, there is an increased layer of complexity, which can lead to a policy risk: competing goals may undermine policy effectiveness. A key example is the car ownership decrease goal vs. the increase in the adoption rate goal. Potentially competing conditional settings may also undermine other policies' workings (e.g., sufficient nearby charging infrastructure vs. car-free streets) in this stage of the transitional period. Finally, there is the dilemma of clustered activities (e.g., parking and charging), and to what extent different types of mobilities and users can benefit the most from these activities. Lack of awareness of temporal interdependencies could lead to suboptimal investments and, ultimately, stranded assets. This is applicable for the expansion of charging infrastructure itself: the best location for charging infrastructure is temporally dependent on the extent to which car ownership is decreased/car-free streets are introduced (locations may become obsolete), as well as the extent to which autonomous fleets are adopted (the distance to a location becomes less relevant). Electricity requirements and charging requirements are temporally dependent on the extent to which EVs are adopted, and the technological developments in ranges and batteries. Facilities that were introduced for the transitional periods, e.g., transferring points for inter-urban fossil vehicles, will become obsolete over time (but highly anticipative and creative policy makers may be able to re-use the facilities to satisfy a new condition). This challenge could be addressed in future studies by selecting policy analysis methods that explicitly address the temporal interdependencies of policies (see Section 3.4.4).

3.4.3. RECOMMENDATIONS FOR MUNICIPALITIES

Municipalities have to work on increasing EV acceptance for different user groups by satisfying their (specific) conditions. User groups have their unique set of conditions that need to be fulfilled in order to transition to a new mobility system. The specifics of these conditions may be different for other municipalities over the world, e.g., in terms of the energy capacity, amount of public space and the level of private parking that users have available. Implementing policy measures per user group or specific policy goal does not always enable the right policy conditions. The inventory summary (Table 3.5) showed how policy measures were mostly addressed to citizens/personal vehicle users (38 percent in Amsterdam, and 32 percent in The Hague). However, we found that the measures addressed more conditions for logistics, cab drivers and shared mobility (Figure 3.3; Appendix, 9.4), as opposed to personal vehicles or goals that concern residents (such as car ownership decrease).

Amsterdam and The Hague also showed room for improvement in addressing specific conditions. In the future, they could aim for a more elaborate mix of charging modalities to increase security and comfort. An example of an overlooked modality is urban fast chargers. Urban fast chargers are still rare, and only 3 percent of national public chargers can be considered a fast charger (RVO, 2021). Meanwhile, the kWh that is charged in a session is increasing yearly (see Table 3.1). Although both municipalities have a policy addressing fast chargers, the target numbers are still quite low compared to normal chargers. Fast chargers can increase acceptance and comfort for cab drivers (Tamis and van den Hoed, 2020), as well as personal drivers (Lieven, 2015). Urban fast chargers require less charging time, which could reduce occupancy rates and therefore reduce one of the main reasons not to get an EV: not enough charging points (ANWB, 2020). We recommend aiming for a proper mix of charging modalities that fit the activities of the driver (e.g., a fast charger for shopping, a smart charger for overnight parking garages), in order to increase acceptance, charging comfort, and charging security while still taking the grid impact into account. Another example from the case study is that both municipalities have a limited number of measures addressing the information exchange policy sub-condition (Appendix, 9.4). Despite knowledge exchange taking place between parties that are in a pilot, additional information exchange measures could be introduced to include residents, as well as smaller municipalities with decreased pilot opportunities and other stakeholders. Municipalities will have to anticipate technological developments by considering their impact on charging requirements, parking requirements, energy requirements and mobility service models. At the time of writing, neither Amsterdam nor The Hague included many pilots with disruptive technology in their mobility policies. Amsterdam mentions a few specific use cases: drones as a delivery service, and the use of a test location for autonomous vehicles (AVs) in a closed mobility system (office area). However, what happens if, for example, AVs are included in a city-wide mobility system? There are implications for autonomous charging (cable requirements, decreased charging station hogging), as well as potential for autonomous delivery options, and AVs could increase the accessibility (flexibility in location and driver's license) of shared mobility and other mobility services. Earlier developed scenarios suggest that AVs are to be expected on the Dutch roads between 2025 and 2045 (Milakis et al., 2017) and emphasize the importance of policy making in the successful adoption of AVs. The policy making on AVs is still limited in both case study municipalities. It is likely that the introduction of AVs will be accompanied by the adoption of other disruptive technologies such as wireless charging (Angrisani et al., 2014) and space-efficient self-automated parking lots (Ferreira et al., 2014) Another technological development which may disrupt the current charging infrastructure is battery development. An increase in battery size has already been shown to influence the amount and length of charging sessions (Wolbertus, R., van den Hoed, R., 2020). Municipalities, as well as other stakeholders, have to make a continuous effort in identifying and anticipating these new developments, in order to avoid unsatisfying conditions or stranded assets.

3.4.4. FUTURE WORK

In Section 3.4.2, we identified some temporal interdependencies as a challenge for urban mobility policy alignment. Future work could include the selection of policy analysis methods that explicitly address these interdependencies. Pierson (2000) wrote about the difficulties of determining relevance and identifying path dependencies. Webster (2008) illustrated how the roll-out of one policy affects the possibility landscape for future decision making (irreversibility). Taeihagh et al., (2013), introduced a method for policy sequencing, which considers not only conditions but also contradictions and synergies between policies. These views and approaches could be especially helpful when a researcher can consult the policy maker prior to the roll-out of a policy roadmap, emphasizing the importance of involving a wide variety of experts in policy consultation. Additional evaluation criteria could be added to broaden the context for the analysis. Additional data could be used to estimate policy effectiveness in more detail. The suggested evaluation framework could be expanded, for instance, by adding acceptance or maturity levels, implementation and maintenance costs and the use of public spaces. This could provide further insight in the long- and short-term costs and benefits that are associated with the implementation of different policies. Municipalities could be further supported by stimulating the monitoring of these types of criteria in their local context, for example, by designing a decision support tool. Such a tool could be designed with the help of experts in mobility, transport, climate and urban planning.

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4

Case Studies of EV Charging Under Various Policy Conditions

This chapter summarizes the analysis of three different policy interventions in the Netherlands. The types of analysis include desk research and statistical analysis. For these analyses, open data, relevant literature and charging transaction data are used. Together, these studies provide insights on the effects of policy interventions on different local levels. For convenience, these three studies are referred to as "case studies" throughout this chapter. The chapter includes the following studies:

- *Challenges in developing the charging market from a competition law perspective (4.2).*
- *Aftermath of COVID-19 on public charging in the G4 municipalities and MRA-E (4.3).*
- *Inter-urban charging behavior of Amsterdam-based cab drivers who live in the MRA-E (4.4).*

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4.1. Introduction

In Chapter 3, mobility policies of two large municipalities were discussed to determine the policy landscape of EV charging. The chapter analyzed the potential effects of policy interventions on the development and use of charging infrastructure. However, the influence of policy context in a geographical area cannot be fully anticipated by literature alone. Therefore, it is important to determine how policies affect charging. The second sub-question of the thesis, *"How do policy interventions affect public charging infrastructure?"* relates to the case studies, as the case studies can provide examples of how policies have affected public charging. Case studies are commonly used in policy analysis to investigate policy effects. Pal (2005) states that analysis of case studies can help define problems in their full context, and this can lead to more insights than traditional research analysis. Case studies also help identify the results and effects of policies within the local context and within the context of the policy objectives. This could create valuable insights to improve future policy (de Asis and Widner, 2022). In this chapter, three different case studies are investigated and discussed. The first case study looks at the effect of policy settings on the procurement and development of charging infrastructure (4.1). The second case study looks at the effect of COVID-19 policies (lockdowns and curfews) on the use of charging infrastructure (4.2). The last case study investigates the effect of electrifying cab drivers in the city of Amsterdam on the charging demand in neighboring cities (4.3). This gives us the following sections:

- National & Regional level: Challenges in developing the charging market from a competition law perspective (4.2).
- Regional level: Aftermath of COVID-19 on public charging in the G4 municipalities and MRA-E (4.3).
- Municipal level: Inter-urban charging behavior of Amsterdam-based cab drivers who live in the MRA-E (4.4).

The last two paragraphs of the chapter summarize the effects of the studied cases on public charging.

4.2. Competition in EV Charging

4.2.1. Introduction

In the Netherlands and some neighbouring European countries, the electric vehicle (EV) charging sector is receiving attention from market regulators. Concerns relating to competitive processes in this rapidly growing sector are being raised by stakeholders. This literature study identifies specific markets where regulation can help increase the level of competition for the development of affordable and accessible public charging infrastructure, both within the built environment (slow charging) as well as along highways (fast charging). Barriers to competition include exclusive concessions at the municipality level and long-term exclusive concessions at locations along highways.

Research Questions

A desk study was carried out to identify the challenges in the developing charging market. The research questions are:

1. What are the challenges in developing public on-street slow charging?
2. What are the challenges in developing highway fast chargers?
3. What are the challenges in enabling smart charging?

4.2.2. THE PROFITABILITY OF PUBLIC EV CHARGING IN THE NETHERLANDS

THE DEVELOPING BUSINESS CASE FOR PUBLIC SLOW CHARGING

Public slow chargers are located within city boundaries (e.g., on-street and in public parking lots). Roughly 22% of charging sessions in the country (and 45% of the sessions in the G4 region) are public slow charging sessions. Public slow charging is more commonly used in urban areas than rural areas. For example in the more rural north of the country, only about 12% of charging occurs in public slow chargers as opposed to 22% at the national level and 45% in the G4 (RVO, 2021c). The costs of developing slow chargers in the public environment consist of the allocation in the public space (appr. €350), a grid connection (appr. €750), installation, and hardware (appr. €2000) (Dutch Ministry of Infrastructure and Water, 2020). Operational costs include electricity, ICT, and maintenance. Costs have decreased in recent years but are subject to increase with the emergence of new standards and technologies, and a reduction in subsidies. The profitability related to charging infrastructure depends on several factors: the electricity charged, the number of users, the price of electricity, the use of renewable electricity, and the lifespan of the charging station (5-7 years, Dutch Ministry of Infrastructure and Water, 2020). Public funding has contributed to development of the business case for public slow charging. Until 2018, municipalities partially financed charging infrastructure through the use of government grants, through the Green Deal GD-185 (RVO, 2015). In the past, the electricity used for public charging has been taxed at a lower rate. In most municipalities, infrastructure is financed with joint procurements (either as a municipal or regional concession), to lower investment risks and to develop charging in rural areas.

BENEFITS AND CHALLENGES OF SMART CHARGING

With smart charging, the charging speed is adapted dynamically to increase grid flexibility, reduce peak electricity demand, and to use renewable sources effectively. The use of smart charging can help delay the expensive grid expansions needed at certain locations for public slow charging. Several Dutch pilot projects have illustrated the benefits of smart charging at home (ElaadNL; Enexis; Enpuls; Maxem, 2020) as well as for public slow charging (Ligthart et al., 2020). As EV adoption progresses, the use of smart charging is necessary for ensuring access to charging in the future, and is expected to become the Dutch norm after 2025 (Dutch Ministry of Infrastructure and Water, 2022). The support for smart charging is increasing because it can help avoid the high societal costs associated with the electricity grid, such as expensive grid expansions or potential blackouts of the electricity system. Dutch decision-makers were found to consistently value smart charging above other charging techniques (van der Koogh, Chappin, et al., 2023).

Public smart charging also has some potential issues. Charging speeds vary with smart charging, which affects the social acceptance of users and markets. Besides, the lack of agreements between chargepoint operators and DSOs makes flexible pricing more complicated, which prevents the charging market from evolving into a capacity market. Stakeholders have been exploring solutions to further enable public smart charging, for example by suggesting improvements in tariff structures and potential compensation of market adopters (Monteban et al., 2021). The Dutch National Charging Infrastructure Agenda (NAL) suggests that the availability of transparent, up-to-date information and agreements between parties would provide a stimulus for the smart charging market and the consumer (Nationale Agenda Laadinfrastructuur, 2022). DSO's are exploring flexible contracts to enable smart charging during peak hours in neighbourhoods with low grid capacities (Stedin, 2021).

High costs of public fast charging along highways

Fast charging infrastructure is a variation of publicly available charging, but with other stakeholders and legislations involved. This is because fast chargers are mainly located along highways, where EVs can recharge quickly to continue their journeys. Since the land alongside highways is state-owned and regulated, fast chargers are almost entirely public. The business case for fast charging is affected by the higher costs of grid connections and the high costs of the fast charging points. Due to these factors, the electricity tariffs that vehicle users pay for fast charging are higher than those paid for slow charging. Despite the high tariffs which customers seem willing to pay, the fast charging market is still struggling with profitability. In 2023, Fastned, the current market leader of highway fast chargers, became profitable after 11 years of operating (Fastned, 2023).

4.2.3. Competition in public charging in the Netherlands

Slow charging in the built environment

Policymakers typically use one of the following models to ensure charging infrastructure in their municipality (kennisplatform laadinfrastructuur, 2021), depending on the stage of development, citizens access to driveways, and local adoption rates.

1. Exclusive concessions model: A single party is granted the rights to install and exploit charging infrastructure in a specific area for a fixed duration of time.
2. Commission model: The municipality, or a third party commissions charging infrastructure and carries the investment risk.
3. Open market model: All market parties can apply for chargepoint permits. Some market parties allow citizens to make direct requests through their websites.

It is common for municipalities to award exclusive concessions. Some of these concessions are at the regional level, which enables a larger network of charging across municipalities, strengthens the business case for the market party, and reduces the work for individual municipalities (laadinfrastructuur, 2021). Vulnerabilities of the exclusive model include the risk that a single party is not always able to keep up with demand, and that parties sometimes have to add unrealistic pricing in their plans towards municipalities to win the concession. A group of CPOs complained that the awarding process of municipalities is too focused on the lowest suggested price (Stichting Doet, 2021). In comparison to exclusive concessions, the open market model shows several benefits. If a single party is unable to deliver infrastructure, other parties can be contracted to meet the demand. EV drivers have a sense of choice, and market parties can compete, not only with initial pricing but also with other aspects such as customer service. Some drawbacks of the open market model for municipalities include lower control over the development: lower control over prices, roll-out strategies, and roll-out deadlines. Due to allocation and traffic decisions, the awarding of permits may also be slower. The commission model can be a solution for rural areas where profitability is a challenge. The municipality is able to set their own pricing and protocols (such as smart charging). Using this model, profit is no longer a barrier to ensuring charging in these areas, but as the municipality is responsible for this infrastructure, the workload of the policymaker may increase.

Fast charging along highways

Highway fast charging procurement falls under the jurisdiction of the national policy makers of the Dutch Ministry of Water and Infrastructure. The ministry awards two types of permits (Langman and Lugt, 2022):

1. Primary facility permit: A single primary facility permit is awarded per rest area along the highway for facilities like a fuel station, a restaurant or a fast charging station.

2. Additional facility permit: These are given to existing establishments with a primary facility permit for extra facilities at the location, such as fast charging or food and beverage sales.

The development of fast chargers is sometimes challenging, because both permit structures know their limitations.

The primary facility permit is given to parties who want to develop and exploit chargepoints on an assigned piece of land for a given time. Challenges in primary permits include the high initial costs for grid connections, which should be gained back by the exploiter within contract time, and the delay in development of fast charging points. Exploiters are not always able to deliver in time because of necessary grid expansions or supply-chain issues, and because of the exclusive nature of the permit, that area will stay undeveloped until the permit holder is ready (Rijkswaterstaat, 2021).

One issue with the additional facility permit structure is that it gives established restaurants and petrol stations an advantage, since they could apply for additional permits outside of the tender. Primary facility permits are exclusive to the area and are competed for through tenders. In the past, additional facility holders were able to exploit their primary function (e.g. petrol station or restaurant) for extra service such as food shops and toilets, whereas the primary charge facility holders could not apply for these additions, which was another disadvantage for them. The court decided in a handful of cases that this was unfair, and that these permit holders should also gain the opportunity to add facilities (e.g., judgement 201905907/1/R4).

Economists looked at the fast charging policies for highways and noticed that there is no advantage for the consumer to have multiple fast charger exploiters in one area. They recommend one primary permit for tank stations, and one primary permit for chargers. They do not recommend additional chargers, because this has no financial benefit for the user and the business case for both parties is weaker. For restaurant additions, this is a different case, say the economists, as they can compete with different products. An alternative pathway to developing fast charging infrastructure is to re-organize each area individually (petrol stations will turn into a complete charging station after permits have expired, leading to an full-area transition (Langman and Lugt, 2022).

4.2.4. CONCLUSION AND RECOMMENDATIONS

To conclude, public on-street charging and highway fast charging is developing rapidly, but some barriers and challenges still exist today:

- *Challenges in developing public on-street slow charging:* Challenges in public slow charging include barriers to market entry related to concession models, lack of profitability in rural areas, which leads to limited competition options for EV users.
- *Challenges in developing highway fast chargers:* Challenges in fast charging include development delays, the need for additional grid infrastructure and challenges in entering the market because of permit models.
- *Challenges in enabling smart charging:* The challenges in smart charging include the lack of flexibility agreements and financial agreements between the CPO, EMSP, and DSO.[1]

The following paragraphs will give some recommendations to overcome these challenges.

PUBLIC SLOW-CHARGING

Based on the observations made in the paragraphs above, the following recommendations can be made to improve the public on-street slow charging market:

1. Reduce long-term area exclusivity to lower the barrier to entry for competitors
2. Ensure access to EV charging in rural areas where either low grid capacity or low utilisation of charge points lead to weaker business cases and correspondingly low market participation.
3. Provide guidelines to protect consumer interests in areas with low competition such as price ceilings, access to customer service and minimum expected maintenance

[1] Since this study was published, the legislation around flexible agreements has been updated (Netbeheer Nederland, 2024).

Smart Charging

Similarly, a few recommendations can be made to improve the smart charging case in public on-street charging:

1. Facilitate flexibility agreements between DSOs and charging point operators, using the avoided costs of grid expansions to determine the value of flexibility [2]
2. Provide governmental funding to enable smart charging in lower grid capacity areas as a way to address the geographical disparity in charging infrastructure and ensure equal access to charging.
3. Make the scarcity of grid capacity explicit in the price paid for charging by consumers at public slow charging stations by transitioning from static prices to variable pricing which reflect the time-variant scarcity in grid capacity, and by adding smart charging requirements for neighbourhoods with low grid capacity.

Highway fast charging

For the development of highway fast charging, the recommendation is to reduce the financial risk for market players, and to make the development of charging less dependent on a single market player. This can be done by reducing contract durations, facilitating take-overs, and allowing other market players to step in when development is stagnated. The following recommendations could help obtain these goals:

1. Enable the take-over of grid connections and existing infrastructure by new market players for a fee, based on permit terms and depreciation.
2. Ensure compliance with interoperable standards for installed infrastructure to make these take-overs possible and to avoid technology lock-in, vendor lock-in and to reduce switching costs.
3. Enable others parties to enter the market if the permit holder of the designated area shows significant delay in developing the infrastructure
4. Take into consideration the already recommended pathways, as suggested by consultants, to reorganising the permit structures (Rijkswaterstaat, 2021 and Langman and Lugt, 2022).

4.3. The Aftermath of Covid-19 Lockdowns on Public charging

4.3.1. Introduction

COVID-19 lockdowns halted transport movements all across the world; electric vehicles were no exception. People were working from home more and contacting each other through digital means. Car–related transport temporarily decreased by up to 50 percent in 2020 (Kim and Kwan, 2021). The use of electric vehicles in the Netherlands saw a similar drop. Many suggested that the effects of working from home would last longer than

[2] See footnote 1

the COVID-19 lockdowns as the benefits of working from home, such as work effectiveness, decreased commute times, fewer traffic jams, and cleaner air, were experienced at a mass scale for the first time (Huang et al., 2020; Heiler et al., 2020; Kramer and Kramer, 2020). Major companies have announced new work-from-home policies. Additionally, car transport shifted throughout the day as most only ventured out for necessary appointments. These policies also affected the movements, and thus the charging needs, of electric vehicle drivers. This study examines differences in charging behavior during the COVID-19 lockdowns, with a special focus on curfews and user groups, and finally post-lockdown to see the implications of new company policies. This is done by analyzing a dataset on charging behavior from 2020 up to and including October 2022. From this analysis, strategic effects on charging infrastructure planning are derived.

The COVID-19 lockdowns disrupted the EV manufacturers supply chains, productions, and operations (Wen et al., 2021). Despite these disruptions, the full fleet of battery-electric vehicles in the Netherlands grew 70 percent in 2020, compared to 2019 (RVO, 2021b). In 2020 as well as 2021, 1 out of 5 newly sold vehicles in the Netherlands were electric (RVO, 2021a). This is because the Dutch have been the addressing decarbonization of mobility through various policies [3] This has led to an uptake of electric vehicles and the development of one of the densest charging networks in the world (International energy agency, 2021).

The COVID-19 lockdowns affected different aspects of the energy system. For example, the roll-out of PV solar panels was much lower than predicted in 2020 because of manufacturing and supply chain issues and decreased urgency because of lower peak demands during COVID-19 (Aminifar et al., 2020). The effect of COVID-19 and related policies on the charging of electric vehicles has been monitored by various researchers. Two researchers monitored two charging points at a public facility in California (Shahriar and Al-Ali, 2022). They found that charging sessions declined from the start of lockdown and came to a complete halt between August and the first half of November 2020. The state of California then dealt with multiple issues, such as increasing pandemic-related death rates, wildfires, and blackouts, explaining the lack of sessions. At the end of 2020, they monitored charging activity at roughly 25 percent of the original capacity (a 75 percent decrease). The authors also found an increase in sessions starting in May 2021, which they attribute to the roll-out of COVID-19 vaccines. Some researchers have also been monitoring EV charging during COVID-19 lockdowns in Utah (Palomino et al., 2021). Here, only a maximum decrease of 40 percent (or 60 percent of full capacity) was measured, with the steepest decline in May 2020. A group of Dutch researchers focused on three charging locations in the Dutch city of Utrecht (Brinkel et al., 2021). They compared a residential area with an office area and an event location. During the first lockdown, they saw the most decline at the event location (-99.2 percent), followed by the office area (-89.6 percent), and the least decline at the residential area (-73.6 percent). Results from this study differ from the USA studies, since the first lockdown phase around March 2020 had the strongest effect (only 25 percent of full capacity, or a 75 per-

[3] Mobility is one of the four key pillars mentioned in their Climate Agreement (Rijksoverheid, 2019; De Rijksoverheid, 2018), and electrification of traffic is embedded in national (RVO, 2019), regional (MRA-E, 2019), and local policies (e.g., Gemeente Amsterdam, 2020a).

cent decline), whereas the later lockdown phases in 2020 led to a smaller decline. A Chinese study of four cities found similar declines in the range of roughly 50-70 percent in early 2020 and correlated the decline in EV charging demand with the number of confirmed COVID-19 cases and the associated hospitalizations, with one factor being more important than the other, depending on the city (Zhou et al., 2022). There have also been studies addressing the different charging behaviors associated with distinct user segments. In the Netherlands, start times of charging, charging durations, time between charging, the kWh charged, and the number of selected locations to charge can differ significantly between user segmentations (such as residents, commuters, taxi drivers, and shared vehicles) (Helmus and van den Hoed, 2015).

These studies, although insightful, are based on a limited number of observations over a limited time span. This study evaluates charging for different lockdown phases, types of areas, and user segmentations in the Netherlands using a longer measuring period. This enables us to further determine the effects of COVID-19 lockdowns on electric vehicle charging.

Research Questions
The main question of this study is *"What is the effect of COVID-19 lockdowns on charging behavior?"*. The following research questions were used to investigate the effects of COVID-19 policies on charging infrastructure:

1. How does the decline in EV charging during COVID-19 compare to the decline in refueling traditional vehicles?
2. How does the decline in EV charging compare between user segmentations?
3. What were the effects of curfews on the start times of charging sessions?

The overall (not group-specified) effect of lockdowns on charging behavior can be found in van der Koogh, Wolbertus, and Heller, 2023.

4.3.2. METHODS

DATA

Charging data was collected from public charging stations in the Netherlands in the cities of Amsterdam, Rotterdam, Utrecht, and The Hague. In total, more than 7.5 million charging sessions were collected from January 2020 up to October 2022. Background on the dataset and the data collection process can be found in another publication (Maasse, S., van den Hoed, R., 2019). An example of data variables gathered can be seen in Table 4.1.

TIMEFRAMES

We used the ‘Coronavirus timeline’ of the Dutch government to compare important lockdown dates with our charging data (De Rijksoverheid, 2018). The Dutch Central Bureau of Statistics keeps track of traffic, fuel, behavior, and car ownership, among others. This data was available on a monthly basis until April 2021. The energy (kWh) charged was

Table 4.1: Data variables and examples.

Variable	**Example**
RFID	60DF4D78
Address	Prinsengracht 767, Amsterdam
Start Connection Date Time	24-04-2015 13:56:00
End Connection Date Time	24-04-2015 17:14:00
Connection Time	2:18:00
Volume	6.73 kWh

summed with all the charging points that were available at January 2020 to avoid measuring increased roll-out and adoption. Office comparisons were made by selecting public charging points from office areas and by fingerprinting sessions to determine which behavior corresponded with employee charging behavior. A night curfew was installed to combat the spread of the new variants of COVID-19. The curfew was first installed in January 2021 and was extended until the end of April 2021. The curfew had two distinct phases with two different end times. In the fall of 2021, another partial lockdown was installed, and in December 2021, the last hard lockdown in the Netherlands was installed. This final lockdown took place for another month, and from February 2022 on, there were no more lockdowns in the Netherlands. Some restrictions, such as the use of vaccination passports and well-ventilated rooms, continued until the spring and summer of 2022.

4.3.3. ANALYSIS

The initial impact of COVID-19 lockdowns was a reduction of roughly 50 percent (both charging sessions as well as energy charged). Growth of new users (adoption) stagnated until late 2022. Evening peak charging was more spread between hours than before the lockdowns, and this effect persisted after COVID-19 lockdowns. An in-depth description of this part of the analysis can be found in van der Koogh, Wolbertus, and Heller, 2023.

FUEL COMPARISON

COVID-19 has led to a decrease in mobility activities during 2020 and 2021. We compared this decrease of energy charged with the decrease of (traffic) petrol sales using CBS data (Centraal Bureau Statistiek, 2021a). The comparison point was set for January 2020. The data was aggregated into monthly data between January 2020 and April 2021. Only charging points that were in the system as of January 2020 were used in the analysis to avoid adoption growth effects. In April 2021, 97 percent of these locations were still active, indicating a maximum potential loss of 3 percent of locations or location charging data.

Figure 4.1 shows the differences in decreases in petrol and electricity sales for vehicles from January 2020 until April 2021. Both lines show a strong decrease around the first lockdown at the end of March 2020. The underlying data reveals that in March, petrol sales decreased by almost 10 percent, whereas kWh charged decreased roughly 30 percent. In April, the decrease was the strongest, with a 25 percent decrease in traffic petrol sales and 50 decrease in kWh charged. This decrease recovers partially during

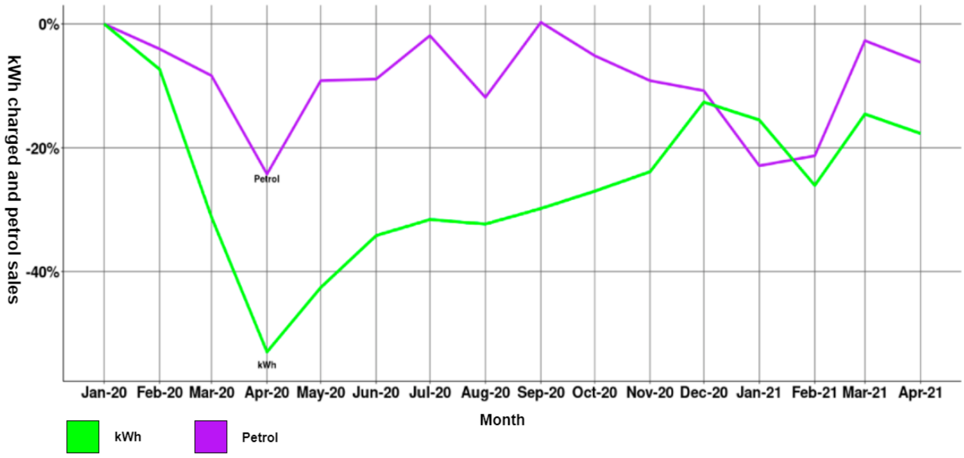

Figure 4.1: Comparison of the decline of national traffic petrol sales with kWh charged in G4 municipalities in 2020

the summer, and in September 2020, petrol sales were even slightly higher than in January 2020. Both lines also show a dip (extra decrease) in petrol sales and kWh charged during curfews, where the initial effect seems stronger for petrol sales but recovers faster.

The much higher reduction in electricity sales compared to petrol can be explained by the different user groups. As electric transport is mostly centered around passenger cars, with only a few trucks on the road, gasoline and diesel vehicles are present in all sectors. Goods transports barely decreased during lockdowns, explaining the difference between the two. The overall reduction in 2020 (compared to 2019) was 20 percent for passenger cars (24 percent for business related travel), and only 3 percent for goods-related transport (Bovag, 2020).

USER GROUP COMPARISON

EV charging had a much stronger decrease during the initial lockdown (March-April 2020) than petrol vehicles. A potential contributing factor to this effect (aside from transport) could be business related. Considering the entire personal vehicle fleet in the Netherlands in 2020, only 17.3 percent is categorized as business (company car, business lease, or personal lease) (Vereniging Nederlandse Autoleasemaatschappijen, 2021). However, this number is much higher for electric vehicles. Additional CBS and RDW data reveals that in 2020, only roughly a third of the electric vehicles on Dutch roads were owned personally (Centraal Bureau Statistiek, 2021b). For full electric vehicles, only 21 percent were personally owned. The charging behavior of professional user groups is analyzed to determine how these groups were affected during COVID-19 and compared to the full set containing all public charging. Decrease rates were calculated using the initial charging numbers for each group in January 2020 (this is the 0 percent point in the graphs). The following sections will discuss charging during COVID-19 for office ar-

Table 4.2: Selection of office chargers and employees

Group	Selection
All sessions (full set)	All public charging data
Sloterdijk Office Area	All charging from 17 charging points in an office location
Suspected employees (office/commuters)	All charging sessions during weekdays (mon-fr), starting between 7–10 a.m. and connected between 3–10 h

eas, employees/commuters, taxi drivers, and shared vehicles.

Office Comparison 2020-2022
A potential explanation for the stronger initial lockdown decrease in kWh charged is the low percentage of personal vehicle owners in the EV fleet. Most electric vehicles are business owned and/or leased. This implies that the vehicle has an important function in either commuting to work, business-related travel, or traffic-related services. Some lockdowns included a work from home policy, either mandated or highly advised, which affected the number of commuters on the road. Working from home was still recommended at times when leisure activities were allowed again. The following paragraphs will address office charging, using three groups to compare (see Table 4.2).

17 charging points that were in Sloterdijk Office Area ('Bedrijventerrein I') are analyzed and compared with all public EV charging in 2020–2022. These chargers are within a geographical scoped industrial area with a variety of companies and offices. The full set of sessions and the office area sessions with the sessions of individual users that are identified as employees are compared. We assumed the following while identifying potential employees on the public charging network: Employees start their charging sessions on weekdays between 7 and 10 a.m., and their connection time is between 3 and 10 h. We found that 7–8 percent of the sessions corresponded with this behavior. In 2020, we see a steep decline for kWh charged in all groups in March-April 2020 (see Figure 4.2). This is when the COVID-19 lockdowns started in the Netherlands. Office area charging points were affected, even more so than the full set of sessions. The energy charged at the office decreased by 70 percent. The green and pink lines (all sessions and suspected employees) do not decrease as strongly and recover more quickly than the blue line (charging points in the Sloterdijk I office area). The 7–8 percent of sessions that we suspect are from employees showed similar decreases to the full set of sessions and recovered more quickly than both groups towards the end of 2020. Charging at the office area did recover slightly by fall 2021. Suspected employees charged more during early 2021 than before, and the demand for this group experienced a steeper growth at the end of 2021. The green line (full kWh charging) and the pink line (suspected employees) exceed 100 percent in 2021, despite our efforts to select only locations that were available from January 2020 on. This shows that, in some cases, the kWh charged per station is higher than before COVID-19. Halfway through 2022, the office area recovers to almost 75 percent of the original kWh charged (before COVID-19). kWh charged by those we expect to commute (suspected employees) peaked temporarily again in March 2022. This can be explained since March has a cold temperature in the Netherlands (which makes batteries less efficient and users likely to drive more), there are 31 days in the month, and

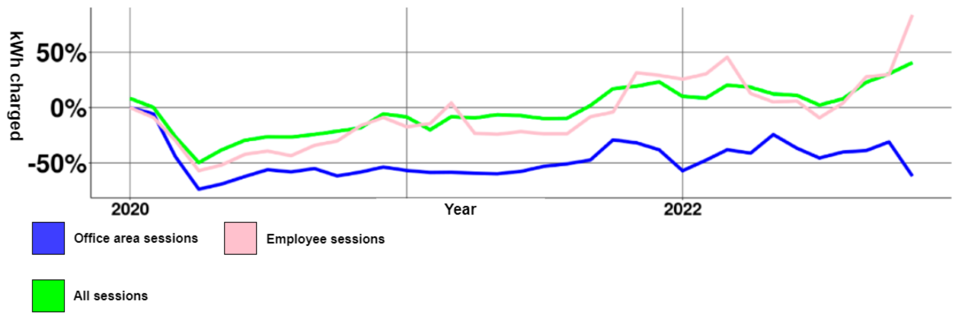

Figure 4.2: Comparing the decline of the full set of sessions with the sessions in Sloterdijk office area and the sessions with commuter patterns ("Employees"). kWh decrease is based on the kWh charged that was observed for each group in January 2020.

no holidays occur during this month. There is an expected drop during the summer for all groups (vacation), but in general, by the general population as well as the suspected employees, up to 25 percent more kWh is charged at these charging points compared to pre-pandemic levels. In November 2022, a similar peak to March 2022 is found, and the overall activity is also higher. In the office area, a reverse effect is found, which cannot be explained by trends or lockdowns. It is possible that charging points were limited in availability and that there were office specific reasons for this drop that cannot be confirmed through the data. We looked at multiple months for each year to account for potential EV adoption growth effects and compare them with the full set of new charging points (Table 4.3).

Growth Adoption effect: The charging points used in the analysis (online since January 2020) were shared by more distinct users than pre-pandemic, after June 2021. The occupancy rates on these charging points have now doubled compared to pre-pandemic. The kWh increase that surpasses pre COVID is therefore partially attributable to the adoption/growth effect, despite measuring the same charging points.
Representativeness: The charging points used in the analysis (online since January 2020) were mostly still online in October 2022. There is no significant loss of charging points, which makes them comparable over the years. Despite the fact that new installations have doubled the number of charging points available, 70 percent of the current (Oct 2022) user base is using the charging points that have been installed since January 2020.

Shared vehicles and Taxi drivers (2020 only)
We were able to distinguish between a group of shared vehicles (185 unique RFIDs, minimum per month active: 175) and a group of Amsterdam taxi drivers (630 unique RFIDs, minimum per month active: 603). These groups also show a similar dip during the first lockdown (see Figure 4.3), with taxi drivers having the most extreme kWh decrease of 80 percent compared to January 2020. The charging of taxi drivers found some momentum again during the summer, when some policies were temporarily lifted and the catering industry opened up. In 2021 and 2022, the number of identified RFIDs drops significantly, to 2/3rd and 1/6th of their original number, respectively. Potential explanations

Table 4.3: Number of active charging points and users. (*the number of RFIDs was higher in December 2020 than January/February 2021, CPO policy may have played a role)

Monitoring locations (online since before C-19)	**unique users (RFIDs)**	**locations used**	**users / location (average)**
January 2020	61,866	7730	8
June 2020	45,460	7502	6.06
January 2021	59,092	7490	7.89
June 2021	71,925	7509	9.58
January 2022	85,344	7326	11.65
June 2022	102,232	7059	14.48
October 2022	119,866	7339	16.33
Monitoring all locations			
January 2020	61,987	7730	8
June 2020	54,787	8841	6.19
January 2021	66,752	10,409	6.41
June 2021	85,225	11,880	7.17
January 2022	110,900	13,310	8.33
June 2022	143,808	14,472	9.94
October 2022	169,989	15,827	10.74

include takeovers, drivers who are out of business, and replaced cards. However, this drop is too significant to confidently represent the segments after 2020; therefore, we chose not to include user segment analysis over a longer time period.

CURFEW ANALYSIS

A curfew was installed to combat the spread of the new variants of COVID-19. The curfew was first installed on 23 January 2021. Curfew times took place between 9 p.m. (21:00) and 4:30 a.m. (4:30). On 31 March 2021, the curfew was extended with a delayed start time of 10 p.m. (22:00). The curfew took place until 28 April 2021. For this analysis, we compared the kWh charged in the evening (after 7 p.m.) over four periods of time: the month before the curfew, the 9 p.m. curfew, the 10 p.m. curfew, and the month after the curfew. Details can be found in the table below (Table 4.4). Percentages are calculated over the entire set of sessions (considering all hours of the day).

Outside of curfews, the percentage of sessions that start between 7 p.m. and 8 p.m. is between 5.3 percent (before curfew measurement) and 5.9 percent (after curfew measurement). During both curfews, this percentage increased to 7.8 percent (during the 9 p.m. curfew) and 7.4 percent (during the 10 p.m. curfew). This means that charging that started between 7 p.m.–8 p.m. increased by almost 50 percent during both phases of the curfew (compared to before and after measurements). Before curfew, the percentage of all sessions that started after 9 p.m. was 7.8 percent. During the first curfew, this number dropped to 2.5 percent. This is a decline of more than 60 percent. During the second curfew, this percentage recovered to 7.9 percent, almost identical to the before curfew measurement. The percentage of sessions that started exactly between 9 p.m. and 10 p.m. decreased to 1.5 percent during the first curfew, a decline of more than 50 percent.

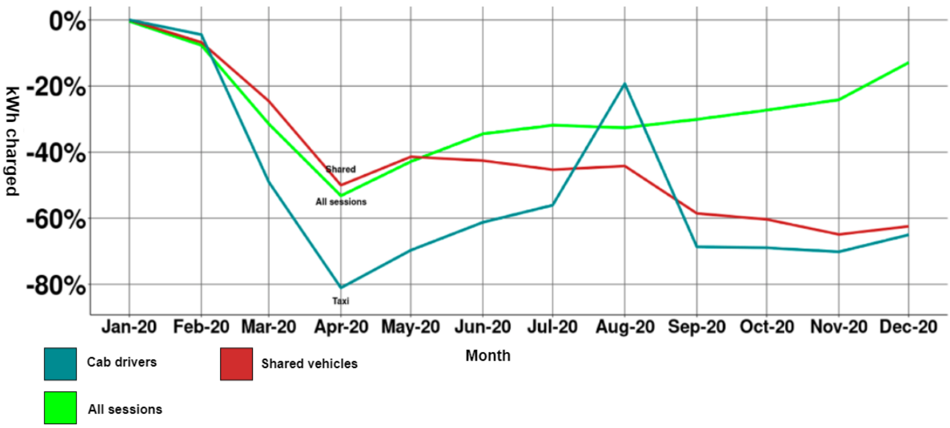

Figure 4.3: User segments and decrease of kWh charged during COVID-19 lockdowns in 2020.The kWh decrease is determined by comparing the kWh charged of each group with their kWh charged in January 2020.

Table 4.4: Summary statistics of sessions started in the evening during Curfew phases

Summary Statistics	**Before Curfew (~1.5 Month)**	**First Curfew (~2 Month)**	**Second Curfew (~1 Month)**	**After Curfew (~1 Month)**
Sample size (# of sessions)	700,633	910,988	314,976	340,565
# of sessions that started between 7 p.m.–8 p.m.	37,477	70,828	23,453	20,207
Percentage	**5.3%**	**7.8%**	**7.4%**	**5.9%**
# of sessions that started between 8 p.m. and 9 p.m.	30,052	40,526	16,958	15,283
Percentage	**4.3%**	**4.5%**	**5.4%**	**4.5%**
no. of sessions after 9 p.m.	54,530	22,828	25,153	22,646
Percentage	**7.8 %**	**2.5%**	**7.9%**	**6.6%**
# of sessions that started between 9 p.m. and 10 p.m.	24,660	13,786	11,361	11,046
Percentage	**3.5%**	**1.5%**	**3.6%**	**3.2%**

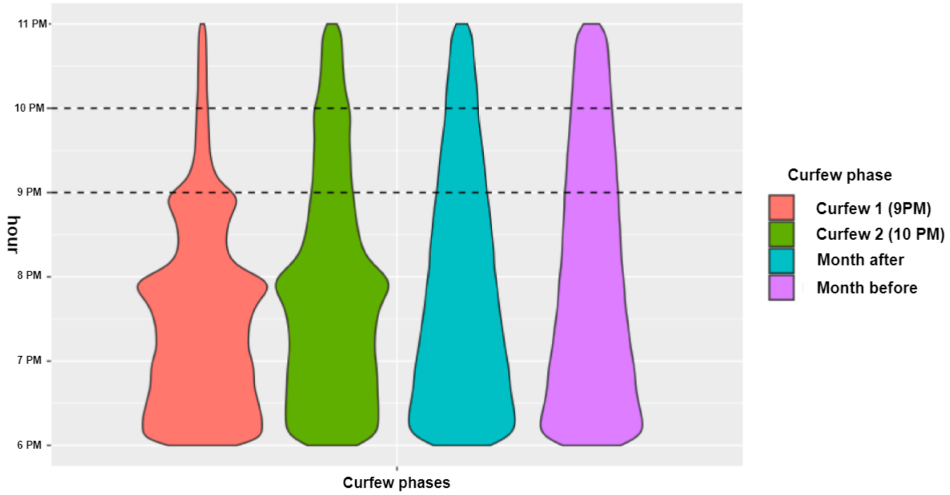

Figure 4.4: Violin plot illustrating the differences in start time distribution between 6 PM and 11 PM

There was barely any difference between the 9 p.m.–10 p.m. start times of the second curfew (3.6 percent) and the before curfew measurement (3.5 percent). We observed no late-evening decline during the second curfew, as opposed to the first curfew.

The violin plot (Figure 4.4) illustrates how curfews affected the start times of public EV charging during lockdown. The month before and after the curfew are almost identical in shape, whereas the shapes of the two curfew periods differ. The first curfew period differs strongly and on multiple occasions in the evening. The second curfew illustrates the same 8 p.m. spike as the first curfew, but later in the evening the shape becomes more similar to the periods before and after the curfew.

DISCUSSION

User group comparisons

The effects on charging commercial vehicles differed between types of vehicles. Taxi drivers, shared vehicles, and office chargers were all affected by lockdowns, though to a different extent. Dutch media and local governments have also reported the challenges of taxi drivers (including non electric taxi drivers). TaxiPro, the Dutch trade magazine for the taxi sector, reported a 90 percent loss of work in 2020 (Krabbendam, 2020). This is more extreme than the 80 percent decrease we have measured for electric taxi drivers who are active in the urban agglomeration of the Netherlands. The municipality of Amsterdam monitored its taxi sector in 2020 and found similar patterns as our sample of electric taxi drivers: an average 77 percent decrease at the first lockdown and a recovery during the summer months (Gemeente Amsterdam, 2020b). Dutch Royal Traffic reported that 30 percent of the taxi drivers that were active in early 2020 had quit their jobs by summer 2020 (Redactie AT5, 2020). The municipality of Amsterdam also reported in their monitor that, despite the loss of taxi drivers and a shrinking sector, the percentage of electric taxi drivers did not change much. Although taxi drivers were affected the most, the initial impact for shared vehicles did not differ much from the full user group. In late 2020, differences started to arise, with the full group of sessions recovering from initial effects while kWh consumption for shared vehicles lowered even more. The electricity demand for public charging in an office area was much lower than the already reduced demand for public EV charging altogether, although the demand that is associated with suspected employee charging did not differ as much from normal charging.

Curfew
During the first (9 p.m.) curfew, the number of sessions that started at 9 p.m. dropped significantly, and the number of sessions between 9 p.m. and 10 p.m. also dropped significantly. During the second (10 p.m.) curfew, we saw some increase in sessions between 8 p.m. and 9 p.m., compared to other periods, but we did not observe a decrease in sessions that started after 9 p.m.

Limitations
EV adoption is growing steadily in the Netherlands. It is challenging to determine the demand reduction long-term, since the fleet is growing and resources are shared between more users over time. This made policy sensitivity analysis more difficult from late 2021 on: it cannot always be said which portion of the demand increasing again can be attributed to lifted restrictions, and which portion should be attributed to the growth of the user base. Another issue is the long-term availability of charging points. Some of the charging points were not used every month, and it is not possible to determine from our data if this is because of user preference or, for example, technical or construction issues that temporarily prevented users from accessing these charging points altogether. In the latter case, some users may have opted for a charging point that was installed after the January 2020 baseline period, and therefore, these sessions were not included in our data analysis. Only 17 charging points in one office area were investigated, and although initial effects are expected because of the work from home policy, additional data is necessary to generalize the after-lockdown effects for the larger population of office chargers. Suspected employees were recognized through an assumption; therefore, it is possible that this group contains some sessions that coincidentally were made under the same behavior by non-employees.

4.3.4. CONCLUSION

This study investigated the effects of COVID-19 lockdowns and restrictions on charging behavior, with special focus on user segmentations. Below, the subquestions of the study are addressed, as well as future implications.

How does the decline in EV charging during COVID-19 compare to the decline in refueling of traditional vehicles?
Lockdown and work from home policies affected energy use in all traffic, but more so (overall) in electric vehicles than in traditional vehicles. A potential explanation is that the majority of EV adoption is personal and business-related. In general, electric mobility was more heavily reduced than vehicles driven by petrol as most applications of elec-

tric mobility are still in personal vehicles. In the Netherlands, most EVs are also company lease cars, so it can be expected that these drivers mostly work at offices, for whom it is easier to work from home than other professions. As well, logistics, which continued to be nearly fully operational during the lockdowns, have not been electrified. Therefore, petrol sales did not fall to the same levels as could be seen with EV charging.

How does the decline in EV charging compare between user segmentations?
As explained in Section 4.3.3, user segments were affected differently by lockdowns and work from home policies. The impact was most visible in April 2020, where consumption was drastically lowered, especially for taxi drivers, and in the measured office area. This was expected because of the work from home policy. The effect of lockdowns on taxi drivers was recognized through local outlets as well. Based on the comparisons by local news outlets and municipalities (Krabbendam, 2020; Gemeente Amsterdam, 2020b; Redactie AT5, 2020), we can conclude that electric taxi drivers in the urban agglomeration were slightly less (but still strongly) affected by COVID-19 lockdowns than the taxi sector altogether and that the percentage of EV adoption among taxi drivers was not negatively affected by the lockdowns. The taxi sector did have great challenges in overcoming its negative lockdown effects.

What were the effects of curfews on the start times of charging sessions?
Both curfews temporarily increased the number of sessions that started between 7 p.m. and 8 p.m. This demand migration towards 7 p.m. to 8 p.m., could have created issues for a larger user pool, since this increase in demand does happen during a peak consumption window. Charging in the later evening declined during the first curfew of 9 p.m., whereas the second curfew of 10 p.m. did not show these effects. Even after the curfew deadline, charging was still occurring. In fact, in the later evening, the second curfew resembled the period before the curfews, indicating that the second curfew had little effect on late night charging and that demand in the late night was not as high as during the first curfew.

Future Implications
The last COVID-19 restrictions (such as vaccination passports and evening lockdowns) were halted in spring 2022, 8 months before the last analysis update of this study in fall 2022. Since then, EV charging has significantly increased again. Since the start of COVID-19, the number of users has more than doubled, and many new charging stations have been installed. The kWh that is charged by various user groups has recovered to 50–70 percent of original kWh use (office charging points) and even more than before the pandemic (commuters and the general population). Office areas have not recovered fully to their pre-pandemic charging levels (see Figure 4.2), and start times of charging sessions also do not follow the after work/evening peak that was observed pre-pandemic (van der Koogh, Wolbertus, and Heller, 2023). This indicates that there is a persisting effect where working from home and working flexible hours are still partially available for employees (more than before COVID-19 lockdowns).

4.4. INTER-URBAN CHARGING BEHAVIOR OF CAB DRIVERS

4.4.1. INTRODUCTION

Cab Sector Agreement

The municipality of Amsterdam signed an agreement with the cab sector in 2018. This agreement states that, from 2025 on, all cabs in Amsterdam should be emission-free. In the beginning of 2020, roughly 1200 electric cabs were identified in Amsterdam through charging transaction data. Some cab drivers who are active in the city center of Amsterdam live in smaller cities surrounding Amsterdam (which can partially be explained by housing prices). The goal of this study is to determine the *additional charging demand of these 1200 cab drivers in other cities*, as a consequence of this agreement. Determining the additional demand caused by this specific agreement could provide relevant insights for future agreements.

The cab sector agreement also included perks for electric cab drivers. Since January 2018, only clean taxis (e-cabs and biogas-powered cabs) that are affiliated with an Amsterdam Taxi Organisation (TTO) are allowed at the Amsterdam Central Station (CS) taxi stand. The data of this fast charging point at the taxi stand was used to identify the sample of the 1200 RFID cards that are associated with cab drivers. These identifiers could then be used to determine the charging behavior of these 1200 cards.

Dataset

The AUAS database contains charging transactions at public charging points in G4-MRA, MRA-E, MRDH and ElaadNL areas (e.g. in Gelderland, Overijssel). The database thus contains the charging transactions at more than 85 percent of all public charging points in the Netherlands.

Research Questions

In this study, we analyze the charging behavior of Amsterdam (e-) cab drivers on the national public charging network. The following research questions will be investigated:

1. In which neighboring MRA cities do cab drivers who work in Amsterdam charge their vehicle?

2. How do cab drivers affect the charging demand at night in these neighboring MRA cities, as well as other G4 and MRDH cities?

4.4.2. METHODS

Data analysis of public charging points is used to determine the impact of the cab sector agreement on charging demand in MRA cities. The following data selection was made for the study:

Timeframe: january - december 2019

Group: cab drivers in Amsterdam, identified through use of a cab-exclusive charging point at Amsterdam Central Station

Group size: 1131 unique RFID cards were identified, after correction, 982 active RFID cards were used in the study.

Table 4.5: Number of public charging sessions per district (Amsterdam) by cab drivers in 2019

City district	Number of sessions
New west	30,178
Center	29,892
South	17,765
West	15,268
North	9,009
East	8,031
South-East	3,511

Number of sessions: 128,752 (public) sessions
Scope: The set includes data from G4 municipalities (Amsterdam, Rotterdam, Utrecht, The Hague), Metropole region of Amsterdam (MRA) and Metropole region of Rotterdam-The Hague (MRDH).

4.4.3. ANALYSIS

IN WHICH NEIGHBORING MRA CITIES DO CAB DRIVERS WHO WORK IN AMSTERDAM CHARGE THEIR VEHICLE?

91 percent of the sessions take place in Amsterdam. This is where most activity for cab drivers during their shift takes place. The two parts of the city with the highest number of sessions are City Center and New-West (See Table 4.5). The other cities in the top 10 include (not scoped on MRA region):

- 3 percent: Zaanstad
- 2 percent: Almere, Haarlemmermeer
- 1 percent: Utrecht
- <1 percent: Beverwijk, Purmerend, Uithoorn and Diemen

For the G4 cities, other than Amsterdam, only Utrecht came in top 10 with 1 percent. Rotterdam and The Hague combined were responsible for less than 1 percent. When we zoom in on MRA region (excluding Amsterdam), we are left with a little less than 12,000 sessions. The top 10 MRA-cities for (e-) cab drivers are:

- Zaanstad (27 percent)
- Almere (25 percent)
- Haarlemmermeer (18 percent)
- Haarlem (12 percent)
- Beverwijk (4 percent)
- Purmerend, Uithoorn, Diemen, Weesp (3 percent)

Table 4.6: Cab drivers charging behavior in the MRA region

City	Sessions	Unique RFIDs	avg sessions/ RFID	% of total city sessions	RFIDs that charge often (>100x)
Zaanstad	3,201	83	39	6%	10
Almere	2,926	65	45	6%	12
Haarlemmer meer	2.189	83	26	3%	8
Haarlem	1,387	20	69	2%	7
Beverwijk	521	19	27	4%	2
Purmerend	393	23	17	2%	1
Uithoorn	385	4	96	22%	1
Diemen	343	19	18	7%	1
Weesp	313	9	35	4%	1
Zeist	286	6	48	<1%	1
Velsen	282	12	24	1%	1

- Zeist (2 percent)

Figure 4.5 illustrates the charging activities in the MRA-E region surrounding Amsterdam. The sessions inside the city of Amsterdam were excluded from this figure to emphasize the charging demand of cab drivers in neighboring cities. The color of the hot spot represents the number of sessions in that geographical location (green = not many, red = many sessions), and the size of the spot represents the density (spread) of charging in that area. Table 4.6 shows the number of users (unique RFIDs) and their charging frequency for each of the top 10 MRA cities. The share of cab driver sessions is also determined for each city. For the city of Amsterdam, roughly 8 percent of all public sessions are made by registered (e-)cab drivers.

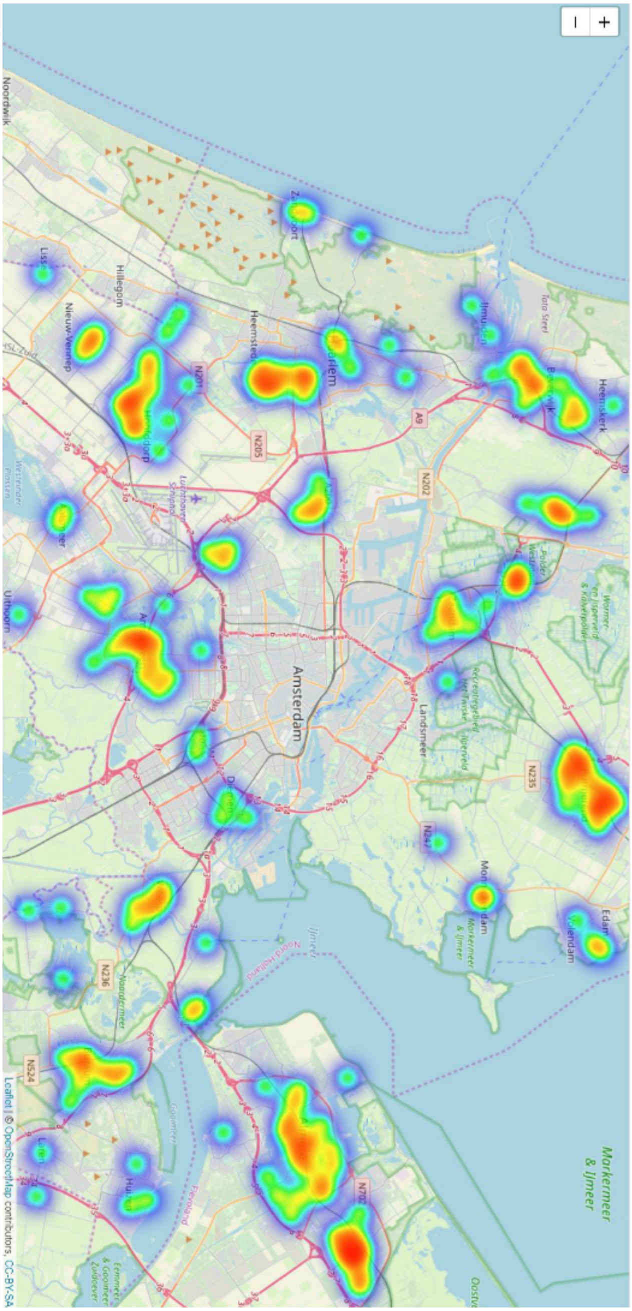

Figure 4.5: Charging activity heatmap of the MRA region. Sessions within the city of Amsterdam are excluded.

HOW DO CAB DRIVERS AFFECT THE CHARGING DEMAND AT NIGHT IN NEIGHBORING MRA CITIES, AS WELL AS OTHER G4 AND MRDH CITIES?

Cab drivers need to return home after their shifts, in the evening, or after a night shift. The previous results showed how cab drivers sometimes live in neighboring cities within the MRA region. The following time slots were investigated:

- **Overnight charging:** Sessions that start between 4PM-12AM and end the next day.

- **After-midnight charging:** Sessions that started beween 12AM and 6.30AM.

A number of cities has more overnight than daytime sessions, e.g. Utrecht (70 percent), Purmerend (56 percent), Almere (53 percent) and Beverwijk (53 percent). The city of Amsterdam itself has a much lower percentage of cab driver overnight charging (roughly 16 percent), charging does take place within these hours but sessions are too short to be included in the selection (see Figure 4.6). Almost half of all cab sessions made in Uithoorn are classified as after-midnight charging. After-midnight charging surpassed overnight charging in the cities of Amsterdam, Rotterdam, and Uithoorn. Haarlem and Zaandstad also have a significant portion of after-midnight sessions (see Figure 4.7).

4.4.4. CONCLUSION

The first question of this study was related to the locations of charging of amsterdam (e-)cab drivers outside of the city. The second question was related to the potential effect of electrifying cabs on charging demand during the evening and night time.

Locations: The cab driver charging sessions within Amsterdam city limits take an overwhelming share of over 90 percent. The rest of the sessions took place mostly in MRA region cities as well as the municipality of Utrecht: Zaanstad, Almere, Haarlemmermeer and Haarlem facilitated the most cab charging sessions of the MRA cities in 2019. Frequent chargers (<100X) were also common here. Haarlem and Uithoorn score the highest in average sessions per RFID card. In Uithoorn, cab drivers are responsible for over 20 percent of all public charging sessions. In other cities, this number stayed below 10 percent. Cab drivers currently have a limited effect on public on-street charging demand in the MRA region. Only 15 out of the 61 MRA cities has a cab driver who charges frequently on the public charging network. Cab drivers in the other cities may be less common, more likely to charge within Amsterdam boundaries, or they may have another charging opportunity outside of public on-street charging.

Overnight and Midnight charging: The overnight charging percentage of cab driver sessions is relatively low for the city of Amsterdam. Overnight charging is more common than daytime charging for some of the surrounding cities. These cab drivers likely live in the cities where overnight charging takes place. Some cab drivers charge after midnight, for example, because they work night shifts. This is less common than overnight charging, but significant enough to take into account when more of the sector will be electrified (e.g., more than 25 percent for some cities).

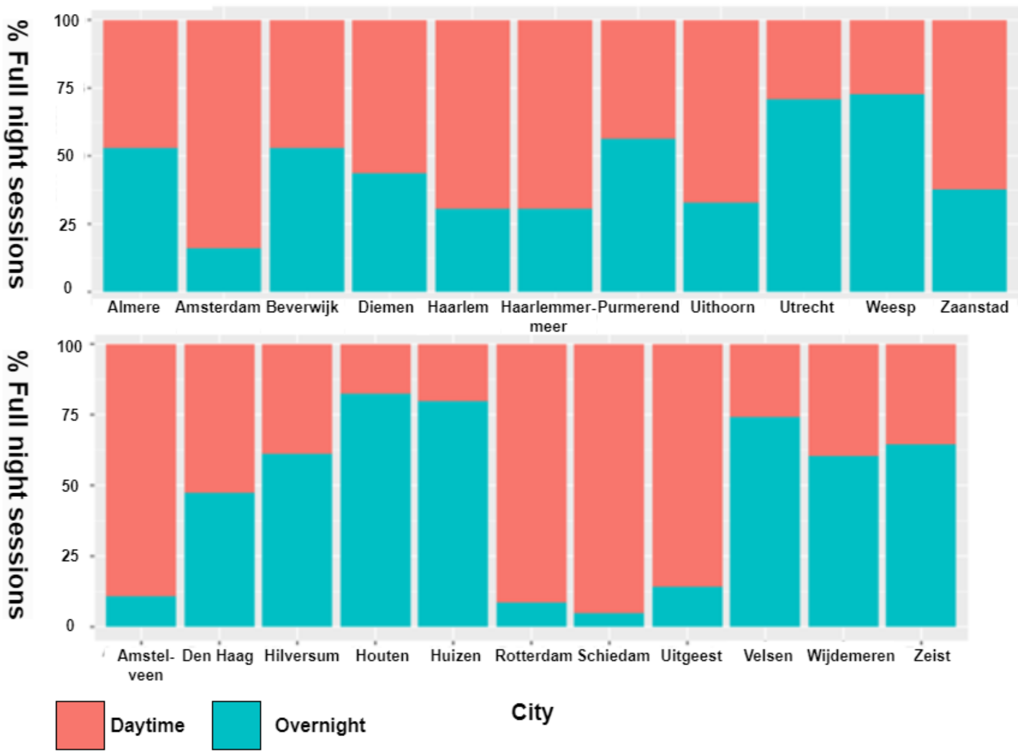

Figure 4.6: Percentage of overnight charging of cab drivers (Amsterdam, G4, MRA, and MRDH).

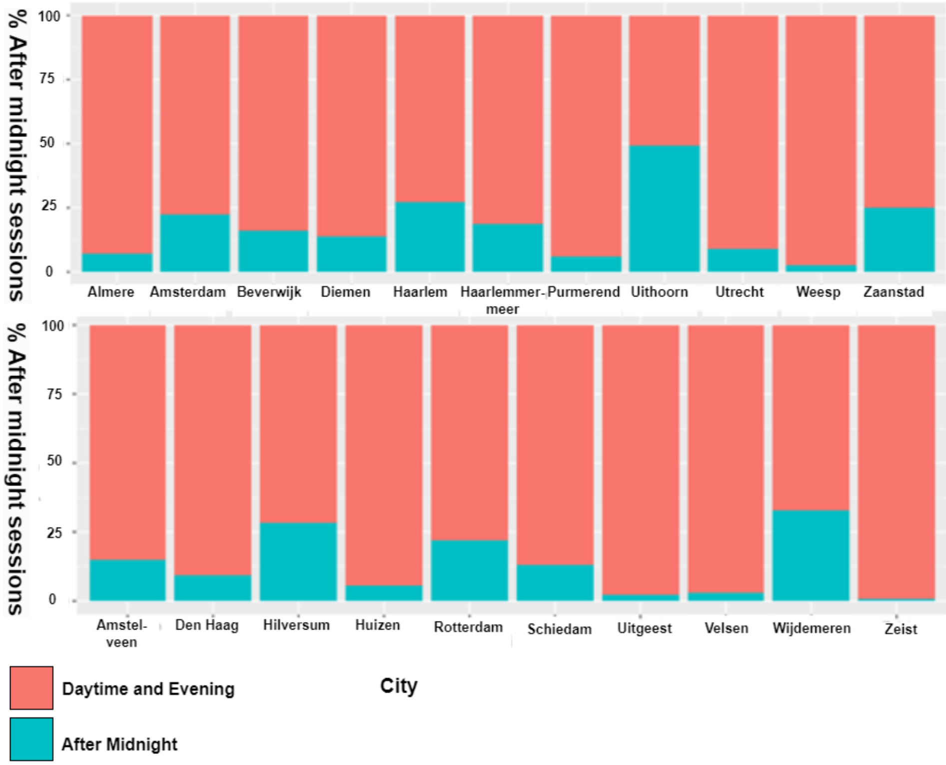

Figure 4.7: Percentage of after midnight charging of cab drivers (Amsterdam, G4, MRA, and MRDH).

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4.4.5. LIMITATIONS AND RECOMMENDATIONS

This study has been executed using a sample that was derived from a fast charging point that was only accessible to cab drivers in Amsterdam. The true population might include more cab drivers. The study interpreted 1 RFID card as one cab driver. We do not have insights in how these cards were used (e.g., the possibility that RFID cards were shared among cab drivers, or that a driver possessed more than one card was unknown). The only fast charger used in the dataset was the selection point. Therefore, the fast charging demand of cab drivers throughout their shift could not be quantified. Additional data is needed to answer this question. Only charging points that exist can be used. Therefore, some cab drivers may live further away from their used MRA point, or charge before going home, because of lack of infrastructure.

Recommended Locations

To facilitate charging demand of cab drivers, we recommend to focus on the MRA cities that facilitate most of the cab drivers sessions: Zaanstad, Almere, Haarlemmermeer and Haarlem. Additionally, it is recommended to consider cities that have a relatively high share of cab driver sessions, such as Uithoorn, Diemen, Weesp and Beverwijk. Cab drivers may have charging needs at other locations that cannot be extracted from charging data. For example, because infrastructure in these locations is still lacking. To satisfy the demand more accurately, additional analysis of cab drivers home locations is needed. When stimulating the electrification of professional mobility, that is dependent on public charging, the demand within the area of operation as well as the demand near the drivers home should be considered. The near-home demand could be estimated by using the chamber of commerce registrations of these drivers. Larger cab driving companies could be asked to provide an aggregated list of waiting areas and postal codes for the same purpose. Finally, it is important to realize that cab drivers may have different charging patterns, such as after midnight charging, which may be more challenging to satisfy under high charging demand since charging points may already be in use when they arrive in the night.

4.5. SUMMARY

This chapter analyzed three different case studies that occurred between 2019 and 2023, to answer the subquestion *"How do policy interventions affect public charging infrastructure?"*. The first case (4.2) discusses the business case and competition in slow on-street and fast highway charging. Competition in public charging in the Netherlands is pursued through various models, such as exclusive concessions, commission models, and open market models. Each model has their advantages and drawbacks, and depending on the area, one may be a better fit than others. The business case of charging is influenced by factors such as costs, funding, smart charging adoption, and highway charging policies. For fast charging along highways, the Dutch Ministry of Water and Infrastructure awards primary facility permits and additional facility permits. Primary facility permits are granted for specific locations, and challenges include high initial costs for grid connections and delays in development. Additional facility permits are given to existing establishments with primary facility permits for extra facilities, such as fast charging. However, there have been issues with the different privileges between primary and additional facility holders, to which since, recommendations have been made by at least two consultancy parties. The second case (4.3) addressed the effects of COVID-19 lockdowns on mobility and charging. The effects of work from home mandates, lockdowns and curfews were analyzed. KWh sales for electric charging decreased more than traditional vehicle refueling. Chargers were used less often, especially the ones located around offices. Cab drivers were affected the most, as their charging activities decreased the most and independent drivers indicated switching jobs during this time. The first few months of the curfew were followed mostly by EV users, as late night charging decreased and peaked just before the deadline of the curfew. This effect didn't persist in the last month, when the curfew deadline was made an hour later. In the last case (4.4), the effects of an electrification agreement for cab drivers in Amsterdam were analyzed. The effects included an increase in fast charger demand in the inner city, as well as an increase in overnight and late-night slow charging demand in smaller municipalities around the city. In some cases, this demand was a significant portion of the total charging demand in a municipality (See Table 4.6).

4.6. CONCLUSION

Looking at the various case studies determined the effects of the studied policy interventions on electric vehicle charging. These insights can be useful to consider for future interventions or for interventions in other cities that are less developed in terms of EV charging.

- **Electrification of professional [4] subgroups:** Following the charging trail of (anonymyzed) individuals, the changes in charging demand could be determined. On-shift [5] activity consisted mostly of short fast charging sessions inside the city, whereas off-shift activity (longer charging sessions) also took place in the smaller municipalities in the same metropole region. Some of these sessions also typically started later than an average session, making the drivers more vulnerable for charging point competition, since their arrival time in general is later than other charging point users.

- **Work from home mandates:** Electric vehicle driving was reduced more during work from home mandates, than driving in traditional vehicles. This is because a large share of the Dutch EV fleet consists of private leased and company leased cars used for working, often at offices. Under this distribution, the business case of charging is more vulnerable under work from home mandates than petrol stations are. Higher work from home rates will therefore reduce mobility in general, but is currently not the most effective way towards cleaner mobility, as the mobility that was the most active during WFH mandates was not the electric vehicle but the petrol vehicle. However, this may change when adoption rates are higher in the future.

[4] Professional subgroups are users of public chargers who drive commercially, examples are cab drivers and parcel deliverers.

[5] The charging that happens while the driver is still within the hours of their work shift

- **Curfews:** The restricting effects of the curfew were temporarily visible, but the effects decreased after a period of time, implying that time restrictions can work temporarily when the support or argumentation for it is convincing enough. It also illustrates how, in this case, the risk of a (95€) fine is not enough to control the timing of charging over a longer period.
- **Competition:** Competition models play a very important role in the development of charging infrastructure. Depending on the type of model, the type of area and the existing infrastructure, the best model may differ. Policy that prioritizes fast development for multiple parties may make it more difficult for these parties to compete, whereas exclusive models may lead to lower customer satisfaction and more delays. The competitiveness in municipal tenders have also led a race to the bottom in terms of charging prices. Given the relationship between these prices, peak hours of charging and the roll-out of smart chargers, a dynamic pricing model could have potential for a market where customer, CPO and DSO can all benefit financially.

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Stakeholder prioritizations of EV charging across time

Electric vehicles have penetrated the Dutch market, which increases the potential for decreased local emissions, the use and storage of sustainable energy, and the roll-out and use of e-car sharing business models. This development also raises new potential issues such as increased electricity demand, a lack of social acceptance, and infrastructural challenges in the built environment. Relevant stakeholders, such as policymakers and service providers, need to align their values and prioritize these aspects. This study investigates the prioritization of 11 Dutch decision-makers in the field of public electric vehicle charging. These decision-makers prioritized different indicators related to measurements (e.g., EV adoption rates or charge point profitability), organization (such as fast- or smart-charging), and developments (e.g., the development of mobility-service markets) using the best-worst method. The indicators within these categories were prioritized for three different scenario's in time. The results reveal that priorities will shift from EV adoption and roll-out of infrastructure to managing peak demand, using more sustainable charging techniques (such as V2G), and using sustainable energy towards 2030. Technological advancements and autonomous charging techniques will become more relevant in a later time period, around 2040. Environmental indicators were consistently valued low, whereas mobility indicators were valued differently across participants, indicating a lack of consensus. Smart charging was consistently valued higher than other charging techniques, independent of time period. The results also revealed that there are some distinct differences between the priorities of policymakers and service providers. Having a systematic overview of what aspects matter supports the policy discussion around EVs in the built environment.

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5.1. INTRODUCTION

Energy transition policy goals are ambitious but necessary to ensure a habitable planet for future generations. The energy transition will require massive change. It will affect our business models, means of travel, consumption habits, building designs, and so on. A substantial share of the required activities for the energy transition occurs within city boundaries. Therefore, this transition impacts urban planning: intensive coordination between a wide range of parties may be needed to adequately shape cities' transportation and energy infrastructure during the transition. This is particularly relevant because of the tensions between the city's short- and long-term (urban) developments, the allocation of budgets to various activities, developments in energy supply and storage infrastructure, expectations related to habitability, and developments in the area of mobility. Because all these elements interact within cities, coordination within cities is crucial for this transition to succeed. At the same time, cities should be able to fulfil the needs of their inhabitants. Changes and innovations should be harmonized with each other as well as with the local environment.

One key ingredient is the diffusion of electric vehicles, which is at the intersection of energy and mobility. Electric vehicles are crucial in obtaining climate goals (Delbeke et al., 2019). In the Netherlands, mobility was responsible for roughly 18–22 percent of the emissions in 2021 (CBS, 2022). The mobility and energy sectors are crucial for a functioning society, and transitioning to electric mobility can reduce their negative effects on the global and local climate. Electric vehicles allow us to store and transport electricity, use renewable energy effectively, match demand with supply, and drive a car without creating local emissions. Charging often takes place in public spaces, and markets (e.g., energy markets) are disrupted by the transition to electric mobility. The future development of petrol stations, parking spots, parking garages, driveways, and energy grids is also affected by this transition. Because of these complexities, there are many stakeholders involved in the transition to electric mobility. On a municipal level, there are implications for policymakers, environmental planners, charging point operators, citizens, grid operators, car manufacturers, energy, logistics, and transport industries. These stakeholders all play a role in the future development of charging infrastructure, and because of their roles, they may differ in opinion regarding the importance of various elements related to electric vehicle charging. Earlier research shows that stakeholders consider different things important when evaluating charging methods, in particular in the implementation of smart charging and fast charging (Wolbertus et al., 2020; Bakker et al., 2014). Other potential conflicts of interest include governance, technical standards, rollout strategies and policy management (Bakker et al., 2014 There may be a lack of alignment between and within organizations that focus on Dutch charging infrastructure that could be improved by co-learning and transparency (van Galen, 2015).

As mentioned before, coordination is very important in this transition. For this purpose, stakeholders will need to identify and compare their goals, address differences, and decide on a direction. In this study, important stakeholders in the field of electric mobility are interviewed to facilitate this process. Taking the interests of multiple stakeholders into account, the prioritizations are systematically determined and compared, identify the most important aspects of charging that need monitoring, and anticipate aspects of charging that will become important at a later point in the mobility transition.

The question for this study is as follows: *"What are the most important issues, according to local decision-makers in the field of electric mobility? How do these change over time?"*

In this study, the best-worst method (BWM) is used as a multi-criteria approach to identify stakeholder consensus and alignment in the future development of public EV charging infrastructure roll-out in municipalities, using a case study in the Netherlands. Multiple criteria decision making (MCDM) allows us to prioritize different aspects, taking into account different stakeholders (Serrano-Cinca et al., 2021). This method allows us to take individual assessments into account and find consensus, which can be useful when working with multiple stakeholders (Diaz-Balteiro et al., 2009). There have also been other studies using a multi-criteria approach in EV infrastructure stakeholder analysis. For example, one study identified critical factors for electric vehicle diffusion in China (technology level, policies and regulations, consumer acceptance, pricing and market structure) using multiple-criteria decision-making methods (Liu et al., 2017). Another study looked at three values for EV station deployment under different location scenarios, using a combination of multiple criteria analysis methods. They identified accessibility as the most important value, followed by traffic convenience and waiting times (Rouyendegh (B. Erdebilli) et al., 2019).

The approach of this study is to interview decision-makers involved in the roll-out of public charging infrastructure for electric vehicles (which includes service providers and local policymakers, among others). Decision-makers selected for this study are directly involved in the development of this public charging network, for example, because they are part of a market solution, they are involved in policymaking, or they are otherwise involved in developing charging in municipal areas. According to the BWM, interviewees determined their prioritizations of various developments and topics, and for different time periods. Details on the conceptualization of developments, time periods, and selection of stakeholders are in the Methods section.

The Netherlands was chosen as a case study, where adoption is relatively high (over 1 out of 5 newly sold vehicles is electric (RVO, 2021), there is a public charge network in the big cities, and explicit policy goals and pilot activities have been introduced to facilitate the energy transition and the adoption of electric vehicles. These policy goals include the development of an accessible charging network, the integration of renewable energy sources in charging, the electrification of traffic, interoperability standards, environmental zones, and traffic sectors (van der Koogh et al., 2021). Because the Netherlands includes some densely populated urban areas, regulations have been made to ensure charging opportunities for EV users: new buildings need to have charging points incorporated in their parking solutions, public parking spots that have a charging point installed cannot be used by conventional vehicles, and some municipalities have deadlines for their inner-city zones for professional traffic to transition into a clean transmission. The effectiveness of policy in the integration of EVs has been assessed by studies in the past. For example, in one study, charging comfort to reduce range anxiety was deemed more important than monetary compensation (Lieven, 2015). Other studies plea for a more integral policy rather than separate policies targeting either the vehicle or the infrastructure (van der Steen et al., 2015), argue that the acceptability of EV in-

Table 5.1: Adapted method (adapted from Rezaei, 2016)

The original method for Linear BWM	Adapted method (temporal comparisons)
Step 1: Determine set of criteria	Step 1: Determine set of criteria
	Step 2: Determine time periods
Step 2: Determine best and worst criterium	Step 3: Determine best and worst criterium
Step 3: Make best-to-others vector	Step 4: Make best-to-others vector
Step 4: Make worst-to-others vector	Step 5: Make worst-to-others vector
Step 5: Find optimal weights	Step 6: Find optimal weights
	Step 7: Compare weights across time periods
Step 6: Validate consistency	Step 8: Validate consistency

centives differs across regions (Davies et al., 2016), and suggest that subsidizing research and development, as well as regulations (for manufacturers) to limit fuel consumption could improve the uptake of electric vehicles (Wu et al., 2021). This study will also take into account the various policy instruments that have been introduced in local policy documents.

This chapter is structured as follows: first, the selected methods and the set-up of the interviews are explained. After that, the most prominent results are discussed. The chapter ends with conclusions and recommendations.

5.2. METHODS

The following section contains a description of the methods used and the design of the experiment. The first subsection describes the multiple criteria analysis method. After, the selected criteria for the analysis are described. In the next subsection, the different time periods that were defined as inputs for the MCDM interviews are described. The last subsection explains the selection process of participants.

5.2.1. MULTIPLE CRITERIA ANALYSIS

The linear best-worst method (Rezaei, 2016) is used as a multiple-criteria analysis method. The method works as follows: the most and least important criterium is chosen from a set. Then, one set of weights is compared to the least important criterium, and one set of weights is compared to the most important criterium. This method is chosen because it's less redundant than the analytical hierarchy process, as all indicators are only valued twice instead of n x n. This study adapts the method by adding three periods in time as scenarios. This study also adds a time-based comparison by calculating how indicator values change over time. We will now illustrate the use of the best-worst method using the steps from Table 5.1. Steps 1 and 2 determine the context of the questionnaire. They are determined in the paragraphs below (see Tables 5.2 and 5.3).

To determine steps 3, 4, and 5, the participant is asked three questions:
Q1: What is your favorite and least favorite option? (step 3)
Q2: How much do you like your other options compared to your favorite (1 = just as much, 9 = nine times worse)? (step 4)
Q3: How much do you dislike your other options compared to your least favorite (1 = just

as much, 9 = nine times better)? (step 5)

This determines the set of weights compared to the best selection *[AB = (ab1, ab2, ... abn)]* and the set of weights compared to the worst selection *[AW = (aw1, aw2, ... awn)]*. For step 6, the min-max model is used to find the weights that have the smallest distance between both lists (See equation 5.1 - 5.3). This model can become more complicated when necessary (e.g., with a high number of criteria and multiple optima). The weights of all criteria in a set should sum up to 1. This means that if there are four criteria in a set and a participant ranks them all as equally important, each of these four criteria would have a weight of 0.25.

$$\min \max(j) \left\{ \left| \frac{wb}{wj} - aBj \right|, \left| \frac{wj}{ww} - ajW \right| \right\} \tag{5.1}$$

$$\sum jWj = 1 \tag{5.2}$$

$$wj \geq 0 \text{ for all j} \tag{5.3}$$

Step 7 contains the delta analysis. The delta analysis works as follows: When a participant has a weight of 0.53 for indicator X at time A, and they are asked to fill out the same question for time B. This time, the participant scores 0.3 on Indicator X. In this case, the Delta score of Indicator X is determined as:

$$\Delta = wj(T2) - wj(T1) \tag{5.4}$$

The Weight of X at time B minus the Weight of X at Time A is - 0,23). This means importance of indicator X is lowered over time by 0.23. The last step is to determine the consistency ratio score, Ksi (ξ). This score is determined by looking at the differences between the values of the sets and the end value. The smaller the difference, the smaller the consistency ratio score.

5.2.2. CRITERIA

Four different papers using indicators for EV and charging infrastructure in cities were consulted to help determine the criteria for the interviews (Helmus and van den Hoed, 2015; Angelakoglou et al., 2020; Di Martino et al., 2021; van der Hoogt et al., 2020). An overview of the selected criteria and related papers can be found in Appendix 9.5, and the definitions of the criteria can be found in Table 5.2. The criteria were split into three categories: measuring, organizing, and development indicators. The Measuring Indicators category contains nine different mobility and energy indicators that can be monitored for informed decision-making. The Organizing category contains seven different criteria related to the configuration of charging infrastructure. The Development category contains four relevant activities at the energy-mobility intersection. Participants were also asked to select relevant policy instruments for each period in time. These instruments were not ranked, and participants were not limited in their number of selections for this category. The list of instruments includes: subsidy, knowledge exchange, restrictions (e.g., zero-emission zones), preferential treatment, voluntary agreements, technical and domain support, and 'other' (free text form).

Table 5.2: Category, indicators, and description of indicators.

Category	**Indicator**	**Description**
Measuring	Car ownership	# of vehicles in possession
Measuring	EV Adoption	The number of sold EVs.
Measuring	Profitability of the business case	Profits for the exploiter (CPO) of the charging infrastructure.
Measuring	Public space	The space that is used for charging and parking.
Measuring	Peak demand	The peak in kW on the busiest charge moments.
Measuring	Use of sustainable energy	The extent to which sustainable energy is used in charging.
Measuring	Local emissions	The level of local emissions (e.g., CO2 levels).
Measuring	Occupancy rate	The % of charge stations in a network that is occupied.
Measuring	User comfort	The level of comfort an EV driver experiences in finding and using a public charge point.
Organizing	The role of fast charging	Anything that isn't slow charging. (DC quick & rapot, not Level I/II AC charging)
Organizing	The role of V2G	Bidirectional charging to store renewables and ensure a stable grid
Organizing	The role of smart charging	Control charging based on (renewable) energy, tariffs, or grid availability to reduce peak demand and charging fares.
Organizing	The role of induction (or autonomous-friendly) charging	Wireless power transfer charging (WPT) or other cord-freecharging technologies.
Organizing	The role of PV (solar) charging	PV charge systems exploit light sources, and can be combined with smart charging, V2G and forecasting for effective use.
Organizing	The role of locations and access	Exploring the role of location and access (e.g. workplace, private, garage etc.) in charging
Organizing	The roles of different user groups in the charging network	Groups such as residents, commuters, shared vehicles, logistics, and cab drivers.
Development	Developing the mobility service market	Examples of these development activities are: shared vehicles, mobility budgets, apps.
Development	Activities in the Energy system	Examples of these energy activities are: grid expansions, peak shaving, and expansion of sustainable energy sources
Development	Roll-out of charging infrastructure	Examples are the roll-out of charging points and the construction of charging hubs.
Development	Stimulating technological developments	Examples are autonomous driving, battery developments, and intelligent transport systems

5.2.3. DEFINITION OF TIME-BASED SCENARIOS

This study has added three consecutive periods in time as different phases in the interview study. These three time periods were introduced to the interviewees with a short description that is based on prognosis and policy goals in the Netherlands. Table 5.3 contains a translation of these descriptions.

5.2.4. PARTICIPANTS

Three participants were recruited through the consortium network of the RAAK-SIA-funded research project "Future Charging" (Amsterdam University of Applied Sciences/Urban Technology). These were policymakers from three of the four largest municipalities (Rotterdam, The Hague, and Utrecht). Input from these policymakers is valuable, since these larger municipalities have already installed public infrastructure and are familiar with some of the most important policy roadmaps since they take place in their areas of operation. Other participants were recruited online. The scope of the study is to determine the priorities of decision makers in the development of the public charging network. After filtering on focus (electric mobility and/or public charging) and decision-making (charging point operator/service provider, policymaker, municipal worker, market developer and/or involved in decision groups), 11 participants were left (see Table 5.4). Interviews were held in April 2021 (first rounds) and September 2021 (catch-up round for participants that were not available).

Table 5.3: Three time-based scenarios based on policy goals and prognoses in the Netherlands (van der Koogh et al., 2021; D. Rijksoverheid, 2018; CityDeal-gemeenten, 2018; Rijksoverheid, 2019; Gemeente Amsterdam, 2020; ElaadNL, 2019; Gemeente Rotterdam, 2015; Ministerie van Infrastructuur en Waterstaat, 2019; PBL, 2019)

Time period: Null (T1)
timespan: 2021-2025

During this period, adoption rates of electric vehicles will increase (prognosis is that 16,4% to 42,7% new car sales are EVs), and we expect more variance in vehicles. The 30-40 largest cities will work towards zero-emission logistics.The government set a goal of 50% electric cabs in 2025. Until 2025, private subsidies are available and road taxes are exempt. The 4 largest cities are also focusing on decreasing street parking, alternative mobility, and more efficient use of the public space.

Time period: Near Future (T2)
timespan: 2025-2030
After 2025, there will be zero-emission zones, and goals for sectors such as public transport, and zero-emission zones for logistics are compulsory for the 40 cities after 2026. Prognosis states that 29,6% - 58% of new car sales are electric. When needed for sufficient CO_2 reductions, additional rules will be made for emission-free construction vehicles. Larger cities will continue to develop alternative mobility, expand public transport, improve bike lanes, and migrate street parking.

Time period: Later Future (T3)
timespan: 2030-2040
This period is still very uncertain. The government's target is to exclusively sell new electric cars after 2030. City centers can install zero-emission zones that also require inhabitants to drive zero-emission. The focus will be on international mobility and European guidelines. Hydrogen vehicles, autonomous vehicles, and drones are expected to become more important. There will be a focus on creating more emission-free mobility sectors such as waterborne and aviation. The vision for inner cities is car-free streets, lots of green areas, recreation, and bike lanes.

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Table 5.4: Participant list

Role	Exp (yr)	Area of Operations
Service Provider, CPO	4	European
Policy Maker (Municipal)	15	Municipal (Rotterdam) & Regional
Policy Maker (Government)	29 (infra) 2 (EV)	National
Service Provider, CPO	12	International & Municipal
Interest Group Rep	6	National
Service Provider, CPO	30	Regional
Market developer	2	National
Market developer	3	Unspecified
Policy Maker (Municipal)	12	Municipal (Utrecht)
Service Provider, CPO	8	Municipal & Provincial
Policy Maker (Municipal)	1	Municipal (The Hague)

Table 5.5: Descriptive table for the reporting of results (see Table 5.6 for results)

Result	Description
Best	The indicator that is selected as 'Best' by most participants for this time period. When more than 2 tied, the result will be noted as 'Mixed'.
Highest avgW	The indicator that has the highest average weight of all rankings of this time period. The average weights are scaled by the number of indicators in the category. Averages of total (time-independent) are calculated using participant levels.
Worst	The indicator that is selected as 'Worst' by most participants for this time period. When more than 2 tied, the result will be noted as 'Mixed'.
Lowest avgW	The indicator that has the lowest average weight over all rankings of this time period. The average weights are scaled by the number of indicators in the category. Averages of total (time-independent) are calculated using participant levels.
SD	Standard deviation, the square root of the variance of the average weight.
KSI	The average consistency ratio score (KSI) for this category and time period. The lower the score, the more consistent individuals have been.

5.3. RESULTS

The interviews were analysed with the use of MS Excel. Values of individual participants can be found in the Appendix 9.6 - 9.14. In the following sections, three of the analyses are discussed. Table 5.6 contains the average weights, and Table 5.5 describes how this can be read.

5.3.1. SUMMARY FOR EACH TIME PERIOD

T1 time period: null (2021–2025)

Measuring: For this period in time, *EV adoption* was selected most often as most important (4 out of 11 participants), among all participants 7 different criteria were chosen as 'Best'. 4 out of 11 participants chose *Local emissions* as 'Worst' (least important), while 3 others chose *Car ownership* as least important and 3 other criteria were chosen by others. The criterium *use of Public Space* was not selected by anyone as either 'Best' or 'Worst'. The rounded average KSI (consistency) score was 0,12. The full weighted table can be found in Appendix 9.6.

Organizing: For this period in time, *Accessibility* was selected most often as most important (4 out of 11 participants), among all participants 5 different criteria were chosen as most important. A small majority (6 out of 11) chose *Induction* (autonomous-friendly) as the least important criterium. The criteria *User Groups* and *Induction* were never chosen as the 'Best' criterium in this time period. The criteria for *Fast Charging* and *Smart Charging* were never chosen as the 'Worst' criterium in this time period. The rounded average KSI consistency score was 0,14. The full weighted table can be found in Appendix 9.7.

Development: 9 out of 11 participants found the Roll-out of infrastructure the most important. The other two found *Activities in the Energy System* the most important. 6 out of 11 found *Developing the mobility service market* the least important. Out of the other five participants, four found *Stimulating technological developments* the least important. The rounded average KSI consistency score was 0,18. The full weighted table can be found in Appendix 9.8. Policy Instruments: 33 selections were made among 11 participants for 2021–2025. The policy instrument that was selected the most for this time period was the Subsidy (8), narrowly followed by Voluntary agreement (7). Knowledge exchange and Restrictions (e.g., zero-emission zones) were also selected by more than half of the participants (6). Other instruments were not or barely chosen (<3) for this period. The 'Other ... ' button was used twice, with input 'Facilitation of market-based infrastructure roll-out' and 'Internal agreements between charging point operator and municipality'.

T2 time period: near future (2025–2030)

Measuring: The 'Best' selections were more mixed towards 2030. *EV Adoption, Car ownership, Peak demand* and *Use of sustainable energy* were all selected as most important by two participants. The other 3 participants selected *Occupancy, Profitability* and *User Comfort*. The criterium that was selected as 'Worst' the most was *Car ownership* (5 times). Another criterium that got selected three times as worst was the *Local emissions*. 2 participants selected *User Comfort*, and one *Occupancy*. The rounded average KSI consistency score was 0,11. The full weighted table can be found in Appendix 9.9.

Table 5.6: Best, Highest average weights, Worst and Lowest average weights for all time periods and categories

T1:2021-2025	**Measuring**	**Organizing**	**Development**
Best	EV adoption (4)	Accessibility (4)	Roll-out infra (9)
Highest avgW	EV adoption (avgW=0.16, SD=0.08)	Smart Charging (avgW=0,21, SD=0.05)	Roll-out infra (avgW=0.40, SD=0,08)
Worst	Local emissions (4)	Induction charging (6)	Develop MaaS (6)
Lowest avgW	Car ownership (avgw=0.06, SD=0.04)	Induction charging (avgW=0.06, SD=0.05)	Develop Maas (avgW=0.14 SD=0.09)
KSI (rounded)	0.12	0.14	0.18
T2:2025-2030	**Measuring**	**Organizing**	**Development**
Best	Mixed (4 optima).	V2G (4) Smart Charging (4)	Roll-out of charging infra (4)
Highest avgW	Peak demand (avgW=0.15, SD=0.06)	Smart Charging (avgW=0.21, SD=0.06)	Act. Energy System (avgW=0.31, SD=0.09)
Worst	Car ownership (5)	Induction charging(5)	Stimulate tech. dev. (5)
Lowest avgW	Car ownership (avgW=0.08, SD=0.07)	Induction charging (avgW=0.09, SD=0.07)	Stimulate tech. dev.(avgW=0.17, SD=0.09)
KSI (rounded)	0.11	0.16	0.41
T3:2030-2040	**Measuring**	**Organizing**	**Development**
Best	Mixed (4 optima)	Induction charging (3), V2G (3)	Stimulate tech dev. (5)
Highest avgW	Sustainable energy use (avgW=0.16, SD=0.08)	Smart Charging (avgw=0.20, SD=0.09)	Act. Energy System (avgW=0.28, SD=0.14)
Worst	Car ownership (4)	Mixed (3 optima)	Roll-out infra (4)
Lowest avgW	Profitability (avgW=0.08, SD=0.04)	User Groups (avgW=0.12, SD=0.09)	Roll-out infra (avgW=0.23, SD=0.09)
KSI (rounded)	0.12	0.14	0.37
Mean (T1-T3)	**Measuring**	**Organizing**	**Development**
Best	EV adoption (8)	Smart Charging (9)	Roll-out infra (14)
Highest avgW	Peak demand (avgW=0.14, SD=0.06)	Smart Charging (avgW=0.21, SD=0.07)	Roll-out infra (avgW=0.31, SD=0.12)
Worst	Car ownership (12)	Induction charging(13)	Develop MaaS (13)
Lowest avgW	Car ownership (avgW=0.09, SD=0,06)	Induction charging (avgW=0.10, SD=0.09)	Stimulate tech dev. (avgW=0.20 SD= 0.10)
KSI (rounded)	0.12	0.15	0.32

Organizing: Both *Smart Charging*, as well as *V2G*, got selected as 'Best' by four participants. The other participants selected *Accessibility*. Five participants found *Induction charging* the 'Worst' (in 2025 this were 6). Among all participants 3 more criteria were selected as least important. The rounded average KSI consistency score was 0,16. The full weighted table can be found in Appendix 9.10.
Development: *Roll-out of infrastructure* was again most selected, but by only 4 participants. Others selected either *Activities in the Energy System* or *Developing the Mobility service market*. Five participants selected *Stimulating technological developments* as 'Worst'. Others selected *Developing the Mobility service market* or *Roll-out of charging infrastructure*. The rounded average KSI consistency score was 0,41. One of the participants had a score over 1, indicating an inconsistency. The full weighted table can be found in Appendix 9.11. Policy Instruments: 32 selections were made among 11 participants. Almost all participants selected Restrictions (e. g., zero-emission zones) for this time period (10). Voluntary agreements were also popular for this time period (8) and Knowledge exchange was selected by almost half of the participants (5). Other instruments were not or barely chosen (<3) for this period.

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T3 time period: later future (2030–2040)
Measuring: The selection of 'Best' criteria was mixed among participants. The criteria *EV adoption, Car ownership, Use of Sustainable energy* and *Peak demand* were all selected as most important by two participants. The other 3 participants selected *Public space, Profitability* and *Local Emissions*. The criterium that was most selected as least important, or 'Worst', for this period was *Car Ownership* (4 times, while in 2030 it was 5 times). *Local emissions* and *Occupancy* were both selected twice, and the other results were mixed. The rounded average KSI consistency score was 0,12. The full weighted table can be found in Appendix 9.12.
Organizing: All Organizing indicators except for *PV* and *Fast charging* were selected as 'Best' at least once. All roles (no exceptions) were selected at least once as Worst for this period in time. The results were mixed. The rounded average KSI consistency score was 0,14. The full weighted table can be found in Appendix 9.13.
Development: In this period, stimulating technological developments was the most popular as 'Best', as 5 participants selected it. The other participants either selected *Developing the mobility service market* or *Activities in the energy system*. Nobody selected *Roll-out of infrastructure* as most important in 2040. The criterium that was most selected as least important or 'Worst' in this period is the roll-out of infrastructure (4 times). The other participants selected a mix of all three other criteria. The rounded average KSI consistency score was 0,37. The full weighted table can be found in Appendix 9.14. Policy Instruments: 27 selections were made among 11 participants. For this period, both Voluntary agreements and Knowledge exchange were the most popular among participant selections (7). The only two other categories that had more than three selections were Technical and Domain support to parties (5) and Restrictions (e.g., zero-emission zones) (4). The 'Other … button' was used once, with the input 'Law and Regulation of autonomous driving'.

Time-independent analysis
Measuring (Figure 5.1, top): The most popular selection was *EV adoption* (8 times). All criteria were selected as 'Best' at least 1 time by 1 participant. The criteria that were selected only once were *Local emissions* and the use of *Public Space*. The criteria that address user experience, *Occupancy* and *User Comfort*, also scored low on 'Best' selection, as they were selected only twice. *Car ownership*, *Use of sustainable energy*, *Peak demand* and *Profitability* were more popular, with 4–5 selections. *Peak demand* was never selected as the 'Worst' indicator and therefore, only the 'Best' selections of *Peak Demand* can be observed in the graph (Figure 5.1). Both *Car Ownership* and *Local Emissions* were often selected as 'Worst'. These criteria both focus on the local environment. The criteria that focus more on user experience (*User comfort, Occupancy*) were sometimes selected as the worst. *EV adoption, the use of public space* and *Profitability* were selected as worst only by 1 participant for 1 period of time, and the use of sustainable energy was selected as the worst only two times.
Organizing (Figure 5.1, down left): Independent of time, the criteria *Smart Charging, V2G* and *Accessibility* were selected as 'Best' more often than the other criteria. All criteria were selected at least once. Independent of time, the criterium for *Induction charging* was selected as 'Worst' or least important most often. However, *Induction charging* got selected as 'Best' more often than 3 other criteria. This is in line with the delta results, where almost all participants found *Induction charging* to be more important towards 2040. The second criterium that got selected as 'Worst' the most was *User Groups*, we've seen in the measuring indicator graphs that user experience criteria also was not selected as 'Best' often. *Fast charging* was not selected a lot as either 'Best' or 'Worst', despite becoming less important over time (towards 2030 as well as 2040).
Development (Figure 5.1, down right): The *roll-out of infrastructure* came out as most selected as 'Best' (14 times), but also is represented in 'Worst' selections (6 times). This further underlines the results in the delta analysis, where the roll-out became more unimportant for more than half of the participants over time. We see an inverse of this phenomenon for the *stimulation of technological developments*, which becomes more important, but time-independently is the least often chosen as 'Best' (5 times). *Activities in the Energy System* were the least selected as 'Worst' (3 times), implying a more stable relative importance over all time periods. *Developing the mobility service market* was selected the most often as 'Worst' (13 times), but policymakers found it more important over time and it ended up also being selected as 'Best' sometimes (6 times). Policy instruments: Policy instrument selections of all time periods summed (92 selections): The use of voluntary agreements was the most selected instrument (22 selections), followed by Restrictions (e.g. Zero-emission zones) (20 selections). Preferential treatment was the least selected instrument (6).

5.3.2. AVERAGE WEIGHTS OVER TIME

Below, the average weight per indicator across time periods are discussed. The average weights consider the inputs of each participant equally. However, the scores of individual participants may differ substantially from these averages. This is why the standard deviation is also included (see Tables 5.7, 5.8, 5.9), as well as the individual changes in

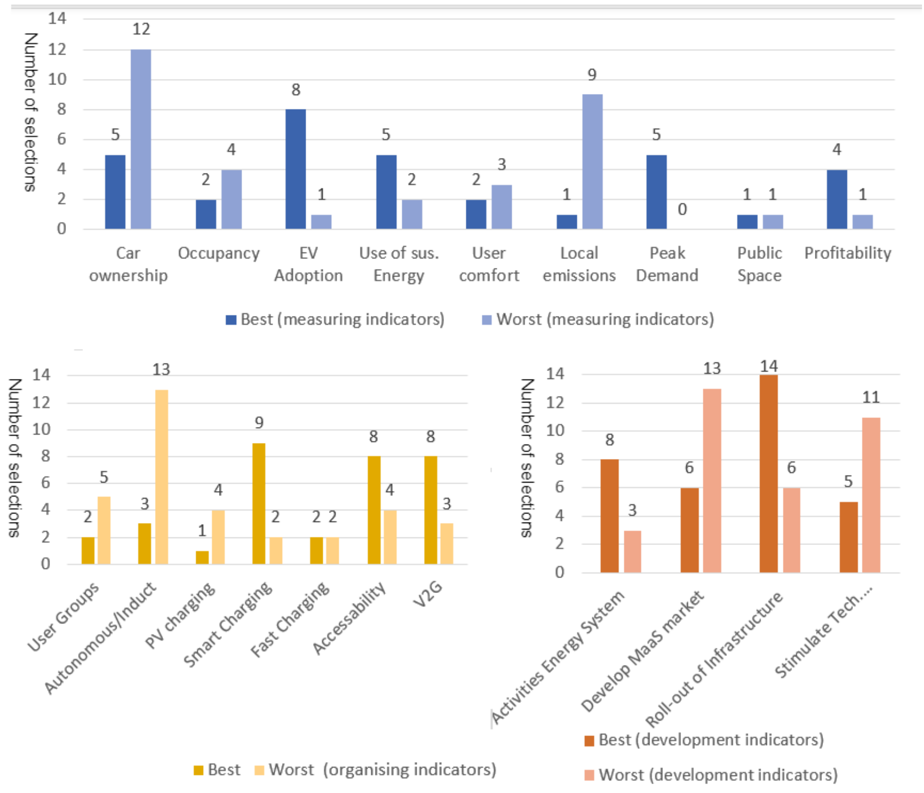

Figure 5.1: Time-independent summation of Best and Worst selection for Measuring Indicators (top), Organizing Indicators (down, left) and Development indicators (down, right). The colors of the figures correspond with the category of indicators: blue for measuring indicators, yellow for organizing indicators and red for development indicators.

Table 5.7: Averages and standard deviations for measuring indicators

	Car owner ship	**EV Adop-tion**	**Profit-ability**	**Public space**	**Peak demand**	**Sus. Energy use**	**Local emis-sions**	**Occu-pancy**	**User comfort**
2025 T1	0.060 (0.038)	0.156 (0.081)	0.114 (0.081)	0.107 (0.040)	0.137 (0.066)	0.102 (0.060)	0.092 (0.058)	0.098 (0.070)	0.134 (0.060)
2030 T2	0.085 (0.067)	0.134 (0.034)	0.117 (0.048)	0.105 (0.050)	0.148 (0.061)	0.122 (0.060)	0.088 (0.054)	0.10 (0.060)	0.101 (0.061)
2040 T3	0.088 (0.07)	0.117 (0.064)	0.079 (0.039)	0.112 (0.053)	0.145 (0.063)	0.155 (0.074)	0.102 (0.071)	0.091 (0.040)	0.112 (0.058)

Table 5.8: Averages and standard deviations for organizing indicators

	Fast charging	**V2G**	**Smart charging**	**Inductive charging**	**PV charging**	**Accessi-bility**	**User groups**
2025 T1	0.192 (0.079)	0.124 (0.065)	0.209 (0.048)	0.061 (0.046)	0.101 (0.061)	0.188 (0.103)	0.126 (0.055)
2030 T2	0.156 (0.037)	0.182 (0.082)	0.207 (0.058)	0.088 (0.074)	0.097 (0.047)	0.150 (0.102)	0.120 (0.073)
2040 T3	0.129 (0.073)	0.161 (0.083)	0.201 (0.091)	0.141 (0.130)	0.121 (0.048)	0.127 (0.065)	0.120 (0.086)

scores over time (see Section 3.3).

Measuring indicators

Some indicators grow in average importance over time: Car ownership, Peak demand and The use of sustainable energy (see Table 5.7). The use of sustainable energy grows the most in average importance over time. There seems to be low consensus across participants for car ownership: the standard deviation is almost as high as the score itself in T2 and T3, and this standard deviation increases over time. Other indicators become less important over time: EV Adoption and Profitability. In the case of EV adoption, the relative average importance is not specifically low, it had the highest score for the first time period (T1), and lowered then. Some indicators stay similarly important on average across time periods: Occupancy and Public space. Local emissions and Peak demand averages did not change much over time either, however, their standard deviation is relatively higher than the other two indicators (See Table 5.7).

Organising indicators

Smart charging has a relatively stable and high average weight. The spread is larger in T3. For Fast charging, the indicator seems to lose a bit of average importance, and also gains more spread in T3, indicating a temporary lack of consensus between participants. V2G becomes more important on average in T2, but the effect stabilizes. Inductive charging starts out with a low average, but becomes much more important, with a very high spread, in T3, indicating a lack of consensus. Accessibility of charging becomes less important on average, with less spread, and PV charging becomes a little more important

Table 5.9: Averages and standard deviations for development indicators

	Develop Maas	Act. Energy System	Roll-out of Infra	Stimulate new tech
2025 T1	0.136 (0.090)	0.299 (0.117)	0.399 (0.089)	0.166 (0.059)
2030 T2	0.226 (0.160)	0.309 (0.090)	0.298 (0.130)	0.167 (0.093)
2040 T3	0.235 (0.119)	0.277 (0.142)	0.230 (0.090)	0.258 (0.127)

on average in T3 (See Table 5.8).

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Development indicators
The roll-out of infrastructure becomes less important over time on average. whereas Stimulating technological developments becomes more important over time on average. Activities in the Energy system has a stable average weight across time periods, however, the spread increases in T3. Development of the mobility-service market (MaaS) is not valued highly on average, especially in the first time period. It also has a relatively high spread across participants, indicating a lack of consensus (see Table 5.9).

5.3.3. DELTA ANALYSIS

For each participant, the delta is calculated as:

$$\Delta = wj(T2) - wj(T1) \tag{5.5}$$

where T1 is the weight calculated for the first time period (null-2025) and T2 is the weight calculated for the near future (2030). This also includes the deltas (differences calculated on the individual level) between the second and third time period. For each participant the delta is calculated as:

$$\Delta = wj(T3) - wj(T2) \tag{5.6}$$

where T2 is the weight calculated for the second time period (2025–2030) and T3 is the weight calculated for the last time period (2030–2040). This shows if the importance is changing, and in which direction in time. Below, the most interesting results are discussed. A full table of the delta analysis for each comparison and category can be found in Appendix 9.1 - 9.6.

Measuring indicators
For 9 out of 11 (82 percent) and all policymakers (N = 4), User comfort becomes less important between 2025 and 2030. A majority (7 out of 11) also finds that the use of sustainable energy becomes more important, and that EV adoption becomes less important. This majority also finds that local emissions become more unimportant. For the other criteria, the results are more mixed. Between 2030 and 2040, EV adoption

and Profitability become less important for 9 out of 11 participants. The subgroup of CPO/Service providers (N = 4), as well as policymakers (N = 4) agree that Profitability becomes less important. Additionally, for all Service Providers, EV adoption becomes less important and the use of sustainable energy becomes more important (quite strongly, an average of 0,10). For 8 out of 11, including all policymakers, user comfort becomes a bit more important towards 2040.

Organizing indicators
For most participants (9 out of 11), Vehicle-to-Grid becomes more important between null and 2030. Also, 9 out of 11 participants, including all Service providers (subgroup, N = 4) found Accessibility to become less important between null and 2030. PV charging becomes more important for 8 out of 11 participants, including all policymakers (subgroup, N = 4), while fast charging becomes less important for 8 out of 11 participants, including all policymakers. The delta of Organizing indicators between 2030 and 2040 differs in direction between participants. The highest overlap in direction is on the role of fast charging (73 percent or 8 out of 11 participants think it becomes less important over time). 1 participant gave identical ratings and distances for 2030 and 2040, which makes the delta 0. All policymakers (N = 4) find that PV charging becomes more important in 2040, while fast charging becomes less important.

Development indicators
8 out of 11 participants find that the roll-out of infrastructure becomes less important after 2030. All policymakers (N = 4) find that Activities in the Energy System will become more important. Participant 7 (P7) had a consistency ratio score for this question that exceeded the threshold of 1. They did not belong to the subgroup service provider or policymaker. The error was nominally small (1–2 points out of 9) and the entry is annotated with an Asterix in the table. Stimulating technological developments becomes equally or more important over time for 8 out of 11 participants (73 percent), while activities in the energy system become equally or less important for 8 out of 11 participants. For all policymakers (N = 4), the development of the mobility-as-a-service market is equally or more important between 2030 and 2040. 1 participant gave identical ratings and distances for 2030 and 2040. Another participant had a consistency score that was deemed too high.

5.3.4. SUBGROUP ANALYSIS

The level of subgroup consensus becomes more apparent when individual weights are plotted over time. Below, the most prominent cases are illustrated in Figures 5.2 - 5.4. The y-axis is not standardized. The colors of the figures correspond with the category of indicators: blue for measuring indicators, yellow for organizing indicators and red for development indicators. Each line represents a participant.

Subgroup consensus: policymakers
As can be seen in Figure 5.2, not only do policymakers have some identical trend directions (more- or less important). In some cases, the distance between the weights is minimized and the level of consensus of the importance seems similar. There seems to

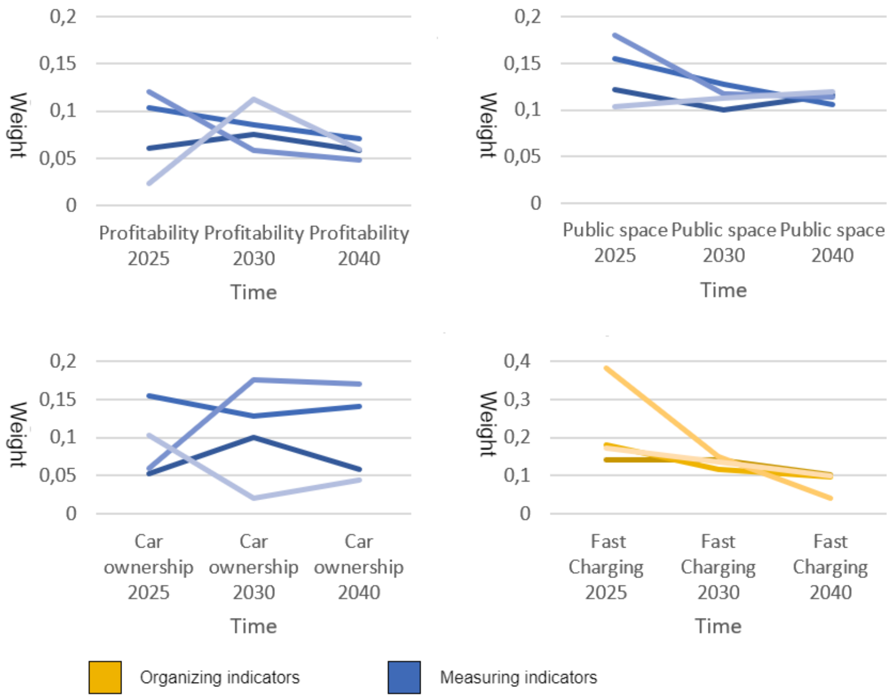

Figure 5.2: Policymaker subgroup plots with notable consensus patterns in weights (y-axis) over time (x-axis) for measuring indicators. Each line represents one participant.

be an agreement of decreasing importance of the measuring indicator Profitability towards 2040, despite different starting points. The importance of Public Space in 2040 is also ranked more similarly, as well as the importance of the organizing indicator Fast Charging, where the weight difference is minimized in 2030. In contrast, the level of consensus for the car ownership indicator is low. The weights, as well as the trend patterns, differ between policymakers.

Subgroup consensus: service providers
Figure 5.3 highlights some consensus patterns for the service provider subgroup. Whereas the measuring indicator for Profitability, EV Adoption, and the Organizing indicator Accessibility start out being valued differently across service providers, the importance lowers over time and service providers rank these indicators more similarly towards 2040 (T3). The level of consensus for these values increases towards later time periods. For the Organizing indicator of different User Groups, the opposite happens: the service providers value it similarly (low) in the 'now' period (T1), but they end up being differently valued at T3: some service providers find that the importance increases, and others don't.

Differences between subgroups
As can be seen in Figure 5.4, in some cases, subgroups have distinct patterns for specific

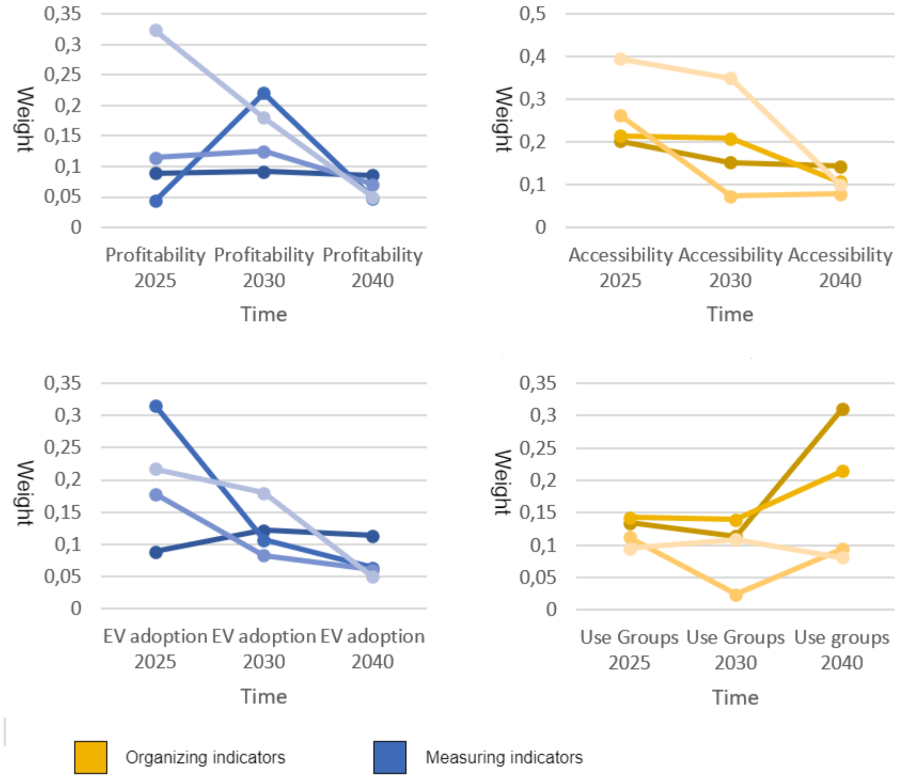

Figure 5.3: Service provider subgroup plots with notable consensus patterns in weights (y-axis) over time (x-axis). Each line represents one participant

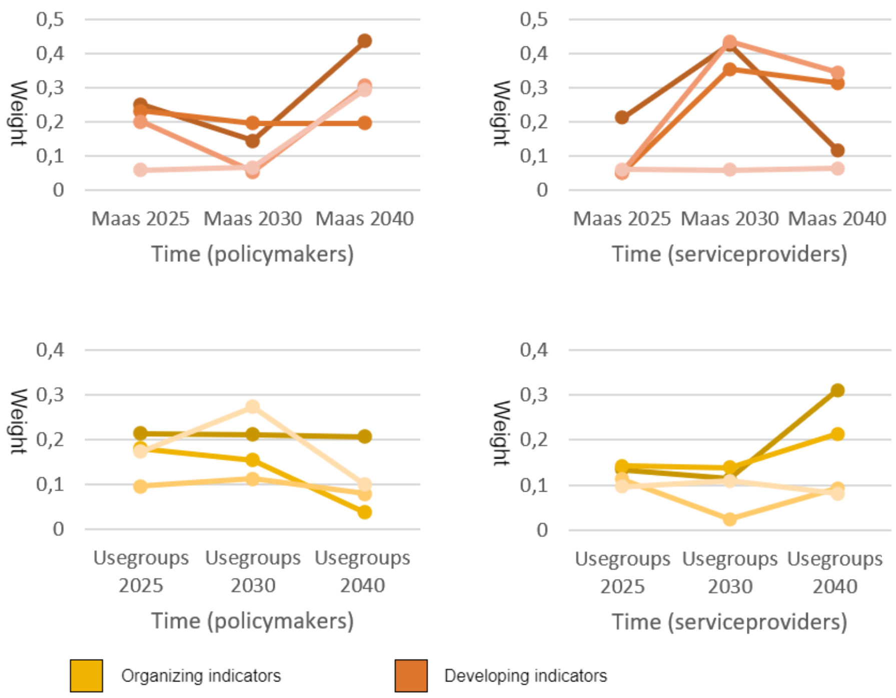

Figure 5.4: Comparing indicator scores of Policymakers (left) and Serviceproviders (right). Each line represents one participant.

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indicators. For the development indicator that addresses the mobility-service-market, the importance increases towards 2040 for policymakers, whereas the importance peaks in 2030 for service providers, and decreases after. The importance of considering different user groups (one of the organizing indicators) has lower overall consensus, as the previous section established: importance increases but consensus decreases over time for service providers. There is an inverse between the two subgroups: for policymakers, the importance decreases towards 2040, whereas the level of consensus increases.

5.3.5. DISCUSSION

Based on these results, four important observations are discussed: current priorities (2025), priorities in the near future (2030) and the later future (2040), as well as indicators with low priority. Figure 5.5 summarizes these priorities in a timeline.

In the near future, prioritizations will shift from adoption and roll-out based indicators to sustainability indicators. EV Adoption, Roll-out of infrastructure and Accessibility of charging are considered important right now. Looking at the firsfit time period (up to 2025), the indicators EV adoption (avgW = 0.16) and Roll-out (avgW = 0.4) had the highest average weights in their category, and were both chosen most often as ‘Best’ within their category. Accessibility to charging points did not have the highest average weight (Smart charging was higher), but was chosen most often as 'Best'. These results indicate that the current emphasis is on adoption, sector electrification, roll-out, and access.

Sustainable charging becomes more important over time. 9 out of 11 (82 percent) of participants found that V2G becomes more important between 2025 and 2030. All policymakers (N = 4) found that the importance of PV/ solar charging increased between 2025 and 2030. The policymakers also find that fast charging becomes less important over time. Service providers find that the use of sustainable energy in charging becomes more important between 2030 and 2040. The exception here is smart charging, a technique that is chosen as 'Best' most often, independent of time, and stays relevant throughout all periods.

The importance of technological developments and autonomous charging will increase at a much later time (2040). Autonomous charging and the stimulation of technological developments were not popular in the first two time periods. However, all service providers increased their importance for technological developments between 2030 and 2040. About half of the participants chose technological development as 'Best' activity in 2040. Autonomous charging becomes a bit more important towards 2040 (with high spread). The role of autonomous charging is therefore still uncertain.

Policy instruments are preferred as more supportive for the first time period and more restrictive for later time periods. Suggestions for different policy instruments were mainly suggested for the first time period. The instrument of voluntary agreements got more popular over time and is considered relevant for future scenarios, whereas the subsidy is popular now but phases out over time. Restrictions (with the given examples of zero emission zones and deadlines) were also often selected. The role of alternative mobility in the EV transition is not prioritized by EV stakeholders. The study examined indicators of alternative mobility and modal shift, such as car ownership and public space usage. Car ownership scored lowest in the time-independent analysis, while public space was of relatively low importance. Some participants did prioritize car ownership. The development indicator of the mobility service market scored low, but recovers by the last time period (T3: 2030–2040). Although it is not entirely clear how participants rank alternative mobility, it is not a priority on a group level. Figure 5.5 summarizes these priorities in a timeline. This timeline represents the priorities of the stakeholders, not taking into account the technical feasibility or the differences between subgroups or individual participants.

The observations made in this section are based on the (subjective) input of decision-makers of public charging in the Netherlands and should only be interpreted within this scope. There is still uncertainty in the future development of EV charging. This development can also be influenced by aspects that are not accounted for in this study, such as international policy and market developments.

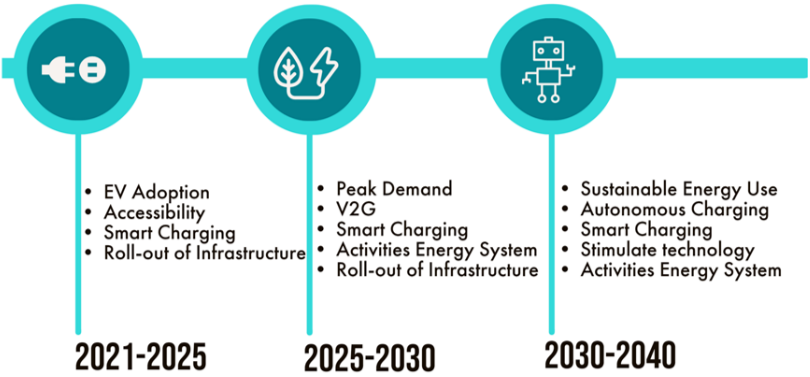

Figure 5.5: Priority timeline based on the most popular selections ('best') and highest average weights.

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5.4. CONCLUSION AND RECOMMENDATION

5.4.1. CONCLUSION

This study addressed the question of which issues are most urgent in public electric vehicle charging, according to stakeholders, and how these priorities change over time. On the basis of stakeholder consultation, we were able to distinguish priorities for different time periods, as well as differences between specific stakeholders (with a focus on policymakers and service providers). We conclude that the short-term focus of key decision-makers lies with EV adoption, roll-out of infrastructure, and accessible charging. Smart charging is already important for most decision-makers, and sustainable charging becomes more and more important over time. In the later future, towards 2040, decision-makers find technological developments and autonomous charging more important, whereas the importance of the infrastructure and the adoption decreases.

Previous studies of stakeholders in the case study area, published in 2014 and 2019, stated that stakeholders find smart charging important (Wolbertus et al., 2020; Bakker et al., 2014) and indicated a lack of consensus within indicators addressing charging methods, specifically the level of user control for smart charging and the importance of fast charging compared to regular charging (Wolbertus et al., 2020). We found that, although values differed across participants, smart charging was among the most prioritized indicators by most participants and was selected as 'Best' by most participants, confirming the importance found in previous studies (see Table 5.6). Table 5.8 also reveals that the standard deviation for smart charging was not particularly high compared to other indicators. The subgroup analysis illustrates how the subgroup of policymakers agrees on the importance of fast charging across time periods. Table 5.8 reveals that the standard deviations for fast charging were not very high in the first two time periods. The delta analysis(Section 5.3.2) shows how 8 out of 11 participants decrease the importance of fast charging over time (T2-T3). This study therefore found a higher level of consensus (and lower long-term importance) on the role of fast charging than previous studies had found. The case study of 2019 found that the type of stakeholder did not predict the type of perspective, except for one of the perspectives, where local policymakers were over-represented. We also found some distinct patterns for policymakers and identified new patterns that were specific to service providers, whereas in the 2019 study, perspectives differed across that subgroup. Policy instruments were also selected for each period. User subsidies were selected the most for the first time period, which users valued lower than comfort and ensured charging, according to Lieven (Lieven2015PolicyPerspective). Another study stresses the importance of research and development (Wu et al., 2021), whereas the similar instrument of this study ("technology and domain support") was only selected a few times for the last period.

In time period T1 (2021–2025) and time period T2 (2025–2030), the indicators public space, user comfort, technology developments and autonomous charging are not valued highly. However, peak demand and the use of sustainable energy are considered important for time period 2, and the technology of smart charging is valued highly for every period in time. Applying these results to the real world could lead to challenges in the demand: The exponential growth in EV adoption will lead to higher demand, not just from the electricity grid. The number of charging points will also need to grow so that drivers can park and charge their vehicles. This will require many resources beyond electricity such as traffic decision-makers, public space, parking spots, charge point installers, grid connections and service providers. The stress during peak hours could increase a lot, whereas most of the infrastructure would not be used during most of the day. In Section 5.4.2, we will discuss some strategies for handling this high demand.

5.4.2. Policy implications

The results on short-term prioritizations imply that creating and satisfying charging demand are the most urgent priorities for decision-makers. The increase in charging demand can be addressed from different perspectives. Various social, local and environmental trade-offs are at play which further complicates the roll-out of urban charging infrastructure (Hensley et al., 2018 ; van der Kam et al., 2020). Below, we discuss two strategies decision-makers can use in future roll-out of infrastructure, and discuss these strategies and their drawbacks in the context of the results of this study.

Strategy A: roll-out of charging resources with protocols to limit grid strain

Facilitate many connections during the same point in time, using smart charging techniques to migrate grid demand, but the demand for other resources (installers, operators, public space, and so on) will be high. This option helps to avoid peak grid overload, and increases user comfort by installing an abundance of charge points. Smart charging can help in scaling up the roll-out of public charging infrastructure, because a significant number of Dutch neighbourhoods don't have enough grid capacity to fulfil the anticipated charging demand without interventions (Michal van der Toorn, 2022). In an Amsterdam smart charging pilot, no significant increases in charging speeds were observed (Bons et al., 2020), although this may differ in a scaled-up scenario. In the future, this setup could be enriched with V2G protocols and techniques to make balancing the grid possible. This would require intensive cooperation between manufacturers, policymakers and installers.

STRATEGY B: SHARING OF CHARGING RESOURCES TO LIMIT RESOURCE STRAIN

This strategy migrates the connection times of EVs by using new technologies (autonomous charging, snake arms, automatic clutch release, induction rotation), user incentives (social charging, tariffs) and introducing alternative mobility (reducing the number of owned vehicles). Car sharers drive up to 20 percent less than personal vehicle owner (Nijland and van Meerkerk, 2017). Intensive sharing of vehicles reduces the need for parking space (Hensher, 2017). *Strategy B* could not only avoid peak overload of the grid, but could also lead to sharing of other resources. When a charging point is used by more users throughout the day, this could improve the business case. Autonomous charging technologies could also be considered future-proof because some technologies allow the vehicle to charge and discharge without driver intervention. This allows for one charging point to be used on multiple vehicles sequentially without user intervention. This option could also be enhanced by V2G in the future, and combinations of technologies (e.g. autonomous V2G balancing fleets) could potentially revolutionize the way we handle electricity demand in municipalities.

The study found that decision makers prioritize roll-out, adoption, and smart charging over car ownership and public space. *Strategy A*, which facilitates connections and uses smart charging techniques, is crucial for successful transitions. However, it has drawbacks, such as increased charging point usage, increased demand for installers and resources, and less profitability for charging point operators with fewer customers per resource. High flexibility without compensating comfort requires more charging points than actively used, requiring more parking space and resources. These resources are already in great demand, and using these resources might be more worthwhile in areas that are underdeveloped in terms of charging. It is undeniable that the future roll-out of charging infrastructure under current grid conditions can only be achieved with the help of smart charging. Nevertheless, other initiatives are necessary too in order to limit the strain on product chains, installers, and public space, and to better connect with other mobility goals, such as modal shift or reduced parking. *Strategy A* can be used to scale up the roll-out of infrastructure that is necessary to ensure charging, and elements of *Strategy B* can be used to limit the charging demand (and therefore, necessary resources) in a spatial area, allowing for more adoption under current grid conditions and a more efficient use of resources. We would like to encourage decision-makers to consider interventions of both strategies before the third time period to ensure charging in the future.

5.4.3. LIMITATIONS

We aimed to include policymakers from all four large municipalities and a national policymaker. One of these municipalities was not available, and therefore, the perspective of only three of the largest municipalities in the Netherlands are included. Additionally, the perspective of rural policymakers is missing. Rural areas in the Netherlands are less developed in terms of public infrastructure, partially because inhabitants are more likely to have their own driveway. However, the importance of public infrastructure will likely grow over time and therefore it is important to consider the rural perspective in future studies. The service providers that were interviewed are employed by different companies. Together they represent a significant portion of the current charging market in the Netherlands. Future work should also consider the perspective of the grid operator, which was not included here. This may give insight into the steps needed to align the perspectives of policymakers, grid operators and service providers. Future work in other countries should be fine tuned to their local context because the stakeholders and issues involved may differ. Since this study focuses on key decision-makers regarding the charging infrastructure, the outcomes do not represent the values or opinions of the users of the charging infrastructure. To generalize the results beyond the case study, additional research with a larger pool of stakeholders is recommended. The best-worst method should only be trusted when the consistency ratio of the outcomes is low enough. This is because pairwise comparison methods do not guarantee a global optimum. Besides that, if participants are asymmetrical in valuing their best- and worst-sets, the consistency ratio is likely to grow since the distance between the outcome weight and sets will be greater. The consistency ratio of the answers overall was acceptable. In the development indicators, Ksi scores were higher in some individual cases. Questionable ksi scores are found for one participant in T2 of the development indicators (1.78) and for two participants in T3 of the development indicators (0.87 and 0.94). We see no substantial effects on the conclusion. Two participants were not able to finish the questionnaire within the meeting; these participants completed the questionnaire within 16hr after the initial meeting. No inconsistencies were found in the data of these participants. When indicators lose priority over time, for example, the roll-out of an infrastructure indicator, there were some participant assumptions that the demand would be satisfied by then because of prior activities. An alternative approach to avoiding these assumptions in future work could be the use of thresholds rather than discrete time periods.

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6

A conceptual representation of short- and long-term decision-making in public EV charging infrastructure

Charging infrastructure in neighborhoods is essential for inhabitants who use electric vehicles. The development of public charging infrastructure can be complex because of its dependency on local grid conditions, the responsibility to prepare for anticipated fleet growth policies, and the implicit biases that may occur with the allocation of charging resources. How can accessible EV charging be ensured in the future, regardless of energy infrastructure and socio-economic status of the neighborhood? This study aims to represent the decision-making in the allocation of public charging infrastructure and ensure that various key issues are accounted for in the short-term and long-term decision making. The chapter first identifies these issues, then describes the decision-making process, and all of these are summarized in a visual overview describing the short-term and long-term decision loop considering various key indicators. A case study area is identified by comparing locally available data sources in the City of Amsterdam for future simulation.

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6.1. INTRODUCTION

The Netherlands is one of the leading countries in public charging infrastructure, and they expect their electric vehicle (EV) fleet to grow to 1.9 million by 2030, which is translated into a need for up to 1.7 million charging points in the upcoming years (RVO, 2019). In the initial roll-out of Dutch public EV infrastructure, strategies were straightforward. Charging points were installed based on citizen requests, or spread out over an area to anticipate new adoption. In later stages, the data of already deployed charging points were used to determine effective expansions of the charging network. However, as more people adopt electric vehicles, it has become apparent that better planning is needed to ensure a robust charging network. Barriers such as limited electricity grid capacity, limited personnel and lack of resources to install charging points, and parking vs charging challenges could hamper this fast adoption. A long-term strategy is necessary to ensure comfortable charging for all citizens in the future.

Technologies to manage grid conditions for public charging

There are various technologies that can be used to manage grid conditions for public charging (Das et al., 2023). For example, already deployed infrastructure can be equipped with smart charging, which takes into account the grid's current capacity and the number of other active charging connections. Alternatively, Vehicle-2-Grid can be used, which enables bidirectional charging between vehicles and the grid, and the car battery can be charged to buffer surplus electricity and discharged to compensate for moments of electricity scarcity. External batteries also buffer surplus electricity and help manage demand during peak hours. New charging infrastructure can be installed, and grids can be expanded. Grid expansions are considered expensive and time-consuming , and need to be planned far in advance. Although these technological solutions can help manage charging under various grid conditions, the scale-up of charging infrastructure also introduces other challenges. Charging demand will only grow, whereas resources and personnel are limited. Resources need to be divided across neighborhoods, and the combination of different intervention strategies needs to be evaluated for various circumstances (adoption rates, grid conditions, planned expansions). This is why new strategies to develop and prioritize areas should be investigated.

Allocation of Charging Infrastructure

Currently, the allocation of public charging infrastructure is mostly determined using one of the following strategies (Gemeente Amsterdam, 2020; Gemeente Rotterdam, 2015; RVO, 2019):

<u>Request-based:</u> EV drivers without the opportunity for private infrastructure request a new charging point, either directly through their municipality or through a charging point operator (CPO) who has a contract with the municipality.

<u>Strategic placement:</u> The municipality and/or the CPO selects locations where new charging demand is anticipated and strategically rolls out new infrastructure.

<u>Data-driven roll-out:</u> New charging points are determined by evaluating the performance and occupancy rates of current charging infrastructure, and by adding new infrastructure in locations with high demand.

<u>Citizen participation:</u> Citizens are sometimes asked by their municipality to participate

in the allocation of charging infrastructure, for example with a voting system on potential locations using interactive online maps.

User Demographics & Equity
A significant portion of the current EV fleet in the Netherlands comes from (private and corporate) lease (Vereniging Nederlandse Autoleasemaatschappijen, 2021). The demographic of EV drivers are predominantly white, male, with relatively high income, and a high level of education (Hardman et al., 2021; RVO, 2021). The design of subsidies, incentives and tax structures have contributed to this demographic (Hardman et al., 2021; Hoekstra and Refa, 2017). They are also likely to be middle-aged and are more likely to own their own driveways and solar panels (Hardman et al., 2021; RVO, 2021). It is not surprising that the distribution of charging points is skewed against low-income areas Hardman et al., 2021). Access to infrastructure in general affects income inequality, according to a study assessing infrastructure and income in 100 countries over 40 years (Calderón and Servén, 2004). Another aspect to take into account is the quality of the infrastructure across different areas. Institutional and technical solutions may be applied with the best intentions to manage charging under various conditions, but what if this leads to higher consumer costs or increased charging times? These aspects should be taken into account when allocating crucial infrastructure related to transport.

Charging point operators and municipalities have catered to current EV users to satisfy the charging demand. This has led to an analysis of charging behaviors and suggestions of charging profiles that were based on a skewed demographic. The European Union has banned sales of new fossil vehicles from 2035 (the Netherlands aims for 2030). This will lead to a larger, more diverse demographic of EV drivers who may not share the same charging behaviors or charging needs. Charging demands are expected to exceed current grid capacities which makes smart charging an important part of the strategy to ensure access to charging (Michal van der Toorn, 2022; Xylia and Joshi, 2022). Technical solutions can enable and manage charging in a scale-up. But it is important to avoid undesirable outcomes, such as grid overload, lack of access, stranded assets, bad investments and missed opportunities.

This study conceptualizes a decision-making mechanism for the future roll-out of EV charging infrastructure, the main question being *'How can the decision landscape of EV infrastructure roll-out be represented to manage charging in neighborhoods with varying conditions?'*

The goal of the study is to conceptualize a potential decision-making method in the roll-out of charging infrastructure, using four different intervention strategies (roll-out of infrastructure, smart charging, Vehicle-2-Grid, and an external battery buffer) and three different roll-out strategies (demand-focused, anticipatory-focused and equity-focused). Meanwhile, taking into account current grid conditions, the planned grid expansions of the grid operator and the expected growth in adoption (derived from planned policy and neighborhood characteristics). This conceptualization can then be used in future studies to experiment with different interventions to work towards an adequate (satisfying demand) and considerate (e.g., by also prioritizing underdeveloped areas) distribution of resources.

The work that is presented here is an intermittent result where issues are identified, the decision-making method is designed, available data sources are compared and a potential case study is suggested. The results of this intermittent work were applied to the selected case study in an agent-based model, using datasets for charging point analysis and socio-economic analysis, and using the NETLOGO software to simulate the decision-making mechanisms under various scenario's. This enabled assessment of the emerging patterns, such as charging satisfaction, spillover effects, and neighborhood equity. The ultimate goal of this simulation is to determine how the prioritization of different indicators and issues under various (grid- and adoption) circumstances affect the development of charging infrastructure in neighborhoods with diverse backgrounds. The following sections in this chapter address the conceptualization and selection of the case study. The simulation outcomes are described in Chapter 7.

6.2. METHODS

The research process of this study consists of five steps. Step 1 takes advantage of a literature study, step 2 & 3 elaborate on the findings in an unstructured fashion, step 4 uses the diagram style of a decision tree while also summarizing relevant aspects of a problem analysis (stakeholders, owners, performance indicators), and in step 5 data sources are identified. A geographical scope and geo-analysis are used to find geographical overlap between the available data sources. A short description of each step can be found below.

1. Identify (anticipated) issues in public charging in neighborhoods (Section 6.3.1): Issues are identified through scientific literature and local policy literature, and the inventions are categorized as short or long-term. Table 6.1 describes the identified issues, and Table 6.2 categorizes the interventions.

2. Determine the short-term application of interventions on already deployed charging points (Section 6.3.2): After step 1, the interventions and issues in the short-term loop are used to determine the application of these interventions, and what is needed to deploy them. Various indicators are identified to collect on a neighborhood level, to make short-term decisions (e.g. the available grid capacity), and tracking of these indicators over time is essential to determine the performance in the long-term decision making (step 3). These indicators are described in Table 6.3.

3. Determine the decision mechanism for long-term interventions and resource allocation (Section 6.3.3): After step 2, and after a prolonged period of applying short-term interventions, the performance of each neighborhood is evaluated using the collected indicators. A pool of resources (long-term interventions) can then be divided using the performance indicators, taking into various aspects of the neighborhood performance (e.g. grid conditions and equity compared to other neighborhoods) for resource allocation. A stepwise comparison is made to determine the distribution of interventions between neigborhoods. This includes potentially updating infrastructure so that more short-term interventions can be deployed in the future.

4. Make a decision tree of the conceptualization (Section 6.3.4): The insights of step 1-3 are combined to design a decision tree as conceptualization, taking into account grid conditions, neighborhood characteristics, and planned policy.

5. Identify a potential case study area by comparing available data sources and projects (See Section 6.4): In order to test decision making under various circumstances, a simulation will be made by initializing parameters of real neighborhoods where charging takes place and considering decision making under realistic (grid- and charging) infrastructure. Such a simulation therefore requires a case study area of which multiple elements of charging can be quantified (e.g. charging points, grid conditions, socio-economic conditions). In Section 6.4, a potential case study is identified by comparing various local data sources.

6.3. CONCEPTUALIZATION

6.3.1. ISSUES IN PUBLIC NEIGHBOURHOOD CHARGING

Section 1 introduced and explained charging management techniques and potential neighborhood charging issues. After this first exploration of neighborhood charging issues and charging management techniques, literature and media outlets were consulted to determine the relationship between our selected management techniques and the concerns of stakeholders in neighborhood charging (see Table 6.1).

Sometimes technology or institutions can alleviate some of the concerns of Table 6.1. The proposed management techniques are owned by different stakeholders (for example: Policymaker, Charging Point Operator, Service Provider, Electricity Provider, Traffic Planner or Network Operator). The way that public charging is organized and the lawmaking that surrounds it differs between countries. For example, differences exist between who gets to exploit the charging infrastructure, how prices are determined, whether the charging point is publicly owned and how subsidies are used (LaMonaca and Ryan, 2022). This is why the decision-making is represented using a neighborhood manager: each neighborhood gets a decision-maker who in reality consists of many other actors and stakeholders, depending on the state regulations and market design. This makes the representation generalizable beyond the Dutch case of public charging markets, and enables exploration of the mechanisms of prioritizing different neighborhoods in a city based on activities and needs. An exception to the list of decision-makers is the DSO and their planning for the grid expansions: these plans are made far in advance, and have to take into account other electricity growth activities (e.g. from households or industries). Therefore, the DSO planning of the local environment should be consulted in advance to represent charging in the future reliably.

Table 6.1: Mapping socio-technical concerns of neighborhood charging under various grid conditions with potential management techniques (Liander, 2022a; Michal van der Toorn, 2022; Liander, 2022b; Glombek and Helmus, 2018; Silva et al., 2021).

	Social concerns	**Technical concerns**	**Charging management techniques**
Access to charging	Walking distance Availability Cost of charging	Grid connection Supply chain Personnel	Install new infrastructure Market regulation Update existing infrastructure (smart charging/Vehicle-2-Grid) Grid expansions (mid-voltage, high-voltage)
Quality of charging	Waiting times Failed sessions	Charging speed Performance Interoperability	Update existing infrastructure (higher capacity) Maintenance/Support Technical standards Enable Vehicle-to-grid
Energy Security	Network tariff Power outage	Grid overload	Install an External Battery (mid-voltage station) Grid expansions (mid-voltage, high-voltage)

Table 6.2: The short-term and long-term decision loop in the roll-out and management of charging infrastructure.

Short-term (daily loop)	**Long-term (policy loop)**
Smart charging, Vehicle-to-Grid	Update Charging Protocols, Increase Capacity, Roll-out of points
Use external battery, DC / Fast charging	Install external battery
Reject session (occupancy- or grid-based)	Do Nothing

Table 6.3: Charging indicators: neighborhood level parameters

Parameter	Description
Failed sessions	Goes up every time a session cannot be started
Maximally occupied	Goes up each time the max occupancy was reached
Grid capacity	The grid capacity at each step (battery, MV)
# of chargepoints	Number of charging points in the neighborhood
# of batteries	Available external batteries in the neighborhood
% of occupied chargepoints	Occupancy rate of charging points
Chargetime (hr)	The time it takes to fully charge a vehicle
Charge load (kWh)	The charging demand expressed in kWh
Distance (Spillover)	The distance between the original charging request and the selected charging point.

6.3.2. SHORT-TERM APPLICATION OF INTERVENTIONS ON CHARGING POINTS THAT ARE ALREADY DEPLOYED

As explained in the previous Section (6.3.1), applying interventions in the form of charging management techniques such as the integration of charging protocols and grid compensations knows two challenges: (1) the roll-out and management of these interventions, and (2) the deployment of these interventions when a charging session takes place. The deployment of these charging protocols is conceptualized in a decision tree (see Figure 6.1). It is also important to collect the right information during sessions in order to make confident choices in the future roll-out of new infrastructure and in installing new protocols on already deployed infrastructure. In order to do that, decision-makers need to be aware of the current conditions and charging performance of the neighborhood. Important indicators to collect throughout the year include the number of failed sessions because of grid overload, the occupancy rates and the number of times all charging points were occupied, the charging behaviors (starttimes, chargetimes, stalling, charge load), and the available leftover grid capacity (Helmus and Van Den Hoed, 2016; van der Hoogt et al., 2020). This conceptualization adds development indicators of the neighborhood so far (currently deployed charging infrastructure, installed external batteries, etc.) to assess the distribution of resources across neighborhoods. The parameters included in the conceptualization are described in Table 6.3. Some indicators are not parametrized, for example, the distribution of start times of charging sessions, and the socio-economic statistics of the neighbourhood, since they can be initialized within the case study using population data.

6.3.3. LONG-TERM INTERVENTIONS AND RESOURCE ALLOCATION

The next step to conceptualize is the decision-making mechanism that is used when rolling out new interventions to manage the occupancy rates and grid needs of public charging. The decision is made with the use of a weight set of parameters that is collected throughout the charging loops that take place within the time span of a year (see Table 6.3). After the year, the evaluation round of the administrators in an area can take place. The evaluation round consists of the following steps:

1. Check if there are any newly planned grid expansions for this year, according to the DSO

timeline.
2. Assess the current charging and social conditions in the neighborhood to determine allocation of new infrastructure.
The future charging needs need to be determined for each neighborhood, for example by assessing how many times sessions failed because of missing infrastructure, the occupancy rates, the socio-economic predictors, the policy planning and the current distribution of charging point locations. To determine if connections are possible, the grid capacity should be assessed. The new charging points will be assigned to neighborhoods, and neighborhoods with higher charging needs, high prognosis or limited development are prioritized. When there is space to realize the connection, and if there are resources left in that year, neighborhoods will receive new infrastructure based on their priority level. Resources are not infinite, and personnel as well as technical components are in high demand, especially in large cities (Liander, 2022a).
3. Assess the current grid conditions in the neighborhood to determine allocation of other interventions.
The currently deployed infrastructure may be outdated, slow, or may not have protocols installed to use the smart charging or Vehicle-2-Grid interventions. Therefore, the potential to update infrastructure should be considered when managing charging infrastructure in neighborhoods. Especially the update to smart charging can be helpful when charging needs exceed grid capacity in neighborhoods, which is something that DSO's foresee happening in the near future (Michal van der Toorn, 2022). When neighborhoods struggle with grid conditions, and new expansions are not planned or still far away, an external battery could be considered to compensate for the excess charging load. The neighborhood should have designated space for the battery, and a need for the battery. The size of the battery is determined by the expected load, for which the maximum number of overlapping failed sessions could serve as an estimate.

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6.3.4. CONCEPTUALIZATION OVERVIEW (DECISION TREE)

Figure 6.1 is a decision tree that illustrates the short- and long-term decision loops in the roll-out of charging infrastructure, taking into account grid conditions. On the top left, the necessary inputs to determine charging management techniques in the short-term loop are defined. In the middle, there is a decision tree indicating the decision process in selecting the right charging protocol, given the current conditions. The top left bar shows the relevant outputs of this decision-making loop. These outputs, combined with case study specific information (such as grid planning and neighborhood parameters), then serve as inputs (bottom left) for the strategic decision making in the roll-out and allocation of charging and grid interventions.

Decision-making: The decision-making is represented in the decision tree that can be found in the middle of the bottom row of Figure 6.1. The decisions can be categorized as the updating of charging points (protocol or capacity), the allocation of new charging points and the introduction of external batteries. Decisions take place in both the short-term as well as the long-term loop. For the short-term loop, the grid capacity, occupancy and type of charging point play an important role in selecting interventions. Some of the objects in the diagram contain a question mark, in which a state is checked. For example in "[charging] protocol?" the question is asked whether a type of charging can be triggered in this session, based on the specifications of the car or charger. In the long-term loop, grid performance and charging point performance important for battery allocation and infrastructure upgrades. Upgrades are determined by grid conditions and charging needs, whereas external batteries are only considered when grid capacity is dangerously low and there is space available for a battery. For the allocation of new charging points, the performance of the infrastructure, as well as other factors (such as socio-economic or policy planning) are considered using a prognosis.

Prognosis: Some researchers and consultants have looked into a variety of indicators to determine the charging potential for on-street public charging at Dutch neighborhoods. Dutch researchers and consultants identified car ownership, driveways, population density, rental houses, proximity to schools and hospitals, age, employment, income, and voting behavior of neighborhoods as neighborhood indicators for future charging needs (ElaadNL, 2020; Koopman, 2023). The exact conceptualization of a prognosis will be dependent on the location of the roll-out, but important elements include the occupancy rates (*what is the current charging demand?*), socio-economic predictors (*which neighborhoods are more likely to experience growth in EV fleets?*), desirable effects (*where do we want to make EV purchases more attractive?*), feasibility (*how many new points can we facilitate under current space and grid conditions?*), and special circumstances, for example, the introduction of policies that may increase adoption rates, or new contracts for shared electric vehicles. This prognosis will vary per use case, to ensure applicability.

Applicability: Other countries than the Netherlands may differ in their challenges and needs and may therefore use other indicators to determine allocation. For example, Asian cities are often more densely built and facilities are more likely to be government-owned, which makes charging hubs at community areas a fitting solution for allocation (He et al., 2022), whereas in Sweden, populations are less dense and private charging is more widely adopted (Xylia and Joshi, 2022). Therefore, the conceptualization considers both the current level of infrastructure development (to assess the distribution), as well as a prognosis, which can be specified within the use case, to determine the priority of new charging points in neighborhoods.

6.4. CASE STUDY

One potentially interesting area the Netherlands is the city of Amsterdam. The available data for this geographical area make an interesting opportunity to investigate potential allocation of infrastructure and interventions. The city of Amsterdam has a high penetration of electric vehicles, and because of the high population density with limited private parking facilities, EV drivers in this city are often dependent on public charging infrastructure. The city also knowns more inequality between neighborhoods than most Dutch cities (Modai-Snir and van Ham, 2020). Amsterdam-based institutions have different projects working on electrification in the city, and this enables access to the following information:

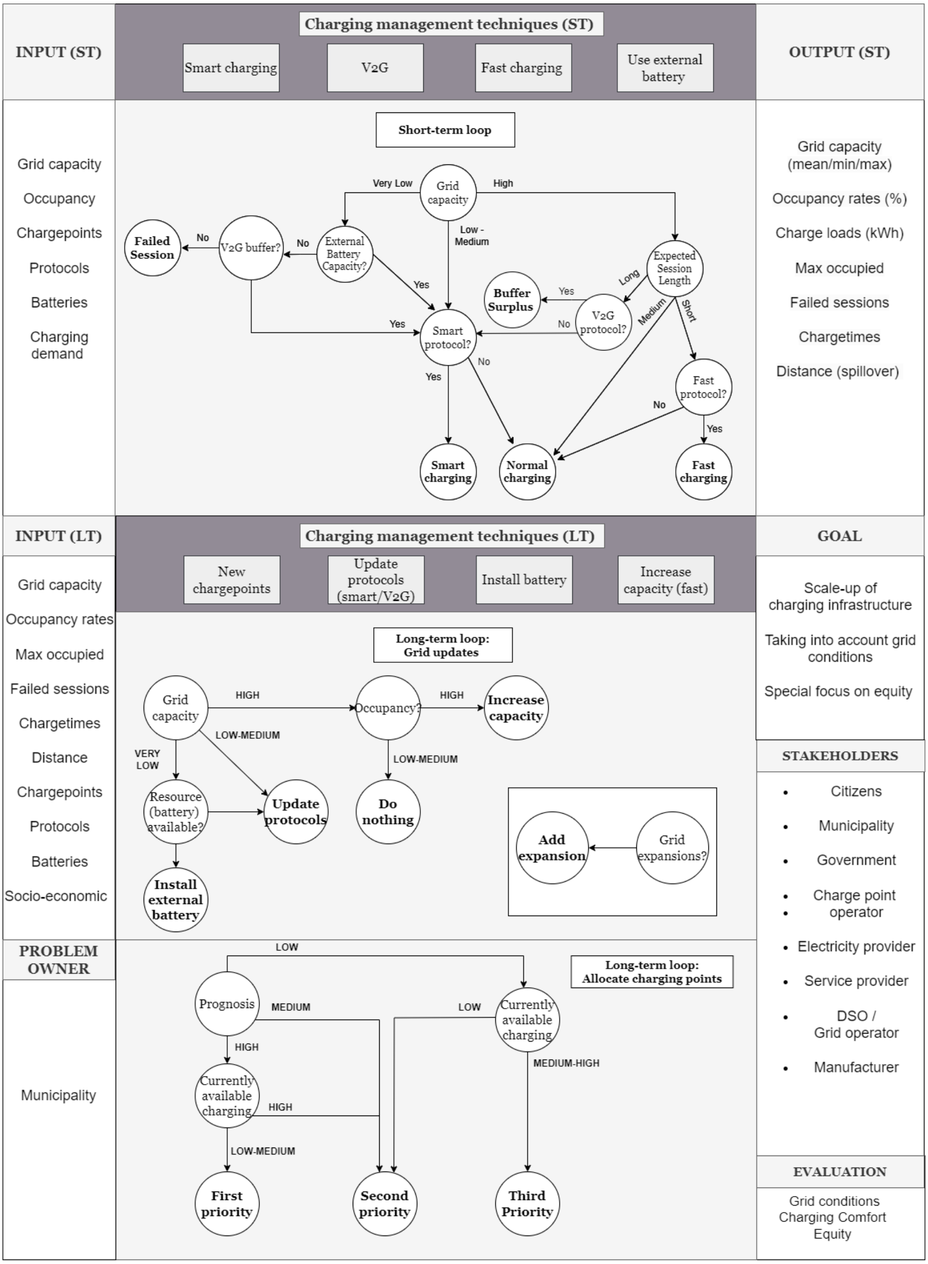

Figure 6.1: Conceptualization of the short- and long-term decision making in public EV charging across neighborhoods, taking into account grid conditions and equity.

Table 6.4: Case study data

Conceptualization components	**Data from case study**
Normal charging	Charging transaction data
Smart charging	Flexpower charging transaction data
Fast charging (not highway)	Charging transaction data (sample of fast chargers)
External battery for charging	Simulation, P&R garage pilot
Vehicle-to-grid	No case study specific data
Socio-economic neighborhood factors	Income, gender, population density, urbanization, cars/household
Grid capacity	Transport capacity maps (national, regional, Amsterdam)
Grid expansions	Timeline of expansions and expected increase of capacity in the city of Amsterdam
Distance (Spillover)	The distance between the original charging request and the selected charging point.

- Charging point data of over 3,000 public charging points in the City of Amsterdam (internal institute database)
- Municipal planning by the medium-voltage grid operator of which stations will be expanded in Amsterdam (Gemeente Amsterdam et al., 2022; Liander and Gemeente Amsterdam, 2021)
- Charging point data of charging points that include the smart charging protocol in Amsterdam (Buatois et al., 2019; Ligthart et al., 2020)
- Simulated and empirical data of a pilot that uses an external battery to buffer surplus renewable energy for charging in an Amsterdam parking garage (Heath et al., 2024)
- Socio-economic neighborhood data from the Central Bureau of Statistics (CBS, n.d.)
- Local policy documents pertaining different electrification goals for commercial and passenger vehicles (van der Koogh et al., 2021). For example, incentives and electrification deadlines for logistics, shared mobility, cab drivers and, from 2030, emission-free zones for passenger vehicles (Gemeente Amsterdam, 2016 Gemeente Amsterdam, 2019; De Rijksoverheid, 2018).

Interesting neighborhoods with widely available data were compared to ensure a rich representation of dynamics between charging and the electricity grid. This means that, in the context of the available data, a selected neighborhood cluster should have at least the following elements so that realistic parameters for behavior and interventions can be ensured:

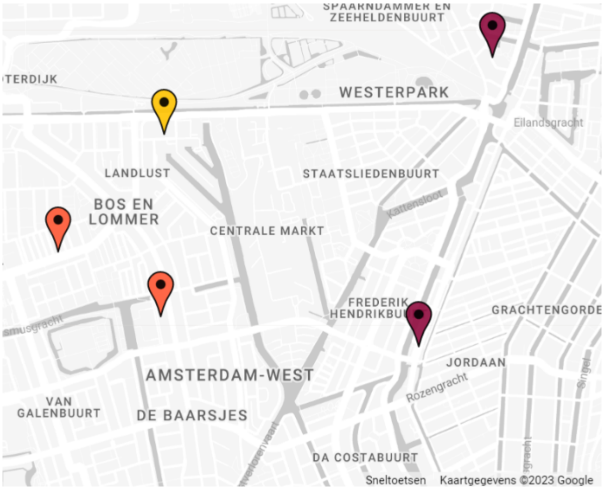

Figure 6.2: Potential Case Study Location (the yellow marker is a planned grid expansion, dark red markers are congested stations, orange markers are smart charging pilots).

1. A major residential function
2. Available charging data and available socio-economic data
3. Close proximity to a number of charging points with the smart protocol installed (if possible)
4. Interesting grid dynamics and close proximity to a neighborhood with planned grid expansions as determined by the planning of the DSO.

The currently available smart charging data takes place in the following districts in Amsterdam: *Bos en Lommer, Grachtengordel west, Hoofddorppleinbuurt, Oostelijk havengebied, Oud-zuid and Rivierenbuurt.* The Bos en Lommer district contains smart charging pilots location. Liander has planned to expand the grid by adding a new underground station in 2024 (Nieuwpoortstraat), located at the bos en lommer area, because of other stations I neighborhoods with near proximity that are experiencing congestion and are nearly overloaded (Marnixstraat, Westzaanstraat). In 2035, Liander planned to expand Station Westzaanstraat for more capacity. These stations are located in neighbouring subdistricts of the Bos en Lommer area, making this expanded area of neighborhood clusters an interesting one to analyze. Figure 6.2 shows these points of interest on a map.

6.5. Conclusion & Future Work

In this chapter, some of the most prominent issues in neighborhood charging were identified (Section 6.3.1) and an approach was suggested for future roll-out of charging management strategies and charging infrastructure, taking into account various factors (grid conditions, socioeconomic factors, policy planning and the current charging behavior). A distinction was made between the short-term (Section 6.3.2) and long-term (section 6.3.3) allocation of interventions and the conceptualization was summarized in a decision tree (Section 6.3.4). A case study location was found (Section 6.4), by comparing available data sources to find an area that is interesting in terms of charging demand, grid challenges, currently deployed infrastructure, existing pilots and policy planning. The next step will be the simulation of this decision-making, using data from the case study. Technical interventions will be improved and newly developed over time, and some technical interventions (e.g. inductive charging and battery swap) were not included in the suggested design because their readiness level in terms of legislation makes their implementation currently less accessible and more uncertain than the technologies now included. However, these technologies can play an important role in the future, for example for commercial fleets with a static location. In the future, the design could be expanded to include these new technologies. Other types of interventions could also be included in future designs. For example, institutional interventions and market regulations could be included to promote fair use and pricing. The design does not take into account compensation options for situations where some neighborhoods have an advantage over others. Compensations such as charging discounts, and public transport discounts could be used to compensate inhabitants of neighborhoods with lesser charging options. The suggested conceptualization could be expanded with other infrastructural challenges in urban planning across neighborhoods, for example, considering renewable electricity generation or challenges of the heat transition, by first exploring the management techniques and determining under which conditions (planning, comfort, grid, equity) they could be allocated (long-term loop) and/or deployed (short-term loop). This could improve the estimation of future energy needs and the charging opportunities of a neighborhood.

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7

SIMULATING THE ALLOCATION OF CHARGING RESOURCES IN NEIGHBORHOODS

Mylene VAN DER KOOGH

This chapter discusses the allocation of charging resources in neighborhoods, focusing on various output parameters such as charging demand, occupancy rates, grid capacity. The roll-out of charging infrastructure is simulated using three different allocation strategies. First, the case study data is analyzed and the conceptualization of decision-making in public charging is formalized. Next, the implementation in an agent-based model is described. After that, the runs and results of the model are discussed. The correlation between allocating infrastructure and the performance of the charging network is analyzed. The effects of roll-out strategies on the within-neighborhood and between-neighborhood competition of resources is also analyzed. Results indicate that the three strategies prioritize neighborhoods differently, the use of batteries can reduce grid overload in neighborhoods with lower grid capacity, the within-neighborhood and between-neighborhood competition can be reduced by using socio-economic and spillover indicators in the roll-out strategy, and that demand-based roll-out can lead to accumulation of chargers in neighborhoods where high adoption of public chargers is not predicted.

7.1. INTRODUCTION

The scaling-up of EV charging infrastructure in residential areas knows a number of challenges, such as challenges in allocating the charging infrastructure, facilitating connections to the grid, expanding the grid infrastructure, making charging more accessible and sustainable, and managing the peak demand of charging. *Chapter 3* of this dissertation described the goals in the mobility transition, including e-mobility goals and the requirements for these goals. This chapter illustrated how charging infrastructure needs to be developed rapidly in order to maintain charging comfort for a growing group of EV drivers, and that various technological interventions can be implemented to make charging more efficient or more fitting to the environment. *Chapter 4* revealed how different policy scenario's and different user groups will lead to differences in charging needs and charging behaviors. *Chapter 5* discussed the stakeholder prioritizations, which initially were roll-out based, but nearing 2025, the priority is shifting to sustainable charging, including V2G, smart charging and renewable energy generation. In *Chapter 6*, these goals and challenges were translated into a conceptualization that could be modeled and simulated. This chapter will describe the software implementation of this conceptualization. The results and implications are also discussed.

The chapter starts by explaining the research questions (7.1) and describing the literature (7.2) that is used to make experimental scenarios. Then, the methods are explained (7.3.1) and the case study environment is further conceptualized using data analysis (7.3.3). After that, the formalization and implementation of the model is described, as well as the experimentation (7.4.2). The chapter ends by sharing the results (7.5), conclusion (7.6) and recommendations for researchers who simulate, and policymakers who are responsible for residential public EV charging (7.7).

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The research question of this study is: *"How do rollout strategies affect neighbourhood dynamics?"*
It is important to allocate charging points responsibly. Current strategies emphasize the measured demand when allocating chargers. What is the difference in allocation if we put more emphasis on other priorities such as socio-economic indicators or literature-found predictors of EV charging demand? What happens to the allocation if we roll-out new charging resources according to these strategies? The charging network should perform well for the EV users. Negative effects, such as demand clustering, long wait times, exceeding grid limitations, and so on, should be minimized. This is why it is important to monitor the performance of the charging network for each simulated strategy. EV users have to share public charging resources among themselves. This could lead to a competition pressure when resources are more scarce than the demand. Changing your preferred charging location (as an EV user) because of competition, can lead to more mobility movements and more user frustration. This is why it is important to also take into account the spillover sessions as an indicator of competition. The sub-questions for this chapter are as follows:

1. *What is the effect of different roll-out strategies on the resource allocation of charg-*

ing resources?

2. *What is the effect of different roll-out strategies on the performance of the charging network?*

3. *What is the effect of different roll-out strategies on the within- and between neighborhood competition?*

7.1.1. FROM CONCEPTUALIZATION TO MODEL IMPLEMENTATION

Chapter 6 contains a conceptualization that was used for this modeling chapter. However, some adjustments have been made to the conceptualization during the implementation steps of the model. These adjustments are discussed below, to avoid continuity issues in the dissertation. The adjustments include:

- Grid expansions of the DSO were excluded, and only the "mobility space" reserved at middle-voltage level was considered. This adjustment was made after finding out that DSO's used this reserved space in their pilot experiments and simulations.

- Figure 6.1 talks about first, second and third priority, whereas the simulation in Chapter 7 prioritizes differently (see Table 7.6)

- Chapter 6 and Figure 6.1 do not differentiate between strategies, and chapter 6 and Figure 6.1 do not differentiate between spillover-from (between-competition) and spillover-to (within-competition). The strategies and output parameters are explained in section 7.4.2. and Table 7.7)

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7.2. LITERATURE

Charging demand can be estimated by using the data of already deployed charging infrastructure. In Germany, Pagany et al.(2019) determined the charging demand of locations using survey data of drivers and vehicle sales information. The suggested allocation of new charging points was optimized by minimizing the walking distance for multiple potential users. Researchers also estimated the future charging demand, using predictive indicators, as well as market and policy developments. in the Netherlands, Wolbertus et al. (2021) used the preferred locations of public charging, the distribution of habitual users and visitors, the kWh charged, battery sizes and occupancy rates to determine locations with high demand. In areas where charging is not deployed yet, other information is needed to determine the charging demand. In some Dutch municipalities, EV owners can request a charging point in their street. Other municipalities collect preferred charging locations through an online public voting system. Machine learning methods and GIS-based analysis are commonly used for predictive studies. In Massachusetts, household incomes and income types were used to predict EV adoption (Gehrke and Reardon, 2022). Dutch studies have identified predictors such as car ownership, income, proximity to schools and hospitals, and political affiliations to forecast charging demand (Refa, 2020; Koopman, 2023). In Belgium, charging demand could be predicted with household size, income and points of interest (De Clerck, 2023). In Brazil, researchers combined future adoption scenarios with points of interest to recommend a balanced distribution of fast chargers (Faustino et al., 2023). In Luxembourg, potential areas for fast charging of shared vehicles were identified using data from traditional ride-sharing apps and websites (Ma and Xie, 2021). Table 7.1 gives an overview of relevant predictors that came out of these studies.

Table 7.1: Predictors and indicators of charging demand, from literature

Study	**Demand predictors and indicators**
Gerkhe and Reardon, 2022	Household incomes, income type
Refa, 2020	Car ownership, housing type, income
Koopman,2023	Income, households, green voters, schools, hospitals
De clercke, 2023	Income, points of interest, household size
Faustino et al, 2023	Points of interest, spatial distribution (for fast charger placement)
Ma and Xie, 2021	Ride-share app information
Wolbertus et al, 2021	Locations, % visitors, charge load, battery size, occupancy
Pagany et al,2019	Survey data, vehicle sales

Predicting charging demand is different from predicting adoption rates. The decision to adopt in individuals is influenced by the total cost of ownership, access to infrastructure and vehicle range, among other things (e.g., (Letmathe and Suares, 2017). This study does not simulate the decision to adopt in individuals, but rather anticipates the charging demand from a neighborhood level.

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The topic of charging accessibility differences as a spatial infrastructure justice issue has been researched more intensively over the past few years. This has led researchers to study initial EV adoption and the deployment of public chargers and home chargers. The problems with access to charging infrastructure related to spatial allocation can be defined as a distributive justice problem. Studies by Hsu & Fingerman (2021) in California, Carlton and Sultana in Canada 2022, and Khan et al. (2022) in New York City have highlighted the limited access to charging facilities in low-income neighborhoods and in black and Hispanic communities. Even when public charging options are available, as noted by Hardman et al. (2021), the higher costs associated with public charging compared to home charging may pose challenges for low-income areas. Tsukiji et al. (2023) suggest stimulating adoption in underserved areas through purchasing subsidies, cost reductions for charging, and job creation. They also emphasize the importance of addressing specific needs of vulnerable groups in travel. Li et al. (2022) identified spatial inequalities in charging opportunities across cities in China, with disparities between city centers and suburbs. In the Netherlands, subsidies helped municipalities deploy public charging infrastructure (RVO, 2015) and helped individuals to purchase EVs. The majority of EVs in the Netherlands are currently leased, rather than owned personally (Centraal Bureau Statistiek, 2021. The distribution of public charging points is also uneven, and often favors densely populated areas (Koopman, 2023). Kelobonye et al. (2020) makes distinctions between within-area and between-area competition for resources such as shopping, public transport and education. Research suggests that the uneven distribution of charging points and charging opportunities should be assessed more critically. The studies described above reveal some of the indicators to make such an assessment (see Table 7.2).

Table 7.2: indicators to assess charging opportunities in urban areas

Study	**Charging accessibility indicators**
Litman, 2022	Per capita access to resource
Kelobonye et al., 2020	Competition (within neighbourhood, between neighborhoods)
Li et al., 2022	Distribution between outskirts and city centers
Carlton and Sultana	Price of charging
Hopkins, 2022	Adoption barriers
Tsukiji et al, 2023	Accessibility for disabled users

This chapter describes a simulation in which the focus is on public charging development in neighborhoods. Vertical justice indicators, such as disabled access and pricing, are important in literature, but not in scope for the case study. The same is true for indicators that focus on the adoption of electric vehicles. Other data and case studies are needed to investigate these phenomena. Therefore, the charging opportunity focus of this chapter will be on the access per capita or household, the level of competition and the distribution of resources.

7.3. Materials and Methods

7.3.1. Agent-based modeling

Agent-based modeling (ABM) was selected as a method. In agent-based modeling, variations of roll-out strategies, adoption rates and charging patterns can be tested. This helps identify emergent patterns, the underlying interactions between parts of the system (Bonabeau, 2002). Agent-based modeling can also be used to simulate situations where there is still a lot of future uncertainty (Lempert, 2002). This study investigates charging demand within- and between neighborhoods, and the effects of local roll-out strategies on the charging system, which includes the monitoring of spillover effects between neighborhoods when local charging demand exceeds the supply (number of charging points). This is why it is important to spatially represent the agents and data that are included in the simulation. The modeling environment Netlogo (Wilensky, 1999) allows for such a spatial representation in an intuitive way, which is why the model was built in this software.

In the book “Agent-based modeling of Socio-technical Systems”, models are described using a few distinct steps (Van Dam et al., 2013). These steps include problem-, actor- and system descriptions, conceptualization, formalization, implementation, verification, experimentation, data analysis and validation. This chapter describes the problem, system and actors in 7.3.2, the input data in 7.3.3, the formalization in 7.4.2, the model verification in 7.4.3, the model experimentation in 7.4.4, and the data analysis of results in 7.5. Conceptualizations and a broader problem statement can be found in *Chapter 6* and the introductory sections of *Chapter 7*.

7.3.2. PROBLEM, SCOPE AND CASE STUDY

The problem which is simulated is a *resource allocation problem*. The underlying issues that the model addresses are the scale-up of infrastructure, grid limitations, within- and between community competition for charging resources and accessing charging resources. The problem owner is the *policymaker*. Other important actors are the Charging point operator (CPO), Service provider (EMSP), grid operator (DSO) and EV user [1]. The systems that are modeled are energy infrastructure (scoped to mobility-related aspects of the middle-voltage grid infrastructure) and EV charging (on the charging point level). Each charging session is modeled individually, and each step in the model represents one hour. The geographical scope is a sample of 9 neighborhoods in the Amsterdam subdistrict “Bos en Lommer”. Output is collected on a neighborhood level.

The Bos en Lommer subdistrict is not part of the CBS deviation of districts. It corresponds with the municipal Area 4. The majority overlap with CBS is with the West District. The CBS neighbourhoods that are included in the Bos en Lommer Area, according to the municipality of Amsterdam, are: Erasmuspark, Landlust, Sloterdijk and Kolenkit. According to inhabitants, Gibraltarbuurt, Gulden Winckelbuurt, Robert Scottbuurt and Laan van Spartaan are also included. We represent 9 neighbourhoods in a 3 x 3 grid in the model, with a selection of these neighborhoods and the (spatially) connecting neighborhoods (see Table 7.3).

Table 7.3: 3 x 3 grid of neighborhoods that are selected as a case study

Top row:	Kolenkit (KK), Gibraltarbuurt (GB), Landlust (LL)
Middle row:	Robert-scottbuurt (RS), Erasmuspark (ER), Bosleeuw (BL)
Bottom row:	Laan van Spartaan (LS), Balbaoplein (BB), Trompbuurt (TR)

The model was initialized combining data from various sources:

- Local charging data: local charging data was used to determine the total number of charging points, the number of smart charging points, and the number of users per neighborhood.
- National household survey (NHS/CBS): The NHS data from the Dutch Central Bureau of Statistics 2022 and 2021 was used to determine the number of residents, households, average income and registered cars per neighbourhood
- EPEX day-ahead market: This data was used to estimate the local peak hours in grid consumption.
- External reports: External reports were used for additional context. This included the report from the municipality and DSO, which includes a planning for grid

[1] These actors are not represented in the model as active agents, but they are implied in various actions that take place within the model (e.g., rolling out infrastructure or charging a car).

expansions (Liander and Gemeente Amsterdam, 2021)and the neighborhood demand prediction from ElaadNL and NAL (2021).

This data is needed to initialize the model environment. The next section describes the input data used to initialize the model.

7.3.3. INPUT DATA

Charging transaction data over the year 2022 was used to determine the number of chargers and users. Smart chargers were identified through the Flexpower project [2], and general charging locations and sessions were identified through a transactional charging dataset.

Table 7.4: Charging stations and sessions in 2022

	KK	**GB**	**LL**	**RS**	**ER**	**BL**	**LS**	**BB**	**TR**
Charging points	13	12	25	12	22	15	2	13	15
Smart chargers	0	0	5	0	4	0	0	0	0
Fast chargers	0	0	0	0	0	0	0	0	0
Sessions (2022)	6810	6196	13,527	6384	13,969	7721	3091	6423	8173

The number of users that connect to a charging point each hour in the day were also monitored on a neighborhood level. Figure 7.1 shows the average number of users each hour of the day. This differs between neighborhoods, but some general patterns can be determined (first daily peak between 08.00 and 10.00, largest daily peak between 16.00 and 18.30). The average number of users for each hour of the day can be found in (Appendix 9.15). The maximum number of users for each hour in the day can be found in (Appendix 9.16).

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Data from the Dutch National Household Survey (NHS), collected by the Central Bureau of Statistics (CBS), is needed to further initialize the model for these neighborhoods. The following information is used in the model:

- Number of households: needed to determine the amount of resources per household
- Registered cars: needed to determine the number of cars and the number of non-traditional (not fuel) vehicles.
- Average income: needed to determine the average income as a predictive indicator

Studies state that important predictors of EV adoption are car ownership and income. The Dutch Central Bureau of Statistics reported the number of registered cars in their 2022 NHS dataset (CBS, n.d.). Income is not reported every year, this is why the 2021 dataset was used to determine average income for each neighbourhood. Car ownership differs strongly between neighborhoods (see Fig. 7.2). Average income differs

[2] Smart charging project in the municipality of Amsterdam (Bons et al., 2020).

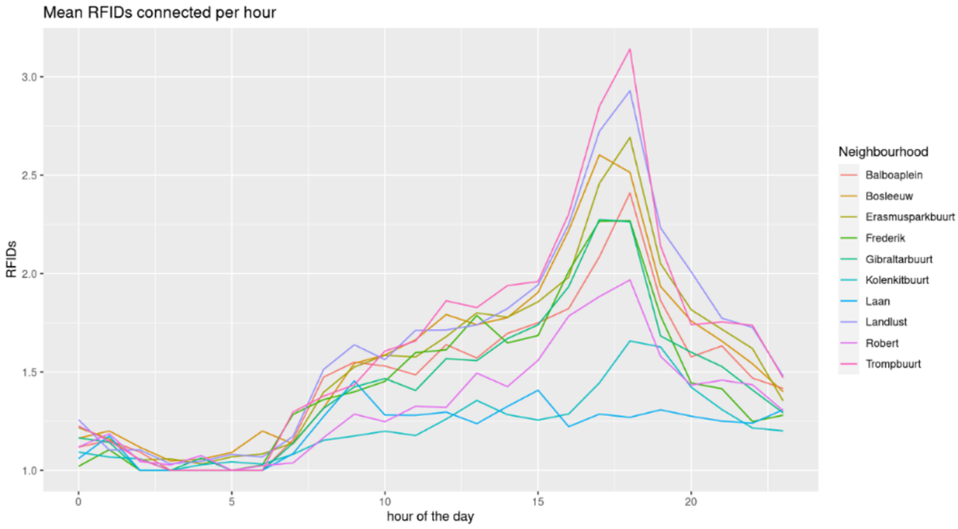

Figure 7.1: The average number of charging point users (of neighborhoods) throughout the day, derived from full set of public charging transactions in 2022.

less between neighborhoods (see Fig. 7.3). Landlust has the most cars, and Laan van Spartaan the least. Trompbuurt and Erasmusbuurt have the highest average income.

In 2021, a neighborhood demand prediction was made by ElaadNL and the National Agenda of Charging Infrastructure (see Fig. 7.4 and ElaadNL and Nationale Agenda Laadinfrastructuur, 2021). This data was included to use as part of the anticipatory roll-out strategy.

The peak hours of electricity are determined by following the average pattern of the EPEX Day Ahead Market (see Appendix 9.7). Peak hours are determined in the model as the hours between 06:00 -10:00 AM and 04:00 – 09:00 PM. During peak hours, the grid space reserved for mobility will be lowered in the smart charging infrastructure, by lowering the power to those connections to roughly 8A per connection. The total grid space is also more limited because of other peak household activities.

CHARGING SPEEDS

The initial charging speed [3] is determined by the current infrastructure, taking into account peak and normal grid availability (mobility reservations of the middle-voltage space), fast charging [4], smart charging [5] and V2G charging (Cañigueral et al., 2024, 'Groen

[3] Normal charging is set at 11kW, which is the speed of roughly 90 percent of the current regular chargers in the area (grid.com, 2024)

[4] If there is no more grid capacity to facilitate fast charging at the moment of charging, the charger will scale down to a normal (11 kW) charger. Scaling down does not happen automatically at peak hours, which is the case for smart charging.

[5] Smart charging can be lowered to 5A-6A according to Cañigueral et al., 2024. If more than 4 cars are connected and smart charging in the MV space, the vehicles will take turn charging with 15 minute intervals. In the model of this chapter, the charging speed will scale down accordingly depending on the occupancy rate.

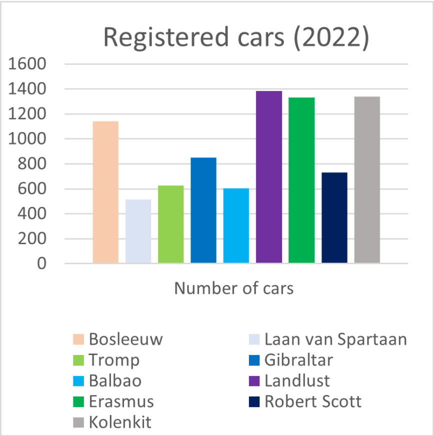

Figure 7.2: Registered cars per neighborhood (CBS, 2022)

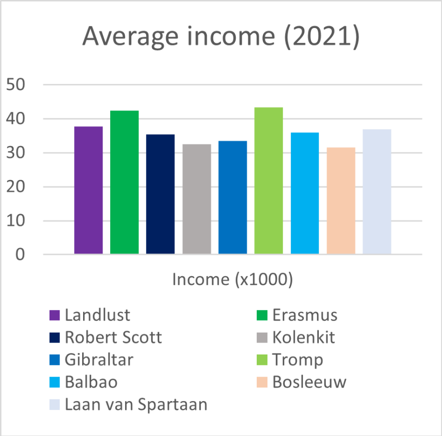

Figure 7.3: Average income per neighborhood (CBS, 2021)

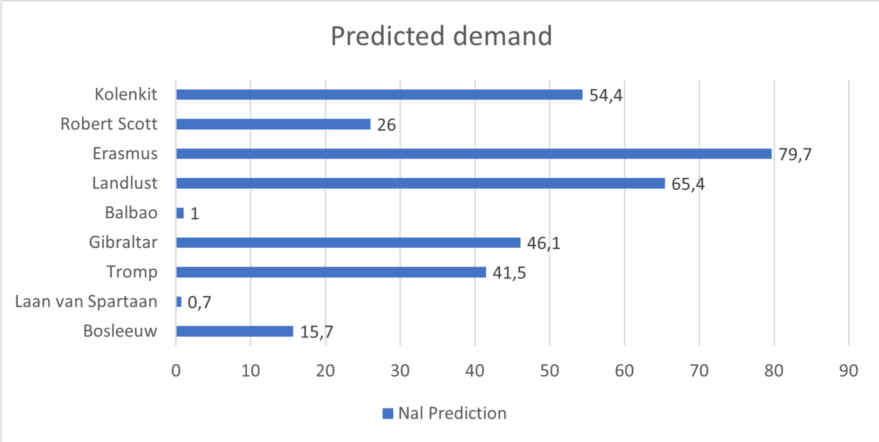

Figure 7.4: Predicted future demand for chargers (ElaadNL and Nationale Agenda Laadinfrastructuur, 2021)

et al., 2022). All charging speeds can be found in Table 7.5.

Table 7.5: Charging speeds

Charging protocol	Time	MV limit	Connection limit	Capacity
(Semi) Fast	Dal	No limit	125A x 400V	50 kW
(Semi) Fast	Peak	No limit	125A X 400V	50 kW
Normal	Dal	No limit	3x 25A x 230V	11 kW
Smart	Dal	No Limit	3x 35A x 230V	11 kW
Normal	Peak	8A-10A/connection	3x 25A x 230V	11 kW
Smart	Peak	32A/MV-space	3x 8A x 230V	4.3 kW
V2G	Peak	Does not apply	3 x 35A x 230V	-8.6 kW

7.4. AGENT-BASED MODEL OF ROLL-OUT STRATEGIES IN NEIGHBORHOODS

The following sections explains how the model was developed, and which steps were implemented in the model. 7.4.1. gives an introduction of the model and explains what the model does. 7.4.2. gives an overview of the agents that play a role in the model, the initialization of the model, the actions of the model in the short-term and the long-term loop (as defined in Chapter 6 and Fig. 6.1), the calculations of the three strategies, the output parameters of the model and the time- and growth aspects of the model. Section 7.4.3. contains the output of the test runs in order to verify the model. Finally, 7.4.4. explains the experimental set-up used to simulate with the model.

7.4.1. MODEL INTRODUCTION

The model is an agent-based model built in Netlogo. This model uses the conceptualization as defined in Chapter 6. The model contains a short-term loop of one hour, and a longer-term loop of one year. The short-term loop contains daily charging activities in which the decision where to charge, and with which charging speed, is made. The long-term loop contains the allocation activities and updates of resources that happen once a year. These concepts are further explained in Section 7.4.2. The neighborhoods are conceptualized using NHS and charging data. Section 7.3.4 elaborates on the use of data for the conceptualization of neighborhoods.

Fig 7.5 shows the dashboard environment of the agent-based model. The nine neighborhoods are found in the 3 x 3 grid on the left side, and distinguishable by color. Each transformer has a number of charging points as a cluster (see Fig 7.6). Competition and spillover took place between neighboring (nearest) neighborhoods. Spillover could not take place across the outside borders of the model (closed model).

The model shows the nine case study neighborhoods in a grid. At initialization, the number of chargers, smart chargers and sessions per hour is set for each neighborhood, corresponding with their actual metrics as measured in 2022. At each hour of the day, the model determines whether the grid is operating on peak hours, whether current charging sessions will end, and whether normal occupancy or peak occupancy takes place in a neighborhood. Based on the occupancy rates, grid status, charging point composition and vehicle composition, a charging mode is selected (normal, fast, smart, V2G, battery) for each session that starts in this hour. When all chargers in a neighborhood are occupied, the charging session request will be moved to the next neighborhood. Neighborhoods collect information about the performance metrics of charging, and the movements of charging session requests throughout the year. Once a year, all neighborhoods are compared and ranked to determine the allocation of new chargers, a new external battery, and the update of a few charging points into fast chargers, smart chargers or V2G chargers.

7.4.2. MODEL FORMALIZATION

The formalization section explains the agents, rules, variables and output of the model.

AGENTS

The model contains three types of agents: MV-transformer, charging point and neighborhood administrator.

The *MV-transformer* represents the electricity infrastructure in the neighborhood. It is an aggregation of all the mobility spaces (load reservations in the grid infrastructure for charging stations) in the neighborhood. The sum of this space is referred to as “grid availability”. The number of charging sessions per hour are requested on the transformer level. The transformer manages the cluster of charging stations in a neighborhood, and allocates the sessions in one of the un-occupied charging stations. If all stations are occupied, the transformer sends the charging request to the nearest next neighborhood. The actions of the MV-transformer can be summarized as: spawn new charging points, assign sessions to charging points, facilitate the spillover.

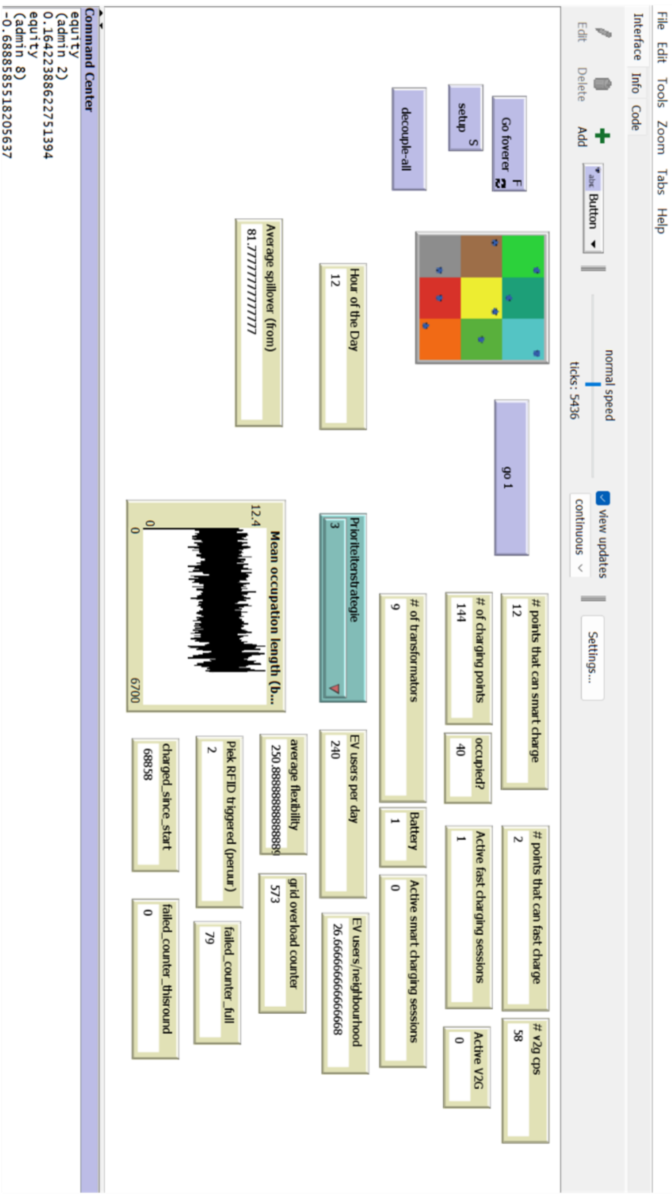

Figure 7.5: Dashboard of the agent-based model

Figure 7.6: MV-transformer (blue house in grid) with 12 charging points in cluster assigned (info panel).

The *charging point* is part of a cluster of charging stations in a neighborhood. The charging points vary in settings (smart chargers, fast chargers, regular chargers and V2G chargers) and when a requested session is picked up by a charging point, their status changes to occupied. The charging speed is selected based on the charging point settings, session details and grid (mobility) space. The charging point can vary in charging protocols and charging speeds, and has an occupancy status that is updated each step in time. The actions of the charging point can be summarized as: starting- and ending sessions, selecting charging protocol, consume electricity, prosume electricity.

The *neighborhood administrator* is responsible for collecting various performance indicators throughout the year. Once a year, all neighborhood administrators rank themselves based on these indicators and the selected roll-out strategy of the simulation. Based on the ranking, new resources are allocated. The actions of the neighborhood administrator can be summarized as: ranking (as group), determine the spawn rate of charging points, determine the spawn rate of batteries, determine the protocol updates of charging points.

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INITIALIZATION

The model environment is initialized using the input data from 7.3. First, the (current) number of charging points are hatched, according to the input data of the neighborhoods. Then, a number of chargers are asked to enable the possibility to smart charge, also according to the neighborhood data. Then, there is a chance of 40% that the charging points can charge bidirectionally in vehicle-to-grid mode.

Short-term loop: Daily charging activities

Each MV-transformer gets a number of charging requests, based on the average occupancy rate [6] of that hour. The session requests are then connected to the nearest charging station in the neighborhood. Based on the grid availability, type of car, and type of charging point, a charging protocol is selected. The protocols consist of regular charging, smart charging, V2G and fast charging. The charging speed for each protocol can

[6] There is a 10% change for each neighborhood, that a higher number of sessions is triggered. This is the "random demand peak".

be determined from Table 7.5. If the charging stations in a neighborhood are fully occupied, the session is passed to the nearest next neighborhood. This is called 'spillover'. If the two nearest neighborhoods are also fully occupied, then the request for a charging session fails. The short-term actions of the model are as follows:

- *Calculate input parameters (administrator level):* The corresponding occupancy rate (of the hour in question) is collected on a neighborhood level. The grid capacity is determined (peak hour with lower capacity, or normal hour with regular capacity).

- *Decouple sessions and v2g question (charging point level):* The first action is to decouple the charging sessions at occupied charging points. If the vehicle is charging for longer than 24 hours, or the state-of-charge surpassed 80 %, the vehicle is decoupled which makes the charging point available again. The vehicle-to-grid mode can also be triggered here, if the state-of-charge is over 40%, there is grid scarcity and the vehicle is connected for less than 10 hours. If the vehicle is connected for more than 10 hours, and is in the vehicle-to-grid mode, the vehicle-to-grid mode will be disabled.

- *Start new sessions (transformer level):* The transformer receives the number of sessions to facilitate in that hour. The transformer assigns sessions to charging points in their cluster (neighborhood). The session is characterized with the following (randomized) values:
  - Battery size of the vehicle (between 15 – 100 kWh)
  - State of charge of the vehicle (between 10-70%)
  - Ability to charge in the vehicle-to-grid mode (50% chance)

- *Select alternative point (transformer level):* If the neighborhood is fully occupied, the transformer will ask the nearest neighborhood if they have the capacity to facilitate the charging session. If so, one of the charging points in the cluster of this nearest neighborhood will be asked to facilitate the charging session.

- *Select protocol (charging point level):* The charging point will select a protocol based on the charging point capabilities, vehicle capabilities and grid capacity:
  - if there is high grid capacity (>100) , and the charging point can fast charge, select Fast charging
  - if there is sufficient grid capacity (>24, <100), select Normal charging
  - if the grid capacity is low (>11, < 24) and the charging point is smart, select Smart charging
  - if the grid capacity is low (>11, < 24) and the charging point is not smart select Normal charging
  - if the grid capacity is too low (<11) but there is battery capacity (>11) select battery charging

  - If nothing fits, grid overload is triggered and charging is stalled until next round (occupancy status stays the same).

- *Calculate output parameters (administrator level):* The output parameters of the model, such as the occupancy rates of the charging clusters, the charging demand (in kWh), and the leftover grid capacity, are calculated at this step.

- *Update battery capacity:* If there is a battery, it will fill up with 10 kW per hour, given that it is not a peak hour in grid consumption

- *Update state-of-charge:* Based on the charging speed of the session, the state-of-charge is updated. In the case of vehicle-to-grid charging, the state-of-charge will become lower.

Long-term loop: resource allocation
Each year, the model can roll-out a group of new charging points based on the number of available resources. In this simulation, 15 charging points can be given away each year. Table 7.6 illustrates the allocation of these 15 charging points given the calculated priorities, where NB1 represents the neighborhood with the highest priority score, and NB9 is the neighborhood with the lowest priority score. Priorities are based on the roll-out strategy perspective that is applied. Based on the literature in 7.4.2, the following strategies were designed: demand-based strategy, anticipatory strategy, socio-economic strategy. The strategies prioritize the neighborhoods based on a number of indicators.

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Table 7.6: Example of allocation

Priority	**NB1**	**NB2**	**NB3**	**NB4**	**NB5**	**NB6**	**NB7**	**NB8**	**NB9**
# CPs	5	4	3	2	1	0	0	0	0

The actions of the model in the long-term loop are as follows:

- *Allocate new charging points:* The administrators rank themselves based on the selected strategyand divide the charging points that are available for the new year between them.

- *Allocate new battery:* An external battery is allocated to one of the neighborhoods, based on the complementary strategy.

- *Update existing infrastructure:* A few of the charging points are updated to smart or fast chargers, based on the complementary strategy.

The roll-out strategies and complementary strategy are explained in the next paragraphs. Figure 7.7 gives an overview of the different actions that take place inside one step of the model.

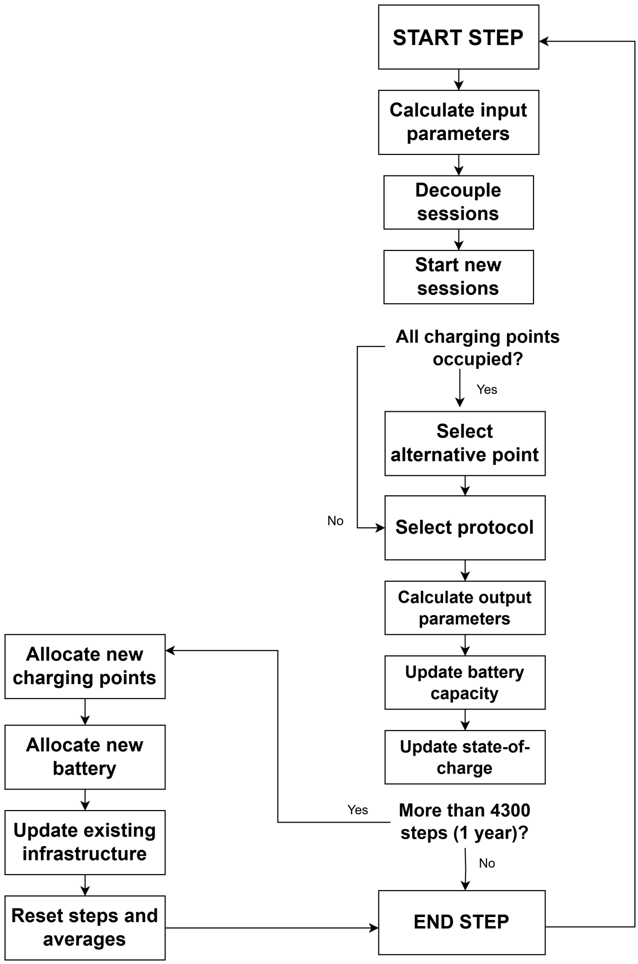

Figure 7.7: Actions that take place inside the model

ROLL-OUT STRATEGIES

The following three strategies prioritize the allocation of chargers in neighborhoods by weighing indicators such as the occupancy rates or the average income of the neighborhoods. These weighted indicators are normalized in a range of 0 to 1.

Demand-based strategy

The demand-based strategy prioritizes based on their occupancy rates, kWh charged and the users per charging point (See 7.1). All input parameters are normalized (0-1 range) so the maximum evaluation score is 4. The highest scoring neighborhood is the first priority, and so on.

$$Demandscore = M\_O + A\_O + D + (U/C) \tag{7.1}$$

- M_O (normalized) is the number of times the max occupancy was reached in the neighbourhood
- A_O (normalized) is the average occupancy rate in the period of one year
- D (normalized) is the total sum of electricity charged in the neighborhood for one year
- U/C (normalized) is the average number of users (sessions) per day, divided by the number of charging points.

These normalized variables all come from the simulation environment.

Anticipatory strategy

The anticipatory strategy is based on the fleet potential (number of registered cars that are not EVs), the predicted demand scores (ElaadNL and Nationale Agenda Laadinfrastructuur, 2021), the average income of the neighborhood and the total number of registered cars (See 7.2). All input parameters are normalized (0-1 range) so the maximum evaluation score is 4. The highest scoring neighborhood is the first priority, and so on.

$$Anticipatoryscore = P\_F + P + Inc + T\_C \tag{7.2}$$

- P_F (normalized) is the fleet potential (total number of cars – number of EVs) based on the NHS data and the number of users in the model
- P (normalized) is the predicted demand score, based on ElaadNL and Nationale Agenda Laadinfrastructuur, 2021.
- Inc (normalized) is the average income as reported by NHS and as a predictive indicator for demand
- T_C (normalized) is the total number of registered cars in the neighborhood as reported by NHS and as a predictive indicator for demand

These normalized variables use the input data from the Central Bureau of statistics (see Fig. 7.2 and 7.3). These variables are selected because they are often used to predict demand in other studies (see Table 7.1). The prediction score P is based on the predicted demand (see Fig 7.4).

Socio-economic strategy
The socio-economic strategy first identifies the neighborhood with the least number of chargers. This neighborhood gets an extra 0.10 on their score. Other than that, the within-competition (the number of times the users could not charge in their own neighborhood) and between-competition (the number of times a neighborhood had to facilitate a user from another neighborhood) are considered. These all come directly from the simulation environment and are normalized in a range of 0 to 1. Lastly, the investment of chargers per household is subtracted. The number of households per neighborhood is determined through the input data of the Central Bureau of Statistics. (See 7.3). These three indicators are normalized (0-1) range, so the maximum evaluation score is 2.10.

$$Socio-economicscore = B + S\_F + S\_T - Inv \tag{7.3}$$

- B is the 0.10 bonus of the neighborhood with the lowest number of chargers in general
- S_F is the spillover-from indicator (representing the within-competition)
- S_T is the spillover-to indicator (representing the between-competition)
- Inv is the investment, chargers divided by households

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These normalized variables use the simulated competition paramaters and number of charges, whereas the number of households are determined from the National household survey as reported by the Central Bureau of Statistics (CBS, n.d.).

Complementary grid strategy
There is a complementary strategy to update the resources based on grid capacities. Because grid limitations are relevant in each perspective, this strategy is deployed next to one of the three main strategies mentioned above. This strategy has two components: Battery update (See 7.4) and charging point update.

$$Battery(min\{g1 \dots g9\}) += 1 \tag{7.4}$$

In the battery update, the neighborhood with the lowest average grid space (g) is selected, and gets an external battery, if they do not have 5 batteries yet. There is 1 available battery per year, and the battery can buffer electricity (10 kW equivalent) each tick (up to 109 kW equivalent). The battery can be used in sessions where there is not enough grid capacity to charge. The available charging points are also updated. The 3 neighborhoods with the lowest available grid capacity are asked to change one (randomly selected) charging point into a smart charger, if it is not already a smart charger. Similarly, the 3 neighborhoods with the highest grid availability are sorted, and the one that has the longest mean occupancy length is asked to change a charger into a fast charger, if it is not already.

Limits

Limits are set in the model to avoid unrealistic growth:

- The battery can be charged up to 109 kWh. This allows for the charging of roughly 10 sessions, given the battery is fully charged.
- The maximum number of batteries that can be installed in a neighborhood is 5, because more batteries may lead to challenges with allocating sufficient public space.
- The growth scenario cannot exceed the total number of (EV- and non-EV) cars as registered in the NHS.

MONITORING AND OUTPUT

In the model, various indicators are monitored as part of the short-term decision-making loop (charging point selection, protocol selection) as well as the long-term decision-making loop (resource allocation, infrastructure updates). Table 7.7 describes the output parameters of the model. These are used:

- In the short-term loop of the model, as indicators to select a charging protocol
- In the long-term loop, of the model, as weighing indicators of the strategies
- In the evaluation of the model outcomes, as performance indicators

TIME AND UPDATES

The model works on a 1-hour time resolution, which means that every 24 ticks represents a day. A year is 180 days in the model, to reduce the output data to approximately 50%. First, the model runs 4300 ticks (approximately 1 year) in the short-term loop where charging sessions are assigned to charging points and protocols are selected. After this year, the long-term loop is triggered and new allocation and updates of infrastructure are decided, based on the averages of the monitored indicators. This decision event also triggers the demand growth, which can be between 5-20% (depending on the experiment) and differs randomly between neighborhoods. The demand growth is rounded, which means that sometimes multiple iterations are necessary before the actual number of users will grow for that hour (see example Table 7.8, where it takes 4 years to grow from 1 to 2 sessions at the 6AM ticks).

The potential factor (total cars – EVs) is also updated based on the growth. After this event is triggered, the decision parameters are reset and the short-term loop is again triggered for a year. The model runs for 10 years.

Table 7.7: Output parameters

Output parameter	Unit	Description
Charging demand	kW	The charging demand of neighborhood
Sessions per day	#	The number of sessions per neighborhood, per day.
Occupancy length	hr	The time it takes to charge the vehicle
Occupancy rate	%	The occupancy rate of the charging point cluster in a neighborhood
Grid capacity	kW	The available capacity of the grid (mobility space scope, nb level)
Grid overload	#	The number of times the grid capacity got exceeded
CPs received	#	The number of charging points received throughout the simulation
Batteries received	#	The number of batteries received throughout the simulation
Spillover from	#	The number of times an EV had to charge at other neighborhood
Spillover to	#	The number of times a neighborhood facilitated an outsider
V2G discharged	kWh	The charging load that was bidirectionally charged in one hour
Smart sessions	#	Total number of smart sessions in a year, per neighborhood
Fast sessions	#	Total number of fast sessions in a year, per neighborhood
V2G sessions	#	Total number of V2G sessions in a year, per neighborhood
Total sessions	#	Total number of sessions in a year, per neighborhood

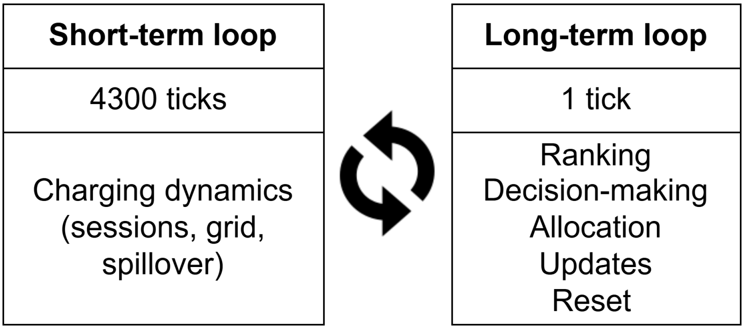

Figure 7.8: Time representation of the model. 1 tick represents 1 hour, 180 days represents 1 year.

MODEL VERIFICATION

This section describes how the mechanisms of the model were tested. The model was tested throughout the development using static parameters, manual runs and print statements. Some test runs have been done within the model interface, monitoring the parameters at each step to avoid unexpected loops or effects. Some effects, such as the spillover rates, are dependent on many variables and could not be verified. However, the inner mechanism of the spillover was tested by printing the neighborhood that was fully occupied, printing the new selected neighborhood, and the coordinates, whether that neighborhood was also fully occupied, and if not, which charging point was selected. After that, there was a manual check to verify that the neighborhoods were indeed neighbors and the charging points assigned were indeed part of the targeted neighborhood cluster. The runs were analyzed on an all-neighborhood level, to see if the outcomes were within reasonable boundaries. The number of resources, growth rate, number of grid overloads and occupancy times were checked, see below:

Is the new number of resources correct?
In all three runs, the number was set to 15 charging points a year, and indeed, after 10 years, the number of charging points grew from 129 to 279. The technical maximum for batteries was 10 (1 every year), and the technical minimum was 5 (only 1 neighborhood needs them every time, but surpassed the maximum [7]). In the three runs, the number of installed batteries was between 5 and 8, therefore this number is also realistic.

Is the growth rate realistic?
The model was tested in the 5-20% growth per year setting. This means that the technical minimum would be ~162%, if 5% growth is always triggered for everyone, and technical maximum is ~619%, if 20% growth is always triggered for every neighborhood. The numbers were all (~253% – 327%) within these boundaries for all three runs.

Is the number of times that the grid was overloaded realistic?
It is difficult to predict what is realistic, but a high share grid overload in the of sessions

[7] if the maximum condition in a neighborhood was reached (5 batteries), the installment was skipped.

(e.g. 15% of sessions or higher) should not be allowed in the model. This is because this is unlikely to occur in real life, since these issues would have been met with interventions by the government and DSO. Therefore, it was important to test that the grid overload stayed below catastrophic failure under the simulated growth circumstances. Grid overload took place between 0.86 and 1.46% of the sessions in all three test runs.

Is the time it takes to charge your vehicle realistic?
The mean was calculated for all session lengths, at each run. A lower and upper boundary was written into a graph at each step. The mean occupancy length of all runs had a lower boundary of 5 and upper boundary of 12 hours at the beginning of the model, and in later years this stabilizes to a more specific lower boundary of 7 hours and upper boundary of 11.7 to 12 hours. These are reasonable charging times given the current charging behavior data [8] [9].

MODEL EXPERIMENTATION

Each experiment, as indicated in Table 7.9, was simulated with 25 runs[10]. The output was collected for each 6 hours in time, and included the following parameters for each run:

- Charging points received
- Batteries received
- Mean occupancy length (in hours)
- Percentage of chargers occupied
- The number of times spillover-from occurred
- The number of times spillover-to occurred
- Grid capacity
- Charged load
- Battery charged load
- Discharged load
- Average number of users per day
- Total number of sessions
- The number of times the charging was regular, fast, smart, v2g, or battery charged
- The number of times a vehicle did not charge for an hour because of grid overload

[8] some research communicates 15-16 hours of mean connection time, however, this model automatically decouples sessions after 24 hours which excludes long idle sessions from the simulation and reduces the mean.
[9] The difference in lower boundary can be explained by a higher need for vehicle-to-grid and smart charging use and more occurrences of grid overload in the later (more busy) years of the model.
[10] After the 25 runs, the output was assessed and patterns of the last few runs did not reveal new information. This is why no additional runs were executed.

7.5. RESULTS

The results were collected through runs of the model. The data was analyzed to provide insights in the behavior of the model. First, the allocation of charging stations and battery installments is discussed for each neighborhood and perspective (7.5.1). Then, the performance of the network was analyzed by looking at the correlations between assigned resources, perspectives and the performance indicators, while also addressing the role of external batteries, fast chargers and bidirectional (V2G) charging (7.5.2). The correlations between assigned resources, perspectives and the level of competition is also discussed (7.5.2.) and reflected on (7.5.3). Finally, the results are discussed.

7.5.1. ALLOCATION OF CHARGERS AND BATTERY RESOURCES

ALLOCATION OF CHARGERS

Figure 7.9 gives an overview of charging point allocation. The columns consist of the nine neighborhoods: *Kolenkit, Erasmus, Landlust, Robert scott, Laan van Spartaan, Balbaoplein, Gibraltar,* and *Tromp*. Each row shows the divide of resources at the end of one run. The number of resources was then color scaled from high (dark green) to low (light yellow).

The demand-based allocation prioritizes Kolenkit and Robert Scott (Table 7.10). Four of the neighborhoods get at least two charging points per run. The other neighborhoods were not guaranteed a charging point within a run. Standard deviations[11] are different between neighborhoods, implying more static and more dynamic allocation based on the location and other parameters. The anticipatory allocation has a strong preference for Robert Scott, Laan van Spartaan, Balbaoplein, Bosleeuw and Gibraltar (Table 7.11). These all get 24 to 27 charging points assigned at each run. The other neighborhoods are not prioritized, get to divide 6 among them each run. The socio-economic runs are more flexible and lead to a more widespread allocation of charging points (Table 7.12). No neighborhood is guaranteed to receive charging resources within a run. Only one neighborhood, Laan van Spartaan, is never prioritized in this strategy.

Some things stand out looking at the allocation of the different strategies. The demand-based strategy prioritizes the neighborhood Kolenkit, whereas neither the Socio-economic strategy or the Anticipatory strategy prioritizes them, compared to other neighborhoods. The maximum number of assigned charging points to one neighborhood within one run is 27 for the Anticipatory and Socio-economic strategies, whereas it is 45 for the Demand-based strategy. This implies that the Demand-based strategy may lead to more accumulation of charging points within one neighborhood, than the other strategies. Appendix 9.8 shows the accumulation of charging points for each neighborhood over time, given each strategy.

ALLOCATION OF BATTERIES

The battery allocation is not part of one of the deployed strategies, but part of the grid strategy which works the same in each deployed roll-out strategy. However, there is a

[11] Standard deviations were rounded to two digits behind the comma.

Table 7.8: Growth example

Year	Example: number of sessions at 6AM	Growth rate	New number
1	1	20%	1.2
2	1	20%	1.44
3	1	20%	1.72
4	**2**		

Table 7.9: Experimental set-up

Exp	Strategy	Growth setting	Resources (CPs)	Runs
1	Demand-based	5-20 percent /yr	15/yr	25
2	Anticipatory	5-20 percent /yr	15/yr	25
3	Socio-economic	5-20 percent /yr	15/yr	25

Table 7.10: Demand-based allocation of charging points

ID	KK	ER	LL	RS	LVS	BB	BL	GB	TR
Total	988	554	574	691	107	170	67	139	85
Min	25	9	9	2	0	0	0	0	0
Max	45	34	34	43	43	29	16	30	14
Mean	39.52	22.16	22.96	27.64	4.28	6.8	2,68	5.56	3.4
SD	4.33	7.012	6.73	11.25	10.47	8.83	4.31	6.95	4.22

Table 7.11: Anticipatory allocation of charging

ID	KK	ER	LL	RS	LVS	BB	BL	GB	TR
Total	36	45	48	636	651	645	639	639	36
Min	0	0	0	24	24	24	24	24	0
Max	3	3	3	27	27	27	27	27	3
Mean	1.44	1.8	1.92	25.44	26.04	25.8	25.56	25.56	1.44
SD	1.5	1.47	1.44	1.5	1.4	1.47	1.5	1.5	1.5

Table 7.12: Socio-economic allocation of charging

ID	KK	ER	LL	RS	LVS	BB	BL	GB	TR
Total	189	573	561	387	33	480	342	345	465
Min	0	0	0	0	0	0	0	0	0
Max	27	27	27	27	3	27	27	27	27
Mean	7.56	22.92	22.44	15.48	1.32	19.2	13.68	13.8	18.6
SD	9.45	6	7.25	10.95	1.49	11	10.46	9.86	10.66

Demand-based charger allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	42	27	21	36	0	0	7	2	0
2	41	29	10	37	0	1	0	17	0
3	41	23	9	25	33	0	0	1	3
4	40	27	32	2	0	20	2	11	1
5	38	9	20	35	0	29	1	3	0
6	33	14	26	40	0	0	1	7	14
7	35	26	17	3	43	11	0	0	0
8	43	28	17	27	0	0	16	0	4
9	39	22	12	34	0	25	0	3	0
10	41	13	23	32	0	18	0	4	4
11	40	29	34	16	3	0	12	1	0
12	35	20	26	39	2	0	0	2	11
13	43	21	30	28	1	0	0	1	11
14	40	27	19	31	1	8	8	1	0
15	45	27	27	18	1	11	0	1	5
16	40	34	23	22	0	11	2	2	1
17	45	13	31	29	0	0	2	15	0
18	40	18	31	30	15	0	0	1	0
19	33	11	24	43	1	2	0	9	12
20	40	12	16	29	1	3	0	30	4
21	43	28	27	24	0	8	0	1	4
22	25	30	22	42	1	0	6	3	6
23	42	19	31	5	0	20	0	14	4
24	42	30	23	27	4	0	1	7	1
25	42	17	23	37	1	3	9	3	0

Anticipatory charger allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	3	3	3	24	24	24	24	27	3
2	3	3	0	24	27	24	27	27	0
3	3	3	0	24	24	27	24	27	3
4	0	3	3	24	27	27	27	24	0
5	3	3	3	24	27	24	24	24	3
6	0	0	3	24	27	27	27	24	3
7	0	3	0	27	27	24	27	24	3
8	3	3	3	27	24	27	24	24	0
9	0	0	3	27	27	24	27	24	3
10	0	0	3	27	27	24	27	27	0
11	0	0	3	27	27	27	24	24	3
12	0	0	3	24	27	27	27	27	0
13	0	3	0	27	27	27	24	24	3
14	3	0	3	24	24	27	27	24	3
15	3	0	0	27	27	27	27	24	0
16	3	3	3	27	24	27	24	24	0
17	3	3	3	27	24	24	24	27	0
18	0	3	0	24	27	27	24	27	3
19	3	3	3	24	27	27	24	24	0
20	0	3	0	27	24	27	27	27	0
21	0	3	3	27	24	24	24	27	3
22	0	3	3	24	27	24	24	27	3
23	3	0	0	24	27	27	27	27	0
24	0	0	3	27	27	24	27	27	0
25	3	0	0	24	27	27	27	27	0

Socio-economic charger allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	3	24	27	21	3	27	6	0	24
2	27	27	27	0	0	24	24	3	3
3	0	24	27	15	3	27	9	3	27
4	3	24	21	6	3	27	3	21	27
5	24	24	24	24	3	0	27	6	3
6	0	27	12	3	0	27	24	21	21
7	3	24	24	27	0	3	27	0	27
8	6	27	27	0	3	27	0	21	24
9	0	21	27	27	0	27	24	9	0
10	3	24	24	21	0	3	9	24	27
11	0	27	3	3	3	24	24	24	27
12	0	24	27	27	0	27	0	6	24
13	3	24	27	27	0	3	3	24	24
14	24	27	18	3	0	27	27	9	0
15	21	24	27	3	3	0	6	27	24
16	15	18	0	24	0	27	24	27	0
17	0	27	27	18	3	24	6	6	24
18	3	21	24	0	0	27	24	9	27
19	15	27	21	9	0	3	9	27	24
20	0	24	27	27	3	24	3	24	3
21	6	24	27	24	0	27	9	15	3
22	0	24	27	27	0	27	0	3	27
23	6	27	18	27	3	0	3	27	24
24	27	0	21	0	3	24	27	6	27
25	0	9	27	24	0	24	24	3	24

KK Kolenkit
ER Erasmus
LL Landlust
RS Robert scott
LVS Laan van spartaan
BB Balbaoplein
BL Bosleeuw
GB Gibraltar
TR Tromp

Figure 7.9: Final charging point allocation at the end of each run (25 runs per strategy)

slight difference between the battery allocation between roll-out strategies. Figure 7.10 illustrates the allocation of batteries across strategies and neighborhoods, where each row represents a run and a column was made for each neighborhood, filled by green numbers that show how many batteries were allocated to the neighborhood at the end of each run.

Batteries were assigned to various neighborhoods, and at least one neighborhood often got the maximum number of batteries assigned, which was five. Regardless of strategy, the neighborhood Landlust was prioritized the most. *Landlust* was followed by *Balbaoplein* and *Trompbuurt*, where *Trompbuurt* received a similar number of batteries as *Balbaoplein* at the demand-based and anticipatory runs, but received more batteries in the socio-economic runs. *Bosleeuw* and *Robert scottbuurt* also received batteries across runs from different strategies, with the exception of *Robert scottbuurt* receiving no batteries at the socio-economic runs. The other neighborhoods (*Kolenkit, Erasmus, Laan van Spartaan,* and *Gibraltarbuurt*) never get batteries, and they are also associated with low / no grid overload within their respective runs. This implies that the battery strategy is working as intended in prioritizing areas with lacking grid capacity.

7.5.2. PERFORMANCE OF THE CHARGING NETWORK

CORRELATIONS BETWEEN DEPLOYED ROLL-OUT STRATEGIES, PERFORMANCE AND COMPETITION

The performance of charging within the neighborhoods is analyzed by calculating the correlations first. The following processing steps have been made to calculate the correlations: A subset was made for each neighborhood, containing all strategies and runs. This is needed to determine the potential correlations between roll-out strategies and other indicators. Empty columns were removed (for example, some neighborhoods never received a smart charger, or never experienced grid overload). The correlations between indicators, received resources and deployed strategies were calculated using Pearsons correlations coefficient, which measures the relationship and direction of the relationship between variables. Occupancy length and occupancy percentage were the performance indicators with the highest correlation to the roll-out strategies. For all strategies, the % occupied decreased for some neighborhoods and increased for others. This also happened with the mean occupancy (session) length. There seems to be an inverse effect: when there is a positive correlation on the occupancy length (longer charging times), there is a negative correlation on the occupancy rate (more charging points available), and vice versa. This should be investigated further by looking at the direct correlation between the assigned resources and the performance indicators. The spillover-from rates had lower correlation scores with the deployed roll-out strategy. However, the correlation scores for spillover-to were higher in some cases, especially during the deployment of the socio-economic strategy. The kWh correlation scores were mostly close to zero, an exception are the neighborhoods *Kolenkit* and *Erasmus*, who have higher scores than other neighborhoods in the kWh-Strategy correlations. The correlation scores between grid indicators and deployed roll-out strategies were also lower. Grid overload did not occur for 1/3rd of the neighborhoods in the run. All other correlations were close to zero, but anticipatory strategy had more positive correlations (slightly more likely to get grid overload) whereas socio-economic had more negative correlations (slightly less

Demand-based battery allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	0	0	0	0	0	0	0	0	5
2	0	0	0	0	0	0	0	0	5
3	0	0	5	0	0	3	0	0	0
4	0	0	2	5	0	0	1	0	0
5	0	0	0	0	0	0	5	0	0
6	0	0	2	0	0	5	0	0	0
7	0	0	5	0	0	0	0	0	0
8	0	0	5	0	0	0	0	0	0
9	0	0	5	0	0	0	0	0	3
10	0	0	0	0	0	0	0	0	5
11	0	0	0	0	0	0	0	0	5
12	0	0	5	0	0	0	0	0	0
13	0	0	5	0	0	0	0	0	0
14	0	0	5	0	0	0	0	0	0
15	0	0	5	0	0	0	0	0	0
16	0	0	5	0	0	2	0	0	0
17	0	0	0	0	0	5	0	0	0
18	0	0	5	0	0	0	0	0	0
19	0	0	5	0	0	0	0	0	0
20	0	0	1	0	0	5	0	0	0
21	0	0	5	0	0	0	4	0	0
22	0	0	5	0	0	0	0	0	1
23	0	0	3	5	0	0	0	0	0
24	0	0	0	0	0	5	0	0	0
25	0	0	2	0	0	0	5	0	0

Anticipatory battery allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	0	0	2	0	0	5	0	0	0
2	0	0	5	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	5
4	0	0	5	0	0	3	0	0	0
5	0	0	0	0	0	0	0	0	5
6	0	0	0	0	0	5	0	0	0
7	0	0	5	0	0	0	0	0	2
8	0	0	5	0	0	2	0	0	0
9	0	0	5	0	0	0	2	0	0
10	0	0	0	0	0	0	5	0	0
11	0	0	5	0	0	0	0	0	0
12	0	0	5	0	0	0	0	0	0
13	0	0	5	0	0	0	0	0	0
14	0	0	5	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	5
16	0	0	5	4	0	0	0	0	0
17	0	0	0	0	0	5	0	0	0
18	0	0	5	0	0	0	0	0	3
19	0	0	2	0	0	5	0	0	0
20	0	0	0	0	0	0	5	0	0
21	0	0	5	0	0	3	0	0	0
22	0	0	2	4	0	0	0	0	3
23	0	0	5	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	5
25	0	0	5	0	0	0	0	0	0

Socio-economic battery allocation

run	KK	ER	LL	RS	LVS	BB	BL	GB	TR
1	0	0	5	0	0	0	0	0	0
2	0	0	5	0	0	0	0	0	2
3	0	0	5	0	0	0	0	0	0
4	0	0	5	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	5
6	0	0	5	0	0	0	2	0	0
7	0	0	1	0	0	5	0	0	0
8	0	0	5	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	5
10	0	0	3	0	0	5	0	0	0
11	0	0	5	0	0	0	0	0	0
12	0	0	2	0	0	0	4	0	3
13	0	0	3	0	0	5	0	0	0
14	0	0	0	0	0	0	0	0	5
15	0	0	5	0	0	0	0	0	1
16	0	0	5	0	0	0	0	0	0
17	0	0	5	0	0	0	0	0	0
18	0	0	5	0	0	0	0	0	0
19	0	0	0	0	0	5	0	0	0
20	0	0	0	0	0	0	0	0	5
21	0	0	2	0	0	0	0	0	5
22	0	0	5	0	0	0	2	0	0
23	0	0	0	0	0	5	0	0	0
24	0	0	3	0	0	0	2	0	4
25	0	0	5	0	0	0	0	0	0

Neighborhood	
KK	Kolenkit
ER	Erasmus
LL	Landlust
RS	Robert scott
LVS	Laan van spartaan
BB	Balbaoplein
BL	Bosleeuw
GB	Gibraltar
TR	Tromp

Figure 7.10: Final battery allocation at the end of each run (25 runs per strategy)

likely to get grid overload). What is interesting is that the neighborhoods who did not experience grid overload ('NA' in Table 7.13, 7.14, 7.15), also did not receive a battery in the battery allocation (see Figure 7.10). Also, the Erasmus neighborhood has higher correlation scores for grid overload in some of the strategies, where anticipatory strategy was positively correlated with grid overload occurrences and socio-economic strategy was negatively correlated.

Table 7.13: Pearson's correlation scores of charging performance for demand-based strategy

ID	session length	% occupied	spillover (from)	spillover (to)	kW charged	grid capacity	grid overload
KK	0.36	-0.34	0.04	-0.07	-0.16	0.07	NA
ER	0.13	-0.12	0.03	0.04	-0.02	0.01	-0.02
LL	0.19	-0.17	-0.03	0.02	-0.01	0.01	0.03
RS	0.10	-0.12	0	0.08	0.02	-0.01	0.02
LVS	-0.26	0.29	-0.02	-0.05	0	0	NA
BB	-0.35	0.34	-0.06	-0.01	-0.01	0	-0.04
TR	-0.12	0.14	0.04	-0.04	0	0	-0.02
GB	-0.24	0.19	-0.01	-0.07	0.05	-0.03	NA
BL	-0.38	0.38	0.01	0.06	0	0	-0.02

Table 7.14: Pearson's correlation scores of charging performance for anticipatory strategy

ID	session length	% occupied	spillover (from)	spillover (to)	kW charged	grid capacity	grid overload
KK	-0.26	0.22	-0.07	-0.07	0.05	-0.02	NA
ER	-0.26	0.24	-0.02	0.08	0.09	-0.04	0.13
LL	-0.35	0.34	0.05	0	0.02	-0.01	0
RS	0.12	-0.17	-0.05	-0.01	-0.02	0.01	0.01
LVS	0.51	-0.56	0.02	-0.05	0	0	NA
BB	0.29	-0.29	0	0.03	0.01	0	-0.03
TR	-0.20	0.21	0.01	0.04	0.01	0	0.04
GB	0.25	-0.18	0.02	0.06	-0.10	0.04	NA
BL	0.35	-0.33	0.03	0.05	0.02	-0.01	0.02

Table 7.15: Pearson's correlation scores of charging performance for socio-economic strategy

ID	session length	% occupied	spillover (from)	spillover (to)	kW charged	grid capacity	grid overload
KK	-0.11	0.12	0.03	0.14	0.10	-0.05	NA
ER	0.13	-0.12	-0.01	-0.11	-0.07	0.03	-0.10
LL	0.16	-0.17	-0.02	-0.02	-0.01	0	-0.03
RS	-0.22	0.28	0.05	-0.06	0	0	-0.04
LVS	-0.25	0.28	-0.01	0.11	0.01	0	NA
BB	0.06	-0.06	0.06	-0.03	0	0	0.07
TR	0.32	-0.35	-0.05	0	-0.01	0	-0.02
GB	0	0	-0.01	0	0.04	-0.01	NA
BL	0.03	-0.05	-0.04	-0.11	-0.02	0.01	0

CORRELATIONS BETWEEN ASSIGNED RESOURCES, PERFORMANCE AND COMPETITION IN THE CHARGING NETWORK

The correlations between performance indicators and strategies can become complicated, because many other mechanisms may be at play. Also, neighborhoods that are prioritized somewhat similarly by the different strategies may not have high correlations with the strategies at all. This is why it is also important to look directly at the effect of the resource allocation as performed by the strategies. We do this by looking at charging points received and batteries received for each neighborhood.

Most of the correlations between new charging resources and the performance indicators can be explained: the occupancy rate will initially decrease when new charging points are placed in an area, the kWh charged will increase when more charging stations are used, and the grid capacity will be lower because there is more power consumption. Both the spillover-from and spillover-to are mostly positively correlated, implying that placing new resources is associated with more intensive charging within- and around the neighborhood. There is also a positive correlation with grid overload: more connections means more grid consumption, which makes a neighborhood more vulnerable to grid overload. The inverse effects between occupancy length and occupancy rates can be observed for both the correlations with assigned resources as well as the direct correlations with deployed strategies (see Table 7.13 - 7.16). More charging points means that the demand can be spread out more (lower occupancy), and simultaneously, it means that more connections can be used at the same time, which could potentially trigger the charging mechanisms leading to a longer charging time (e.g., the smart charging speed, or the use of bidirectional V2G charging). To test this hypothesis, the correlations between assigned resources and the number of smart charging and bidirectional sessions are also calculated (Table 7.17).

Both indicators (smart and bidirectional charging) are positively correlated to newly assigned charging resources, if they are available at all in a neighborhood. Bidirectional charging is more strongly correlated with newly assigned resources than smart charging, however, there is a model bias here[12]. The two neighborhoods who already had smart chargers installed at initialization of the model and in real life (*Erasmus* and *Landlust*), had more similar correlation scores for smart charging and bidirectional charging. These findings imply that longer charging times could be explained by charging mechanisms that are triggered when charging demand increases.

[12] The model initializes the interoperability with V2G/bidirectional charging equally across neighborhoods, as opposed to smart chargers (initialized as in real life situation), making V2G-ready charging points more common and more accessible across neighborhoods (compared to smart chargers), in the model.

Table 7.16: Pearson's correlation scores between newly deployed charging resources and performance indicators

ID	session length	% occupied	spillover (from)	spillover (to)	kW charged	grid capacity	grid overload
KK	0.43	-0.39	0.29	0.02	0.14	0.01	NA
ER	0.21	-0.15	0.34	0.20	0.46	-0.08	0.31
LL	0.21	-0.14	0.27	0.22	0.55	-0.08	0.29
RS	0.52	-0.39	0.41	0.04	0.65	-0.07	0.54
LVS	0.67	-0.73	0.24	0.10	0.40	0	NA
BB	0.63	-0.44	0.46	0.01	0.56	-0.06	0.52
TR	0.49	-0.36	0.19	-0.08	0.29	-0.02	0.38
GB	0.52	-0.39	0.39	0.25	0.40	-0.06	NA
BL	0.57	-0.39	0.34	0.16	0.55	-0.06	0.42

Table 7.17: Pearson's correlation scores between newly assigned charging resources and the use of smart and bidirectional charging

ID	# smart charged	# V2G charged
KK	NA	0.03
ER	0.32	0.42
LL	0.37	0.27
RS	0.02	0.52
LVS	NA	NA
BB	0.01	0.54
TR	0.01	0.35
GB	NA	0.08
BL	0.24	0.45

CORRELATION BETWEEN GRID STRATEGY (BATTERIES RECEIVED), COMPETITION AND GRID INDICATORS

Batteries are placed in the neighborhood when grid capacity is scarce and the neighborhood does not have 5 batteries yet. Not every neighborhood received a battery, despite various roll-out strategies and growth circumstances. For the neighborhoods that did get batteries, the correlation scores with grid capacity and grid overload is determined (Table 7.18).

Assignment of a battery was correlated negatively with grid capacity. This makes sense, because a battery will only be allocated to neighborhoods who struggle with grid capacity. Out of the four neighborhoods that did not receive a battery, three did not experience grid overload at all. In the other neighborhoods, the occurrence of grid overload was mostly negatively correlated to receiving a battery, implying that the battery has succeeded in reducing the occurrence of grid overload. Receiving a battery was also positively correlated to competition indicators, both spillover-from and spillover-to, implying that receiving batteries is associated with more intensive charging within and around the neighborhood.

FAST CHARGERS

Fast chargers[13] were not initialized at the start of the simulation. Once a year, the three neighborhoods with the highest grid capacity were asked which of the three had the longest occupancy length. This neighborhood would receive a fast charger. A maximum of 9 fast chargers was assigned in a model run. Only three of the nine neighborhoods received fast chargers, regardless of strategy. The three neighborhoods that received fast chargers throughout their runs included *Kolenkit, Erasmus* and *Gibraltar*.

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The three neighborhoods could enable the fast charging protocol, because they did not experience grid overload in the simulations. The anticipatory strategy led to more use of fast chargers than the other strategies (Table 7.19), possibly because two of the neighborhoods were less prioritized in charging resources (compared to other strategies), so they had less connections to foster. *Kolenkit* had a much lower average fast charging share in the demand-based runs. This is probably because the neighborhood is prioritized very highly compared to other neighborhoods, which leads to more chargers and connections to foster. Can the use of fast charging be associated with a lower occupancy length altogether? Let's take a quick look at the correlation scores between occupancy length and the use of fast charging, for the three neighborhoods: *Kolenkit* (-0.18), *Erasmus* (-0.22), and *Gibraltar* (0.02). The model uses semi-fast chargers of 50kW, which is reduced to normal charging during peak hours. This is a bit lower than current highway fast charging because in this simulation, the transformer should be able to facilitate charging on the middle-voltage level. The use of fast chargers is a trade-off. In a real life scenario, fast charging could be used in cases where it is difficult to install new chargers, e.g., because of lack of space or infrastructural delays, and where there is a high penetration of vehicles that are not residents and will stay parked for charging shorter (e.g., visitors or shared vehicles). Alternatively, the excess grid capacity in

[13] The use of charging speeds cannot be compared with one another, because they were triggered by different mechanisms and were not divided equally across neighborhoods. This is why only a within charging-speed analysis is made, to compare the use of the charging speed between different neighborhoods and strategies.

Table 7.18: Pearson's correlation scores between grid indicators and receiving battery resources (NA indicates a lack of assigned batteries).

ID	**grid capacity**	**grid overload**	**spillover (from)**	**spillover (to)**
KK	NA	NA	NA	NA
ER	NA	NA	NA	NA
LL	-0.09	-0.22	0.28	0.33
RS	-0.06	0.13	0.14	0.52
LVS	NA	NA	NA	NA
BB	-0.10	-0.36	0.13	0.68
TR	-0.08	-0.31	0.11	0.63
GB	NA	NA	NA	NA
BL	-0.05	-0.19	0.05	0.60

Table 7.19: Fast chargers used in percentages (compared to total number of sessions). Only the neighborhoods that got fast chargers assigned in the simulations are included.

Kolenkit	**% fast charged**
Demand-based	9%
Anticipatory	25%
Socio-economic	24%
Erasmus	**% fast charged**
Demand-based	10%
Anticipatory	17%
Socio-economic	9%
Gibraltar	**% fast charged**
Demand-based	24%
Anticipatory	26%
Socio-economic	14%

the neighborhoods could be used to reduce or avoid grid overload in the surrounding neighborhoods, or for household consumption.

BIDIRECTIONAL (V2G) CHARGERS

Despite the still limited roll-out of the technology, bidirectional chargers were widespread in the model to investigate their potential in residential areas. There was a chance of 40% at initialization that a charger had the ability to charge in V2G mode. Additionally, the three neighborhoods with the lowest mean grid capacity were asked to turn one of their chargers into a V2G charger every year. Bidirectional charging can happen within a normal charging session. Therefore, the share of sessions is not calculated through the number of sessions. Rather, the power charged is compared with the bidirectionally charged power. For example, the sum of charged power in all 25 runs is roughly 35 GWh for Bosleeuw in the Demand-based strategy. Bidirectionally charged power is summed to 1,3 GWh for all 25 runs. This means that the bidirectionally charged power has the size of 3.71% of the total power charged in the neighborhood. This share gives an idea of how much power is charged bidirectionally, compared to the total sum of charged power. Runs where 0 kWh was bidirectionally charged were excluded from the analysis. Laan van Spartaan did not have any V2G chargers spawned in any runs, regardless of strategy. This may be because of their lower number of initial chargers, and lack of urgency to update the charging protocol during the interventions. The strategies had different effect directions on different neighborhoods, implying that there is a direct effect of prioritization on the use of bidirectional chargers (Table 7.20. Although the effect directions differed, the anticipatory strategy is overall associated with slightly higher use of bidirectional charging. This was especially true for the neighborhoods who were most dependent on bidirectional charging (>3%). Some neighborhoods barely use bidirectional charging, compared to the fully charged power (e.g., Kolenkit and Gibraltar). These were neighborhoods that also did not experience grid overload. . The resource allocation may contribute more consistently to the use of bidirectional charging, as we have seen in Table 7.17. The neighborhoods that use bidirectional charging the most (>3%) are the three neighborhoods that are spatially located on the right side of the neighborhood cluster, but this may be a coincidence.

7.5.3. WITHIN- AND BETWEEN NEIGHBORHOOD COMPETITION

Within competition (spillover-from), as well as between competition (spillover-to) correlates to newly assigned charging resources, as well as newly assigned battery resources (Table 7.16 & 7.18). The allocation of charging resources is more strongly correlated to the within competition indicator (Table 7.16), whereas the allocation of battery resources is more strongly correlated to the between competition indicator (Table 7.18). Direct correlations between deployed roll-out strategies and competition was weaker than for assigned resources (Table 7.13 - 7.15). For these direct correlations, the between-competition indicator (spillover-to) was more strongly correlated to strategies than the within-competition indicator (spillover-from), especially in the case of the socio-economic strategy. All charging speeds, as well as grid overload and the users-per-day, correlate positively to spillover indicators, and the grid capacity correlates negatively with spillover indicators. This is because a higher number of charging activities is directly indicative of competition. There were differences between strategies and the number of positive and negative correlations for competition parameters (see Table 7.13 - 7.15). In general, spillover-from is an attempt to find a new neighborhood and spillover-to is the succeeded attempt in a neighborhood. Therefore, at the end of each run there are more spillover-from occurrences than spillover-to occurrences. Table 7.21 summarizes the interaction between the model interventions and the competition indicators.

7.5.4. DISCUSSION

In this study, we chose for a general representation of a rich number of interventions (charging speeds, charging point allocations, battery allocations, charging point updates) in a rich environment (dynamic growth, fluctuating grid capacity, day patterns of users, various SoC and battery sizes). For example, the grid capacity was scoped on the mobility space of the transformer, and the peak hours were determined by an EPEX day-pattern and did not take into account seasonal patterns or generation of renewable power. The lowest aggregation of agents was the charging point itself, rather than the users of the charging point. Bidirectionally charged power was not re-used for charging, only registered to determine its potential. These decisions has some positive and negative consequences for the analysis of the model and answering the research question. A positive consequence was that the relationship of many contributing factors and the effect of interventions on various performance metrics could be investigated without introducing too much noise. This has led to a rather quick convergence of results for most of the parameters between runs (see figure 7.9 and 7.10). The identified relationships reveal some interesting directions for future models that can be scoped on a single intervention and a smaller set of metrics, which allows more detailed representation of the subsystem. Recommendations for these future research directions are discussed in section 7.9. A negative consequence of this general representation is that the true complexity of the system is not represented. This means that numbers cannot be interpreted literally. The short-term interventions (V2G, fast charging, smart charging, bidirectional charging) could therefore not be compared with one another (more variation in access and boundaries would be necessary to make a honest comparison). However, the associated parameters could still be compared for different strategies and neighborhoods. This has provided generic insights in the interaction between performance of charging, allocation of resources, use of charging speeds and the within- and between-neighborhood competition, which inspired some recommendations to improve the current roll-out methods, and identifies potential for future in-depth modeling.

7.6. CONCLUSION

7.6.1. GENERAL CONCLUSION ON THE ALLOCATION OF RESOURCES

The three different roll-out strategies that were employed led to distinct differences. In allocation, the socio-economic strategy used the most neighborhoods to spread out the chargers, and varied the most between runs. The demand-based strategy spread out the chargers between less neighborhoods, and varied less than the socio-economic strategy. The anticipatory strategy was the most static, with less variations between runs and only a couple of neighborhoods being prioritized. The demand-based strategy led to the highest accumulation of chargers, up to 1/3rd of chargers could end up in the same neighborhood (in some runs). Fast chargers were used extensively when available, and V2G chargers were used in the neighborhoods that experienced grid overload (with V2G charging being used 2-4% of all sessions, and fast charging up to 25% of sessions in a neighborhood). The charging modules were more likely to be used during the anticipatory strategy. Because the anticipatory strategy is more 'all-or-nothing' for most neighborhoods, the charging modules for fast charging (low number of chargers but dedicated grid infrastructure) and V2G charging (for high number of chargers with less capacity) started to play a more prominent role. The areas with a high accumulation of chargers could exploit batteries/smart/V2G more to avoid grid overload, and the areas with a low accumulation of chargers could opt for a faster mode of charging which allows for more transactions. For areas in real-life where distribution has to be skewed (e.g. because of space constraints or urban planning), it may be effective to diversify the modules of the charger similarly to the way they were used in the anticipatory runs. Overall, fast chargers were placed in neighborhoods where grid overload did not occur, V2G was barely used, and no battery was received. Batteries were divided between some of the neighborhoods. Others, who belonged in the group of fast charging and no grid overload, never received batteries. Batteries were associated with lower grid capacity and less grid overload

RQ1. WHAT IS THE EFFECT OF DIFFERENT ROLL-OUT STRATEGIES ON THE RESOURCE ALLOCATION OF CPS?

- Demand-based roll-out could lead to a high accumulation of chargers.
- Socio-economic roll-out is more sensitive to changing the allocation based on the environment metrics.
- Anticipatory roll-out leads to higher relevance of charging modules such as bidirectional and fast charging, because of the 'all-or-nothing' deviation that only prioritizes a few neighborhoods.
- In a real-life all-or-nothing scenario (e.g. because of spatial constraints), diversification of chargers becomes more relevant.

7

7.6.2. PERFORMANCE OF THE CHARGING NETWORK

The strategies had a direct effect on the length of the charging session and the occupancy rates, but the effects differed between neighborhoods. In general, the direct effect of allocation was easier to identify than the effect of a strategy altogether: since strategies favor some neighborhoods over others, the effect direction differs between neighborhoods. Therefore, it was easier to determine the effect of allocation (as a consequence of strategy). The allocation of charging points within a neighborhood was positively correlated with higher competition between EV users in a neighborhood, more power consumption, slower charging times, lower occupancy rates and more occurrences of grid overload. Additional analysis revealed that slower charging times occurred because higher allocation of charging resources was correlated with more use of bidirectional and smart charging, which increases the time a charging session takes. These charging speeds get triggered when there is less grid capacity, which is more likely when more charging connections can be used. Battery allocation was correlated with lower grid capacity, but also with lower occurrence of grid overload, implying that the use of an external battery could help avoid these problems in some cases. Neighborhoods who never had grid overload occur did not get a battery assigned at all. Instead, these neighborhoods received fast chargers that were regularly used.

RQ2. WHAT IS THE EFFECT OF DIFFERENT ROLL-OUT STRATEGIES ON THE PERFORMANCE OF THE CHARGING NETWORK?

- Strategies perform differently across neighborhoods, because their effect may benefit one neighborhood but not benefit another neighborhood.
- A higher allocation of charging points is correlated with higher competition, more power consumption, slower charging times, lower occupancy rates and more occurrences of grid overload.
- Batteries can help to satisfy charging demand in areas with low grid capacity.
- Without grid interventions, time-to-charge becomes longer in areas with more accumulated chargers, because smart- and bidirectional charging is used more often.

7.6.3. EFFECT OF STRATEGIES ON COMPETITION

More assigned charging resources was correlated with more competition, especially within a neighborhood. When there is more competition, the demand becomes higher. Highly competitive areas are prioritized by one of the strategies, whereas high demand areas in general are prioritized by another strategy, which may explain these correlations. Allocation of a battery was also correlated with higher competition, especially between neighborhoods. The correlation between strategies and competition was weaker than the correlation between allocated resources and competition. In the socio-economic strategy, the between-neighborhood competition was affected more than in other strategies (negatively correlated for more than half of the neighborhoods), the same for within-competition (to a lower extent). In the demand based strategy, competition was affected differently (positively or negatively, depending on the neighborhood). The anticipatory strategy only led to less competition for three of the neighborhoods. A potential explanation for the stronger correlation in the socio-economic strategy is the higher spread of allocated charging points across neighborhoods (Figure 7.8) compared to the two other strategies. This spread may potentially reduce the need for EV users to charge outside of their neighborhood boundaries. In real-life areas where competition starts to play a negative role, the roll-out strategy could be complemented with some of the socio-economic elements, to reduce this competition in the future.

RQ3. WHAT IS THE EFFECT OF DIFFERENT ROLL-OUT STRATEGIES ON THE WITHIN- AND BETWEEN NEIGHBORHOOD COMPETITION?

- The allocation of charging points was correlated with within-neighborhood competition (as competition/occupancy is a potential cause for prioritization in the strategies).
- The allocation of batteries was correlated with between-neighborhood competition.
- The socio-economic strategy was correlated with less competition than other strategies.
- The anticipatory strategy leads to higher competition than the other two strategies.

- Socio-economic and competition-based markers can be used to improve roll-out strategies for highly competitive areas.

7.6.4. LIMITATIONS

LITERATURE LIMITATIONS

The literature used to conceptualize the three strategies (see section 7.2) includes various studies. Some of these studies are dedicated to public charging infrastructure, but other studies may also include private charging infrastructure and workplace charging infrastructure. The demographics of users of private and public charging infrastructure are slightly different. For example, in the Netherlands, EV users in rural areas are more likely to own and use private infrastructure than in urban areas (RVO, 2021).

MODEL LIMITATIONS

The last step of allocation was not registered in the model output because the registration is made every six steps, leading to 135 assigned charging points per run instead of 150 (last roll-out day is cut off). The charging of the external battery does not take into account other dynamics such as solar and wind generation. Bidirectional charging is only collected as parameter, the electricity is not reused in the model. Growth rate and charging points are rolled out “at once” every year in the model, whereas in reality this would happen more gradually. Charging points were rolled out not taking into account real-life constraints such as parking spaces, street architecture, grid architecture and delays in installment. Grid dynamics were only modeled for infrastructure within a neighborhood, and the grid dynamics between neighborhoods were out of scope. For the within- and between-competition analysis, a neighborhood was assumed to be a community in which all residents belong. However, in real life, residents that live on a border between two neighborhoods may not feel like they belong in the heart of the neighborhood, and spillover may be acceptable for them since their distance may be shorter. For models where EV users are individually modeled, it may be more acceptable to use a radius around the individual users and work with within-range and out-of-range competition for individuals.

INPUT DATA LIMITATIONS

The model does not take into account full grid demand (only mobility space reserved for EV charging). Only public charging data was used and private chargers are not included in the model. EPEX averages were used to determine daily peak patterns in the grid. Yearly or seasonal patterns were not included in the model. Growth scenarios were randomized and could be smarter, for example by combining them with predictive models.

ANALYSIS LIMITATIONS

The data analysis uses correlation scores to reveal the relationship between performance indicators (grid indicators, competition, charging indicators) and interventions (strategies, resources, charging mechanisms). However, correlational analysis does not take into account the temporal aspects of the model. Further analysis could include a temporal aspect to further reveal the cause-and-effect and relationship directions.

7.7. RECOMMENDATIONS

RECOMMENDATIONS FOR POLICY MAKERS

The model showed that using the current demand to determine allocation can lead to accumulation of charging points. This accumulation also did not reflect the anticipated growth and adoption predictions from ElaadNL and Nationale Agenda Laadinfrastructuur, 2021, in the model. Competition between EV users was generally lower in the socio-economic strategy, and in the demand-based strategy, competition was half/half (less for some neighborhoods and more for others). The anticipatory strategy was the least appropriate method to minimize competition between EV users. None of the tested strategies turned out to be a silver bullet, as some neighborhoods would perform better under one strategy at the expense of another neighborhood. Adjusting the current dominant roll-out strategy (which is somewhat similar to the demand-based strategy) to account for the vulnerabilities of demand-based roll-out may therefore be more effective. Charging data currently plays an important role in determining the demand and allocating EV charging infrastructure. To reduce accumulation of charging points, reduce movement of vehicles (because of competition), and account for predicted growth, new roll-out strategies should also consider other factors. An improved strategy could, for example, include a validation of the allocation with growth scenarios and consider the distribution of charging points across a subdistrict or district. Additionally, policy-makers could consider database coupling to calculate the (anonymized) distance between a charge transaction and the residential postal code of the EV user. This could help monitor and quantify within- and between-neighborhood competition for charging resources. For example, if competition in general is high in a whole district, a more distributive roll-out may be more effective, whereas if measured competition is very local, more specific areas could be developed. The area of need can then be identified by using the origin of the charging demand, rather than the measured charging session. In general the strategy should be adjusted based on demand, competition, grid constraints and spatial constraints of the area of interest. In the model, the use of an external battery in a neighborhood was associated with lower occurrence of grid overload, despite lower grid capacity compared to other neighborhoods, and bidirectional and smart charging was used in neighborhoods with higher number of newly assigned charging points. In areas where there is grid scarcity, smart chargers, bidirectional charging and the use of external battery buffers in combination with battery charging may be able to relieve the grid of some of the charging demand during peak hours.

NEXT STEPS & FUTURE WORK

The current model allows for much more experimentation. Other simulations can be made by designing more experiments, and making minor refinements to the model. New experiments could for example include more resources per round, more updates of charging infrastructure, other variations of strategies and other growth scenario's. The grid dynamics of a residential area are much more complicated and elaborate than the model boundaries currently are. Additionally, the model uses the mobility space of the middle-voltage (transformer) houses at each neighborhood as the local grid for that neighborhood, whereas in reality, grid dynamics also take place between neighborhoods in a subdistrict. In the future, the model can be refined using more historical EPEX day-ahead data, more data on renewable energy generation, data on household consumption and more detailed data on the grid infrastructure, including grid dynamics across neighborhoods in a subdistrict. Output of predictive models that include weather and cost could be used as input for the model refinement. A more dedicated representation of grid dynamics could allow for a more in-depth modeling of the short-term interventions (V2G, bidirectional charging, smart charging, fast charging), as well as the LT strategy "use of external buffer batteries". The interaction between occupancy rates and these interventions could be determined through the current model, but the exact grid interactions and consequences for the grid on a subdistrict level should be further researched with a model with more detailed grid dynamics. Additionally, the maximum transport capacity could be considered for the feasibility of interventions such as bidirectional charging, and alternatives to grid injections could also be added (e.g., peer-2-peer bidirectional charging). This is a more complicated addition to the model. Another potential future research direction is the competition aspect of the model. The model is able to register the spillover-from (within-competition) and spillover-to (between competition), and with a small edit, the model can register all the attempts while registering the location-from and location-to. A downside to this addition is that the high-resolution registrations lead to larger output in each run, and the registration of other parameters should be minimized in this case.

Table 7.20: Percentage V2G charged

ID	**Demand-based**	**Anticipatory**	**Socio-economic**
KK	<0.001%	<0.001%	<0.001%
LL	3.23%	3.61%	2.82%
ER	0.56%	0.61%	0.72%
RS	2.22%	2.57%	1.81%
LVS	NA	NA	NA
BB	2.24%	2.13%	2.03%
BL	3.71%	3.86%	3.76%
TR	3.02%	3.65%	3.61%
GB	0.02%	0.02%	<0.001%
Average	1.88%	2.06%	1.84%

Table 7.21: Interventions and spillover indicators

Intervention	**Within-competition**	**Between-competition**
Roll-out strategies	Weak (but differs between strategies)	Weak (but differs between strategies)
Allocating chargers	Strong	Medium
Allocating batteries	Medium	Strong

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8

CONCLUSIONS

8.1. MAIN CONCLUSION

The goal of the dissertation was to support the scaling up of public chargers. This was approached in the dissertation by improving the understanding of charging dynamics, and by simulating the roll-out of charging infrastructure.

8.1.1. UNDERSTANDING CHARGING DYNAMICS

This study has improved the understanding of public charging. First of all, the behavioral component of charging is strongly driven by the work patterns of the EV users. This was observed throughout the studies on lockdowns, cab drivers, and chargers located in office areas. The working schedule of EV users, the opportunity to charge at work, and the travel modality to work can all influence the charging demand of EV users, both for professional as well as personal traffic. Policy also plays an important role in the development of public charging. Seemingly unrelated policy can largely influence charging demand, for example, policies on working hours or working locations. Not only do the goals and activities in planned policies play a role in the development of public charging. The procurement, financing and permitting of public charging on can also largely influence how charging develops in the public space. Stakeholders find different things important, but the preferences of EMSPs and policy makers are more similar within their own groups. Stakeholders find environmental and modal shift indicators less important in the development of charging, despite their interdependencies in the public space. This partially explains the separated approach towards these goals in policy documents. At the heart of public charging, there is an intersection between energy, mobility, public space and human behavior. In order to understand charging as a system, we need to improve our understanding of each part, as well as how these parts interactions. The agent-based simulation of this dissertation is an example of a contribution towards this understanding, where the relationship between allocation, charging behaviour and the local electricity grid was investigated. The addition of competition metrics from an EV user perspective illustrated that there is a relationship between allocation, type of allocation (batteries or chargers), and the level and type of competition. Future roll-out strategies should also consider the effect of allocation on the distribution and competition of the entire charging network. The literature, results and recommendations that were presented in Chapter 6 and 7 emphasize the need for decision-makers in public charging to include these aspects in their roll-out strategies.

8

8.1.2. SCALING UP CHARGING INFRASTRUCTURE IN RESIDENTIAL AREAS

The main research question of the dissertation is "How can public EV charging infrastructure in residential areas be scaled-up?". The question was answered using five studies which all contained a research question related to scaling up public charging infrastructure. The results reveal that the scale up of charging infrastructure can be supported from different angles:

- EV charging developments are closely related to other goals of the mobility system. The relationship between these goals can be beneficial, for example, introduction of new mobility for modal shift and MaaS objectives can be combined with an electrification condition. However, the goals may also compete, for example, developing chargers in streets that are planned to be car-free will lead to obsolete chargers in the future [1]. This is why the relationship between different mobility goals should be considered in the roll-out of charging infrastructure.

- Stakeholders should improve their alignment. This includes stakeholders that were not interviewed in Chapter 5, such as the DSO and the car manufacturer. Stakeholder alignment is crucial to facilitate the roll-out of newer charging technologies, such as V2G and autonomous charging. It is also important for stakeholders to understand and discuss their differences in perspectives for the future, so that issues in the future can be avoided [2].

- The allocation of chargers can be improved by focusing more on diversification of chargers [3], evaluating competition and socio-economic aspects of the roll-out, as well as using an array of strategies to ensure charging under grid limitations[4].

- The understanding of charging demand can still be improved. This will make the allocation of chargers more precise and could help predict future charging demand. Additional data, such as the chamber of commerce registrations of package deliverers, cab drivers, and offices with many employees who drive leased cars, could help estimate the public charging demand of professional traffic. Regular charging patterns can be used to determine the preferred charging location for returning users. In districts where chargers are not widely available, assessing EV car registrations and housing type can help determine public charging demand [5].

- The impacts of other urban developments and policy developments on the local charging demand should be taken into account [6]. Improving the communication between charging stakeholders and other policymakers and urban planners, could help anticipate these developments and changes in charging behavior.

8

CONCLUSION OUTLINE

The next sections contain the following parts of the conclusion:

- Section 8.2 answers the research questions that were studied in the chapters of the dissertation.

- Section 8.3 discusses the results and limitations of the dissertation.

- Section 8.4 contains the final remarks.

[1] Chapter 3 contains more examples of this relationship.
[2] Chapter 5 discusses these future perspectives in detail.
[3] e.g., a wider composition of fast, V2G and smart chargers
[4] Chapter 7 contains more detailed recommendations to improve roll-out strategies.
[5] Predictions for EV charging sometimes contain some of these indicators already.
[6] Chapter 4 contains some examples on how charging behavior can be affected by policy developments

8.2. ANSWERS TO THE RESEARCH QUESTIONS

RQ1: TO WHAT EXTENT ARE DUTCH MOBILITY POLICIES RELEVANT TO THE TRANSITION TOWARDS ELECTRIC VEHICLES?

This question was investigated throughout Chapter 3. A policy inventory was made for two municipalities, and analyzed using policy analysis and system analysis methods. Policies were categorized, their effectiveness was investigated through literature, and objective trees were constructed for modal shift- and electric mobility objectives. The identified mobility policies are relevant for the electrification of vehicles, although other local policy themes are also involved (e.g., energy and climate). EVs and EV charging infrastructure were mentioned often in the documents referring to these themes. The policy documents also discuss the use of pilots and instruments that are relevant towards the electrification of vehicles (see Table 3.7 for an assessment on their effectiveness). Policy can be improved by promoting more information exchange, introduce more pilots and pay more attention to the specific needs of professional user groups. Policymakers should be aware of the interdependencies between modal shift and the development of EV charging. Policy documents could also address new technologies better, such as autonomous driving and charging.

RQ2: HOW DO POLICY INTERVENTIONS AFFECT PUBLIC CHARGING INFRASTRUCTURE?

This question was investigated in Chapter 4. Three case studies of policy and public charging were discussed. One case study investigated procurement and competition (from a market perspective), another case study investigated the effects of pandemic-related policies on charging behaviour, and the last case study looked at the inter-urban demand of cab drivers who electrified as a result of local policy. The case studies all revealed how policy affects charging:

- The granting and financing process of municipalities delays charging development in rural areas (case 1)
- The permitting process in highway rest areas affects charging development and the number of market competitors in highway fast charging (case 1)
- The use of restrictive measures (work from home, curfews) reduces the public charging demand of EV users, but not the growth of the user base (case 2)
- A fining system (curfews) has affected the start-time of charging sessions for a short period of time (case 2)
- Electrification of a professional group increases charging demand, and this new demand can look very different from average EV users. For example, the preferred charging speed may be different, but the locations of charging may also vary more (case 3).

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Policymakers should consider their procurement processes and identify potential risks such as delays in development or lack of competition. Charging patterns are often a consequence of working pattern in the current fleet, this relationship should be considered when analyzing charging behaviors [7]. The electrification of professional subgroups can lead to additional charging demand that differs from the average EV user.

RQ3: WHAT DO STAKEHOLDERS FIND IMPORTANT, AND HOW DO THESE PRIORITIZATIONS CHANGE OVER TIME

In Chapter 5, Dutch decision makers in EV charging were asked to prioritize aspects of the charging system for three different periods in time, using the best-worst method. According to these participants, the highest priorities in the first time period are:

- adoption of electric vehicles
- roll-out of charging infrastructure
- accessibility of charging
- smart charging

Then after 2025, the priorities are indicated to change:

- smart charging
- V2G charging
- managing the peak demand
- activities in the energy system

After 2030, priorities are:

- stimulating the development of new technologies
- use of sustainable energy sources
- smart charging
- activities in the energy system

The importance of smart charging was reiterated at each time period. Participants mostly wanted to use agreement and supportive policy instruments in the earlier time periods, and more restrictive policy instruments in the last period. The priorities of policymakers were somewhat different than those of EMSPs.The results imply that charging comfort and flexibility in the grid are prioritized over environmental indicators and sharing initiatives. However, these indicators and initiatives are necessary to embed modal shift goals into the e-mobility transition. Therefore, it is recommended for decision makers to consider these aspects as well. Policymakers and EMSPs should be aware of their differences in perspectives, and how these differences in perspectives can affect the future development of public charging.

[7] the future fleet may also contain users that have different patterns

RQ4: WHICH ROLL-OUT STRATEGIES APPLY TO NEIGHBORHOODS?

In Chapter 6, a conceptualization was made of the decision-making in the allocation of charging infrastructure. A case study was also selected based on available data and relevance. The possibilities for rolling out public charging infrastructure were analyzed and a selection was made for simulation, which included:

- The allocation of public chargers and considerations for the installment of public chargers
- The composition of chargers (V2G, smart, fast, normal)
- The allocation of an external battery
- Updating existing charging infrastructure

Figure 6.1 illustrates how decisions can be made for charging, using these possibilities.

RQ5: HOW DO ROLL-OUT STRATEGIES AFFECT NEIGHBORHOOD DYNAMICS?

The last study, reported in Chapter 7, is about the configuration and simulation of an agent-based model to investigate the relationship between allocation, behavior, competition and the electricity grid. Three perspectives (demand-based, anticipatory and socio-economic) were translated into three roll-out strategies, which prioritize different indicators to determine the best allocation of charging stations across the nine neighborhoods. The strategies were implemented in an agent-based model, while variating the occupancy rates and adoption rates of public charging, for a period of 10 years. The three roll-out strategies led to different allocations. There was no "best strategy" in this simulation: each strategy had benefits for some neighborhoods, and drawbacks for others. Simulation of the strategies revealed some strengths and weaknessses: The demand-based strategy spread chargers across most neighborhoods, but in many runs, there was a high accumulation of chargers in 1 neighborhoods, up to 1/3rd of the total allotted resources for all neighborhoods.The anticipatory strategy was the most static, and only prioritized a few neighborhoods, with little variation between runs. The socio-economic strategy spread chargers across many neighborhoods, and there was more variation between runs, making the strategy more responsive to varying scenarios. Competition was also a bit lower in the socio-economic strategy. The study includes a number of recommendations to improve the roll-out of charging infrastructure in residential areas:

- Demand-based allocation of chargers can lead to accumulation, and this accumulation may very well differ from predictions. Therefore, demand-based allocation should be refined with other considerations (see point below).
- The addition of socio-economic and competition-based markers in the roll-out strategy can help reduce competition in highly competitive areas.
- The allocation of an external battery was correlated with lower occurrence of grid overload, despite being placed in neighborhoods with the lowest grid capacity. This intervention could be considered for areas with lower grid capacity and no planned grid expansions.

- Diversifying chargers[8] is important for efficient charging networks.

8.3. DISCUSSION AND LIMITATIONS

The results of this dissertation support the scale-up of public charging by contributing to the understanding of charging dynamics, proposing a conceptualization of the decision making in the roll-out of chargers, and by providing simulation-based insights for the future roll-out of chargers. This approach could also apply to other transitions in which relevant systems and activities can be linked based on their spatial correlations. In general, simulation of urban areas in transition could help municipalities comply to the environmental code, and help organize permits by recognizing opportunities. It could also help create insights in effects of (combining) local policies, adding new resources, and other activities. Decision-makers were interviewed using the best-worst method in Chapter 5 of this dissertation. Repetitions were made for the best-worst method, with different time scenarios, to keep track of how participants changed their priorities over time. This information can support the discussion between stakeholders, experts and decision-makers, about the level of (current and future) consensus, and the necessary conditions to transition from one priority to the next one.

Some ethical considerations apply to the field of research. One of the challenges of urban transitions is the distribution of burdens and benefits across societal groups (Hughes and Hoffmann, 2020). For example, some demographic groups are more likely to experience air and water pollution in cities than others (Boone et al., 2014). This dissertation investigated charging opportunities across neighborhoods to provide insights into the distribution of charging infrastructure. However, far more research is required to improve charging opportunities across communities, and this study cannot generate sufficient recommendations by itself. For example, disabled visitors in Amsterdam are not able to indicate a need for a charging point in the current request portal for disabled parking (Municipality of Amsterdam, 2015-2024). The impact of excluding these groups from charging needs to be assessed by decision-makers, and other research could potentially help identify these exclusions and impacts. The use of fossil fuels raises ethical challenges, because of their contribution towards climate change. However, the use of technology in energy transition also has negative impacts. For example, the mining of minerals required for this transition also contributes to the destruction of important ecosystems and humanitarian crises (Dunlap and Laratte, 2022). The impact of decision making on these resources was not in the scope of this study. However, it is important to consider planetary boundaries when making decisions that require scarce resources, and other studies should be consulted for this perspective.

Limitations of each study were discussed in the dedicated chapters. In general, representation of some subsystems in charging was limited. For example, the electricity grid, which was only considered and modeled in the scope of EV charging, whereas demand, supply and infrastructure of electricity is much more complicated than that. The same can be said for the mobility system, professional traffic and urban policy. These

[8] e.g., a wider composition of fast, V2G and smart chargers

subsystems are more complicated than analyzed and modeled in this dissertation that only considers the EV charging context. The findings that were reported throughout this dissertation were established within the context of the Dutch charging market. The Netherlands has relatively high adoption rates compared to many other countries, and is densely populated. This makes EV users more dependent on public charging, especially in dense urban areas where there are less private driveways available. Public charging has been (partially) subsidized, which helped many municipalities with pro-active roll-out of charging stations in earlier stages. The Netherlands is also a relatively small country. The distance between petrol stations and cities is small, which means that most national destinations can be reached with one full battery. All of these factors led to an emphasis on both private charging (rural areas) and public on-street slow charging (urban areas) in the current Dutch charging market. However, this may differ for other countries where private charging is more apparent and distances are larger. For example, public fast chargers may play a more important role in countries with longer distances between destinations. The findings for which charging transaction data was used should also be placed within context. The used dataset was scoped on public charging, and the EV users included in the dataset contained many leased cars. The Dutch context does not only pose a limitation on the results. The relatively well-developed market, smaller case study areas and widespread adoption of public chargers helped in developing the necessary data to research further development of EV charging and the effect of policy interventions. Countries that will be more dependent on public charging in the future may also benefit from these learnings.

Another limitation is the effect of the coronavirus on the mobility system (as analyzed in chapter 4) as well as the operational aspects of the study. It was challenging to collect stakeholder inputs because of the limitations of in-person interactions, which led to smaller participant samples in chapter 5 as well as a more limited validation across chapters. Pre-covid mobility patterns no longer applied to the current situation, which meant that a large part of the historical charging transaction data could no longer be used to predict the effects of a scale-up. In each study, this limitation was addressed with the best efforts and relevant assumptions were explained carefully.

8.4. FUTURE WORK

There are some recommendations that can be made for future studies. Charging behavior is a behavior that could be studied more extensively. Developments (such as EV adoption from a wider audience, technological improvements, mobility trends such as modal shift), and new policies affecting mobility, work or lifestyle have an influence on the charging patterns, and by extension, charging demand. The speed and adoption of these developments is also uncertain. For example, EV adoption rates cannot be predicted precisely, and the adoption of modal shift behavior is affected by market developments and urban policy. This is why the baseline of charging is expected to change over time. A better understanding of the relationship between charging behavior and other development could provide insights in how charging patterns and charging demand may shift over time.

There are many objectives that can be identified for the scale-up of public charging, and the objectives depend on the stakeholder. For the EMSP, the costs and benefits of selling the charging service are relevant. For a DSO, managing the grid demand is important. For a policymaker, the development of public charging may be important to facilitate electrification. And for the EV users, chargers are important to satisfy the demand. It could be interesting to further research how these objectives can be combined and how the allocation of charging infrastructure can be optimized given these different objectives.

8.5. CLOSING REMARKS

To sum up, the dissertation aimed to support the scaling up of public chargers by enhancing the understanding of charging dynamics, and by simulating the roll-out of charging infrastructure. The findings highlight the significance of working patterns on charging behavior, the effects of policy interventions on charging behavior, and the effects of public policy on the development of public charging infrastructure. Recommendations were made to improve the roll-out and monitoring of public charging resources. Decision-makers in public charging need to consider various aspects such as competition metrics, socio-economic factors, and future urban and policy developments when planning the allocation of chargers in residential areas. Stakeholder alignment and diversification of chargers were identified as other ways to improve the scale-up of public charging. Moving forward, future studies could delve deeper into charging behavior and its relationship with mobility trends, technological advancements, and other policy interventions.

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9
APPENDICES & SUPPLEMENTARY MATERIALS

Table 9.1: Assumption validation with municipal policy makers

Assumption	Amsterdam	The Hague
Commercial shared mobility providers use the public charging network	X	Depends
Cab drivers (partially) use the public charging network	X	X
Light electric vehicles (LEV) don't use the public charging network	X	X
New commercial shared mobility providers should be electric	X	Preferred
MaaS platforms include: public transport, shared mobility and e-bikes	X	X
Hubs are categorized per user group, sometimes clustered.	X	X

Table 9.2: Policy measures in Amsterdam

ID	Policy Measure (Amsterdam)	Policy plan
A1	Cab driver agreement	Cab Drivers Agreement
A2	Pilot: Mobility budget	Smart Mobility
A3	Decrease inner city touring cars	Car Free
A4	Pilot: Mobility-as-a-service	Smart Mobility
A5	Pilot: Operational mobility center	Smart Mobility
A6	Pilot: Night metro	Car Free
A7	Financial incentives: Kids tickets, attractive PT options	Car Free
A8	New policy on LEV parking	Car Free
A9	E-neighborhood hubs	Green Deal Carsharing II
A10	EV gains parking permit (no waitlist)	Municipality website
A11	Pilot: Neighborhood cars	City Deal Carsharing
A12	Pilot: Impact, behavior and governance	City Deal Carsharing
A13	Pilot: Fast chargers, shared e-mobility and technology	Smart Mobility
A14	Pilot Weesperstraat (reduce traffic)	Car Free
A15	Public transport and touring cars are emission free	Clean Air
A16	Test location for autonomous vehicles	Smart Mobility
A17	Neighborhood e-hubs	Smart Mobility
A18	Pilot: Drone delivery	Smart Mobility
A19	All non-personal traffic is emission free	Clean Air
A20	Dynamic cab access tool	Smart Mobility
A21	EU-VI, PHEV (2030) and non-EV (2025) access deadlines. Extensions (~2027) and subsidy for delivery vans.	Green Deal Zero-Emission City Logistics
A22	All traffic in built-up areas is emission free	Clean Air
A23	Public transport: East-west metro line	Structure vision 2040
A24	Underground building: living and parking spaces	Structure vision 2040
A27	Pilot: DC charging square	AUAS internal project records
A28	Pilot: Positive Energy Districts	Smart-atelier (EU)
A29	Labs: reduce parking, enable pilots, develop standards	Smart Mobility
A30	Public transport expansions, diminished double boarding rates	Car Free
A31	Shared bikes at metro stations and urban e-bike sharing	Car Free
A32	Car-free market area (Albert Cuyp)	Car Free
A33	Development of hubs for city logistics and passengers	Car Free
A34	Stimulating use of indoor parking and P&R spots	Car Free
A35	Cheaper shared mobility options	Car Free
A36	More P&R locations in city borders	Car Free
A37	More space for pedestrians and bikes (9 focus areas)	Car Free
A38	Train rail expansions (phases)	Structure vision 2040
A39	Flexpower: smart charging pilot	Charging Strategy
A40	Pilot: Multiple permits on 1 car (P2P sharing)	Green Deal Carsharing II
A41	Information and subsidy point to start sharing initiatives	Green Deal Carsharing II
A42	100% electric shared fleet in 2025	Green Deal Carsharing II
A43	790 fast chargers (tank stations, highway exits)	Charging Strategy
A44	Pilot: Battery Hub P&R	Charging Strategy
A45	Pilot: V2G (ArenA)	Charging Strategy
A46	Program Plan for Electricity Supply	Charging Strategy
A47	Investment for electric public transport in the city	Vervoerregio Amsterdam

Table 9.3: Policy measures in the Hague

ID	Policy Measure (The Hague)	Policy plan
D1	Subsidized parking permits for shared mobility	Mobility Agenda
D2	Public transport expansions and more bike stalling	Mobility Agenda
D3	Traffic redirection	Mobility Agenda
D4	Flexibility in using living space for parking	Mobility Agenda
D5	Stimulating shared mobility	Mobility Agenda
D6	Designing fast bike lanes	City Logistics Agreement
D7	'Clean-only' logistics slot in the evenings	City Logistics Agreement
D8	Grace period for biofuel vehicles	City Logistics Agreement
D9	Logistics hubs and drop-off to reduce last mile	Sustainability 2021
D10	400+ extra charging points in 2021	Sustainability 2021
D11	Zero-emission cab drivers	Clean Traffic Approach
D12	Declined entry for specific (high-emission) vehicles	Clean Traffic Approach
D13	Subsidized vehicle trade-in	Clean Traffic Approach
D14	On-site hubs, and energyplan for clean construction	Clean Traffic Approach
D15	New vehicles in MRDH emission free (2030)	Coalition Agreement
D16	EV-only parking at time slots	Green Deal Carsharing II
D17	Pilot: Car-free streets (with shared mobility)	Green Deal Carsharing II
D18	Every neighborhood min. 10 shared vehicles	Green Deal Carsharing II
D19	Car sharing requirements for new buildings	Green Deal Carsharing II
D20	Inform and support smaller municipalities	Agenda Traffic Safety (regional)
D21	Adjust max speeds (50 to 30, and 100 to 80)	City Deal Carsharing
D22	Pilot: Energiekwartier (neighborhood-based carsharing)	City Deal Carsharing
D23	Pilot: Cost-benefit analysis and resilience measures	Sustainability 2021
D24	Roll-out of urban fast chargers	Sustainability 2021
D25	Charging strategy for shared vehicles	Sustainability 2021
D26	Agreement with cab drivers	Board report 2020
D27	Mobility-as-a-service platform for MRDH	Board report 2020
D28	Emission-free buses in 2030 (with subsidy)	Board report 2020
D29	Subsidies for public transport PV station charging	Board report 2020
D30	Network for smaller municipalities CO2 reduction	Green Deal Zero-Emission City Logistics
D31	Zero-emission inner city logistics by 2025	Clean Traffic Approach
D32	Zero-emission inner city buses by 2025	Green Deal Carsharing II
D33	Mobipoints (multimodal hubs)	Green Deal Carsharing II

Table 9.4: Policy conditions

Conditions	Condition for	Measures: Amsterdam	Measures: The Hague
User group requirements	Emission-free subgroups	A31, A41	D9, D24
User group agreements	Emission-free subgroups	A1, A8, A20, A21	D7, D25, D26
Transferring into city	Emission-free inner city logistics	A5, A31, A34	D9
Attractive options	Developing MaaS market, increasing SV and PT, emission-free	A2, A7, A10, A33, A47	D1, D13, D18, D27, D29
Knowledge development	Emission-free inner city, subgroups, modal shift	A4, A6, A12, A13, A16, A18, A27	D17, D22, D23
Information exchange	Emission-free inner city, subgroups, modal shift	A39	D20, D30
Electricity supply	Emission-free inner city	A46	D14
Charging- and parking	Emission-free inner city, subgroups, indoor parking	A9, A11, A24, A31	D2, D4, D10, D33
Low-car/ car-free streets	Modal shift	A14, A32	D3, D17, D21
Public transport expansions	Modal shift	A23	D2

Table 9.5: Criteria used in literature (Helmus and Van Den Hoed, 2016,van der Hoogt et al., 2020,Di Martino et al., 2021, Angelakoglou et al., 2020)

Criteria used in literature	Helmus e.a.	Hoogt e.a.	Di Martino e.a.	Angelakoglou e.a.
Car ownership, modal shift				X
EV adoption	X	X	X	X
Cost (benefits), pricing, profit	X	X	X	X
Use of public space	X			
kWh, kW, energy use	X	X	X	X
V2G, smart charging	X	X	X	X
Air quality, CO2 emissions	X	X		X
Occupancy rates, utilization	X		X	X
User convenience, comfort, accessibility	X			X

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Table 9.6: Individual Weights for Measuring indicators T1: 2021–2025

Measure 2025	**Car ownership**	**EV Adoption**	**Profitability**	**Public space**	**Peak demand**	**Sus. energy use**	**Local emissions**	**Occu-pancy**	**User comfort**	**KSI**
P1	0.022	0089	0.089	0.089	0.222	0.133	0.133	0089	0.133	0044
P2	0.052	0183	0.061	0122	0.061	0183	0.183	0.061	0.092	0.183
P3	0.155	0.155	0.103	0.155	0.078	0.078	0.044	0.077	0.155	0.155
P4	0.056	0.316	0.044	0132	0.197	0.033	0.099	0.066	0.057	0079
P5	0.038	0.15	0.1	0.1	0.075	0.1	0.1	0.15	0.188	0.113
P6	0.038	0.178	0.114	0.076	0.229	0.057	0.021	0.057	0.229	0.051
P7	0.049	0.098	0.098	0.073	0.146	0.146	0.146	0.098	0.146	0146
P8	0.035	0.082	0.177	0.035	0.207	0.207	0.015	0.035	0.207	0.071
P9	0.060	0.027	0.12	0.181	0.12	0.052	0.06	0.289	0.09	0.072
P10	0.054	0.217	0.324	0.109	0.072	0.031	0.048	0.072	0.072	0.131
P11	0.103	0.226	0.024	0.104	0.104	0.104	0.155	0.078	0.104	0.294

Table 9.7: Individual weights for organizing indicators T1:2021–2025

Roles 2025	**Fast charging**	**V2G**	**Smart charging**	**Inductive charging**	**PV/ Solar**	**Accessi-bility**	**User groups**	**(KSI)**
P1	0.202	0.067	0.202	0.058	0.135	0.202	0.135	0.202
P2	0.142	0.106	0.213	0.053	0.061	0.213	0.213	0.213
P3	0.18	0.18	0.135	0.108	0.135	0.081	0.18	0.459
P4	0.277	0.042	0.214	0.048	0.061	0.214	0.143	0.151
P5	0.156	0.156	0.156	0.031	0.063	0.281	0.156	0.031
P6	0.169	0.084	0.262	0.027	0.084	0.262	0.112	0.075
P7	0.176	0.118	0.176	0.176	0.235	0.088	0.029	0.118
P8	0.169	0.269	0.269	0.025	0.169	0.042	0.056	0.069
P9	0.382	0.068	0.239	0.036	0.06	0.119	0.096	0.096
P10	0.079	0.158	0.158	0.079	0.035	0.395	0.095	0.08
P11	0.173	0.115	0.27	0.028	0.069	0.173	0.173	0.076

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Table 9.8: Individual weights for Development indicators T1:2021–2025

Development 2025	Develop Maas	Energy Activities	Roll-out of Infra	Stimulate new tech	KSI
P1	0.211	0.316	0.316	0.158	0.316
P2	0.25	0.25	0.375	0.125	0.375
P3	0.231	0.077	0.462	0.231	0.231
P4	0.05	0.275	0.45	0.225	0.175
P5	0.064	0.511	0.32	0.106	0.128
P6	0.053	0.474	0.32	0.158	0.158
P7	0.07	0.296	0.437	0.197	0.155
P8	0.25	0.25	0.25	0.25	0
P9	0.2	0.3	0.45	0.05	0.15
P10	0.06	0.226	0.546	0.169	0131
P11	0.058	0.32	0.466	0155	0.146

2025-2030	Car Ownership	EV Adoption	Profitability	Public Space	Peak demand	Sus. Energy	Local emissions	Occupancy	User comfort
P1	0,03	0,033	0,003	-0,028	-0,1	-0,042	0,05	0,003	0,05
P2	0,048	-0,033	0,014	-0,022	0,039	-0,033	-0,033	0,039	-0,017
P3	-0,027	-0,027	-0,018	-0,027	-0,014	0,05	0,041	0,05	-0,027
P4	0,104	-0,209	0,176	-0,052	-0,037	0,126	-0,045	-0,026	-0,036
P5	-0,011	-0,024	0,026	0,026	0,103	-0,016	0,026	-0,066	-0,062
P6	0,149	-0,095	0,011	0,153	-0,145	0,005	0	0,026	-0,104
P7	-0,029	0,082	-0,018	0,007	-0,026	0,094	-0,026	-0,018	-0,066
P8	-0,018	0,053	-0,041	-0,001	-0,071	-0,011	0,03	0,055	0,006
P9	0,115	0,06	-0,062	-0,064	0,055	0,007	-0,01	-0,036	-0,064
P10	-0,009	-0,037	-0,144	-0,018	0,196	0,03	-0,023	0,018	-0,012
P11	-0,083	-0,052	0,089	0,009	0,121	0,009	-0,043	-0,021	-0,029

Note: the color implies the direction before rounding (green =positive, red = negative)

Figure 9.1: Full deltas of measuring indicators (T1-T2)

Table 9.9: Individual weights for measuring indicators T2:2025–2030

Measuring 2030	**Car ownership**	**EV Adoption**	**Profitability**	**Public space**	**Peak demand**	**Sus. energy use**	**Local emissions**	**Occu-pancy**	**User comfort**	**KSI**
P1	0.052	0.122	0.092	0.061	0.122	0.092	0.183	0.092	0.183	0.367
P2	0.1	0.15	0.075	0.1	0.1	0.15	0.15	0.1	0.075	0.15
P3	0.128	0128	0.085	0.128	0.064	0.128	0.085	0.128	0.128	0.128
P4	0.16	0.107	0.22	0.08	0.16	0.16	0.053	0.04	0.02	0.1
P5	0.026	0.126	0.126	0.126	0.178	0.084	0.126	0.084	0.126	0.073
P6	0.188	0.083	0.125	0.229	0.083	0.063	0.021	0.083	0.125	0.063
P7	0.02	0.18	0.08	0.08	0.12	0.24	0.12	0.08	0.08	0.06
P8	0.017	0.135	0.135	0.034	0.135	0.195	0.045	0.09	0.213	0.075
P9	0.175	0.088	0.058	0.117	0.175	0.058	0.05	0.253	0.026	0.097
P10	0.045	0.18	0.18	0.09	0.269	0.06	0.025	0.09	0.06	0.092
P11	0.02	0.174	0.112	0.112	0.225	0.112	0.112	0.056	0.075	0.051

Table 9.10: Individual weights for organizing indicators T2: 2025–2030

Organizing 2030	Fast charging	V2G	Smart charging	Inductive charging	PV/ Solar	Accessi-bility	User groups	KSI
P1	0.227	0.076	0.227	0.114	0.091	0.152	0.114	0.227
P2	0.141	0.141	0.211	0.085	0.07	0.141	0.211	0.423
P3	0.115	0.092	0.154	0.04	0.154	0.291	0.154	0.17
P4	0.209	0.104	0.209	0.06	0.07	0.209	0.139	0.209
P5	0.169	0.169	0.27	0.025	0113	0.169	0.085	0.068
P6	0.146	0.22	0.146	0.293	0.098	0.073	0.024	0.073
P7	0.169	0.311	0.254	0.101	0.063	0.029	0.072	0.196
P8	0.103	0.318	0.205	0.068	0.205	0.068	0.032	0.093
P9	0.149	0.223	0.315	0.089	0.074	0.037	0.112	0.131
P10	0.145	0.145	0.145	0.073	0.033	0.35	0.109	0.086
P11	0.136	0.205	0.136	0.023	0.091	0.136	0.273	0.068

Table 9.11: Individual weights for development indicators T2: 2025–2030

Developing 2030	Develop Maas	Energy Activities	Roll-out of Infra	Stimulate new tech	KSI
P1	0.425	0.31	0.207	0.057	0.195
P2	0.143	0.286	0.429	0.143	0.857
P3	0.195	0.26	0.39	0.156	0.39
P4	0.353	0.294	0.294	0.059	0.235
P5	0.061	0.429	0.306	0.204	0.184
P6	0.433	0.2	0.067	0.3	0.167
P7*	0.298	0.223	0.223	0.255	1.787*
P8	0.403	0.273	0.273	0.052	0.143
P9	0.053	0.474	0.316	0.158	0.158
P10	0.057	0.24	0.559	0.144	0.16
P11	0.066	0.412	0.209	0.313	0.214

2025-2030	Fast charging	V2G	Smart charging	Induction charging	PV charging	Accessibility	User group roles
P1	0,025	0,008	0,025	0,056	-0,044	-0,05	-0,021
P2	-0,001	0,035	-0,001	0,031	0,01	-0,072	-0,001
P3	-0,065	-0,088	0,019	-0,068	0,019	0,21	-0,027
P4	-0,068	0,062	-0,005	0,012	0,008	-0,005	-0,004
P5	0,013	0,013	0,114	-0,006	0,05	-0,112	-0,072
P6	-0,022	0,135	-0,115	0,266	0,013	-0,189	-0,088
P7	-0,007	0,194	0,077	-0,075	-0,172	-0,059	0,043
P8	-0,066	0,049	-0,064	0,043	0,036	0,026	-0,024
P9	-0,233	0,155	0,076	0,054	0,015	-0,083	0,016
P10	0,066	-0,013	-0,013	-0,007	-0,002	-0,045	0,014
P11	-0,036	0,089	-0,133	-0,005	0,022	-0,036	0,1

Figure 9.2: Full deltas of organizing indicators (T1-T2)

Table 9.12: Individual weights for measuring indicators T3: 2030–2040

Measuring 2040	Car ownership	EV Adoption	Profitability	Public space	Peak demand	Sus. Energy use	Local emissions	Occu-pancy	User comfort	KSI
P1	0.027	0.113	0.085	0.057	0.085	0.264	0.17	0.085	0.113	0.076
P2	0.058	0.116	0.058	0.116	0.078	0.159	0.233	0.022	0.159	0.073
P3	0.14	0.211	0.07	0.105	0.07	0.07	0.018	0.105	0.211	0.07
P4	0.055	0.064	0.048	0.127	0.267	0.191	0.127	0.095	0.025	0.115
P5	0.178	0.119	0.119	0.119	0.178	0.059	0.059	0.119	0.051	0.178
P6	0.211	0.06	0.07	0.141	0141	0.106	0.07	0.06	0.141	0.211
P7	0.031	0.088	0.088	0.088	0.131	0.225	0.131	0.088	0.131	0.038
P8	0.034	0.12	0.177	0.014	0.12	0.177	0.06	0.12	0.177	0.064
P9	0.17	0.257	0.049	0.113	0.113	0.049	0.022	0.17	0.057	0.083
P10	0.02	0.05	0.05	0.228	0.228	0.228	0.05	0.074	0.074	0.069
P11	0.045	0.09	0.06	0.119	0.179	0.179	0.179	0.06	0.09	0.358

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Table 9.13: Individual weights for organizing indicators T3: 2030–2040

Organizing 2040	Fast charging	V2G	Smart charging	Inductive charging	PV/ Solar	Accessi-bility	User groups	KSI
P1	0.216	0.038	0.144	0.062	0.086	0.144	0.311	0.121
P2	0.103	0.206	0.206	0.082	0.059	0.137	0.206	0.206
P3	0.095	0.095	0.239	0.08	0.159	0.295	0.037	0.182
P4	0.214	0.071	0.214	0.107	0.071	0.107	0.214	0.214
P5	0.169	0.169	0.27	0.025	0.113	0.169	0.085	0.068
P6	0.236	0.118	0.047	0.307	0.118	0.079	0.094	0.165
P7	0.152	0.152	0.235	0.152	0.152	0.101	0.055	0.069
P8	0.064	0.292	0.317	0.025	0.193	0.055	0.055	0.094
P9	0.042	0.139	0.139	0.444	0.079	0.079	0.079	0.111
P10	0.03	0.294	0.324	0.068	0.101	0.101	0.081	0.111
P11	0.099	0.197	0.079	0.197	0.197	0.132	0.099	0.197

Table 9.14: Individual Weights for development indicators T3: 2030–2040

Developing 2040	Develop Maas	Energy Activities	Roll-out of Infra	Stimulate new tech	KSI
P1	0.115	0.288	0.192	0.404	0.173
P2	0.435	0.217	0.174	0.174	0.87
P3	0.195	0.26	0.39	0.156	0.39
P4	0.313	0.188	0.313	0.188	0.938
P5	0.063	0.579	0.239	0.119	0.138
P6	0.345	0.172	0.138	0.345	0.345
P7	0.25	0.188	0.188	0.375	0.375
P8	0.209	0.372	0.372	0.047	0.163
P9	0.304	0.063	0.203	0.43	0.177
P10	0.063	0.43	0.203	0.304	0.177
P11	0.294	0.294	0.118	0.294	0.294

2025-2030	Develop MaaS	Energy Activities	Roll-out of Infrastructure	Stimulate new Technologies
P1	0,215	-0,005	-0,109	-0,1
P2	-0,107	0,036	0,054	0,018
P3	-0,036	0,183	-0,072	-0,075
P4	0,303	0,019	-0,156	-0,166
P5	-0,003	-0,082	-0,013	0,098
P6	0,381	-0,274	-0,249	0,142
P7*	0,227	-0,072	-0,213	0,058
P8	0,153	0,023	0,023	-0,198
P9	-0,147	0,174	-0,134	0,108
P10	-0,002	0,014	0,013	-0,025
P11	0,008	0,092	-0,257	0,158

The asterix at P7 indicates consistency issues with this entry (consistency issue arised at Table A7)

Figure 9.3: Full deltas of development indicators (T1-T2)

T2-T3 Delta	Car ownership	EV Adoption	Profitability	Public space	Peak demand	Sus. Energy	Local emissions	Occupancy	User comfort
P1	-0,026	-0,009	-0,007	-0,004	-0,037	0,172	-0,013	-0,007	-0,07
P2	-0,042	-0,034	-0,017	0,016	-0,022	0,009	0,083	-0,078	0,084
P3	0,013	0,083	-0,015	-0,022	0,006	-0,058	-0,068	-0,022	0,083
P4	-0,105	-0,043	-0,172	0,047	0,107	0,031	0,074	0,055	0,005
P5	0,152	-0,007	-0,007	-0,007	0	-0,024	-0,066	0,035	-0,075
P6	0,024	-0,023	-0,055	-0,088	0,057	0,043	0,05	-0,023	0,016
P7	0,011	-0,093	0,008	0,008	0,011	-0,015	0,011	0,008	0,051
P8	0,017	-0,015	0,041	-0,02	-0,015	-0,019	0,015	0,03	-0,036
P9	-0,005	0,17	-0,01	-0,003	-0,062	-0,01	-0,028	-0,083	0,031
P10	-0,025	-0,131	-0,131	0,138	-0,041	0,168	0,024	-0,016	0,014
P11	0,024	-0,084	-0,053	0,007	-0,046	0,067	0,067	0,003	0,015

Figure 9.4: Full deltas of measuring indicators (T2-T3)

2030-2040	Fast charging	V2G	Smart charging	Induction charging	PV charging	Accessibility	User groups
P1	-0,026	-0,009	-0,007	-0,004	-0,037	0,172	-0,013
P2	-0,042	-0,034	-0,017	0,016	-0,022	0,009	0,083
P3	0,013	0,083	-0,015	-0,022	0,006	-0,058	-0,068
P4	-0,105	-0,043	-0,172	0,047	0,107	0,031	0,074
P5	0,152	-0,007	-0,007	-0,007	0	-0,024	-0,066
P6	0,024	-0,023	-0,055	-0,088	0,057	0,043	0,05
P7	0,011	-0,093	0,008	0,008	0,011	-0,015	0,011
P8	0,017	-0,015	0,041	-0,02	-0,015	-0,019	0,015
P9	-0,005	0,17	-0,01	-0,003	-0,062	-0,01	-0,028
P10	-0,025	-0,131	-0,131	0,138	-0,041	0,168	0,024
P11	0,024	-0,084	-0,053	0,007	-0,046	0,067	0,067

Figure 9.5: Full deltas of organizing indicators (T2-T3)

2030-2040	Develop MaaS	Energy Activities	Roll-out of Infrastructure	Stimulate new Technologies
P1	-0,31	-0,022	-0,015	0,346
P2	0,292	-0,068	-0,255	0,031
P3	0	0	0	0
P4	-0,04	-0,107	0,018	0,129
P5	0,002	0,15	-0,067	-0,085
P6	-0,089	-0,028	0,071	0,045
P7	-0,048	-0,036	-0,036	0,12
P8	-0,193	0,099	0,099	-0,005
P9	0,251	-0,41	-0,113	0,272
P10	0,006	0,191	-0,357	0,16
P11	0,228	-0,118	-0,091	-0,019

The asterix at P7 indicates consistency issues with this entry (consistency issue arised at Table A7)

Figure 9.6: Full deltas of development indicators (T2-T3)

Table 9.15: number of sessions per hour (average of measured sample, 2022)

Time	KK	GB	LL	RS	ER	BL	LS	BB	TR
23:00-07:00	1	1	1	1	1	1	1	1	1
08:00	1	1	2	1	1	1	1	1	1
09:00	1	1	2	1	2	2	1	2	1
10:00	1	1	2	1	2	2	1	2	2
11:00	1	1	2	1	2	2	1	1	2
12:00	1	2	2	1	2	2	1	2	2
13:00	1	2	2	1	2	2	1	2	2
14:00	1	2	2	1	2	2	1	2	2
15:00	1	2	2	2	2	2	1	2	2
16:00	1	2	3	2	2	3	1	2	3
17:00	1	2	3	2	2	3	1	2	3
18:00	2	2	3	2	3	3	1	2	4
19:00	2	2	2	2	2	2	1	2	2
20:00	1	2	2	1	2	2	1	2	2
21:00	1	2	2	1	2	2	1	2	2
22:00	1	1	2	1	2	2	1	1	2

Table 9.16: number of sessions per hour (max of measured sample, 2022)

Time	KK	GB	LL	RS	ER	BL	LS	BB	TR
00:00-07:00	3	3	3	4	3	3	2	3	3
08:00	3	5	5	3	4	4	3	3	4
09:00	3	5	5	4	7	5	4	4	5
10:00	3	6	5	4	5	7	4	5	6
11:00	3	3	6	4	6	5	4	5	5
12:00	3	4	6	4	6	5	3	4	6
13:00	6	6	8	5	7	6	4	5	6
14:00	4	7	7	4	7	5	4	4	7
15:00	4	6	9	5	7	5	7	5	8
16:00	3	6	7	5	7	6	3	8	8
17:00	5	6	10	7	7	7	4	7	8
18:00	5	8	12	7	10	7	3	7	10
19:00	5	5	8	5	8	5	4	8	6
20:00	5	4	7	5	6	6	4	6	5
21:00	4	4	7	4	7	5	4	6	5
22:00	3	4	5	4	7	5	3	5	5
23:00	3	3	4	3	6	4	3	4	4

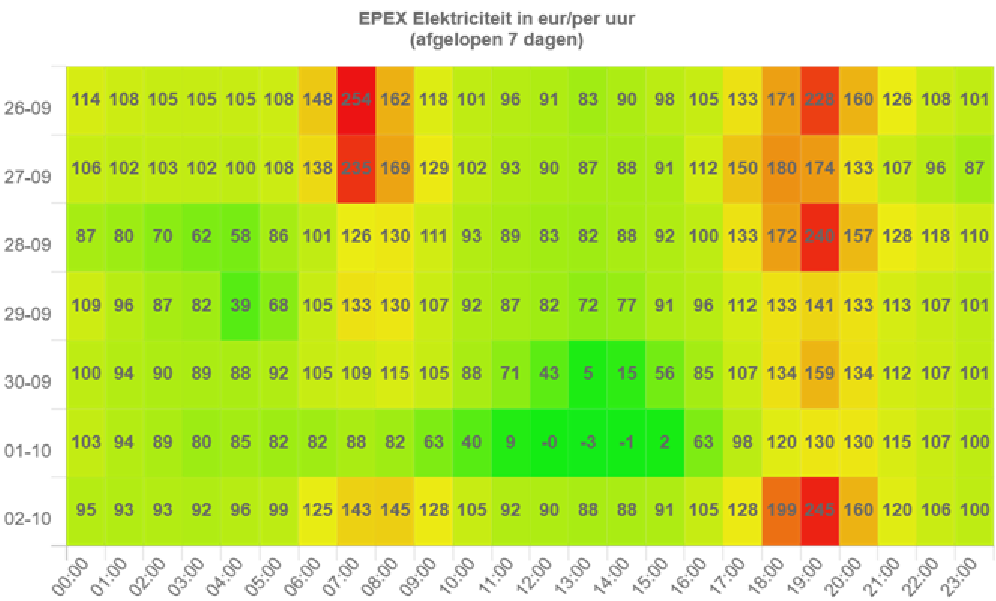

Figure 9.7: EPEX day-ahead market sample of 1 week (September 2023)

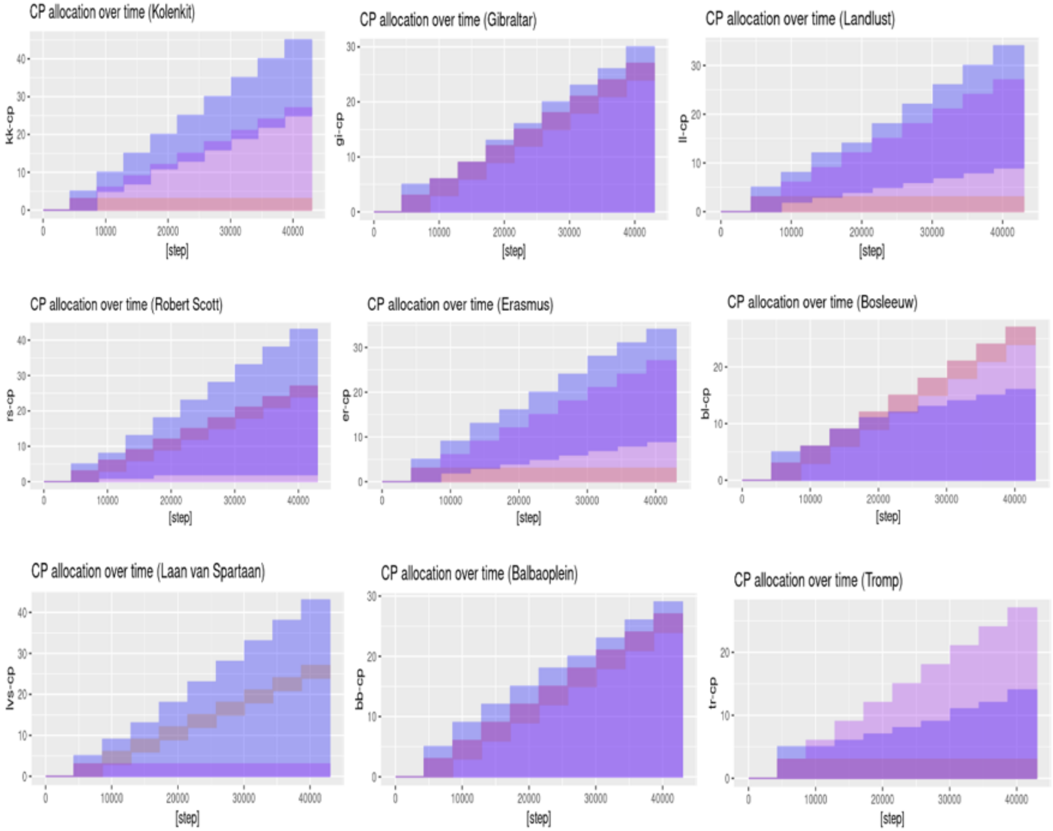

Figure 9.8: Temporal analysis of charging point allocation

Curriculum Vitæ

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Education

2010-2015	B.Sc in Lifestyle Informations Vrije Universiteit Amsterdam
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Positions

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LIST OF PUBLICATIONS

- **M. van der Koogh, E. Chappin, R. Heller, Z. Lukszo (2023)**, *A conceptual representation of short-term and long-term decision-making in the roll-out and exploitation of public EV charging infrastructure in Dutch neighborhoods,* Transportation Procedia **70**, 178–187
- **M. van der Koogh, E. Chappin, R. Heller, Z. Lukszo (2023)**, *Stakeholder prioritizations for electric vehicle charging across time periods,* Transport Policy **142**, 173–189.
- **M. van der Koogh, R. Wolbertus, R. Heller (2023)**, *Charging after Lockdown: The Aftermath of COVID-19 Policies on Electric Vehicle Charging Behaviour in The Netherlands,* World Electric Vehicle Journal **14**, 3 .
- **M. van der Koogh, R. Ghotge (2022)**, *State of Competition in the Dutch EV charging sector. Emerging issues in a developing market,* Mededingingsrecht in de Praktijk **4**, 14, 19-27.
- **M. van der Koogh, E. Chappin, R. Heller, Z. Lukszo (2021)**, *Are We Satisfying the Right Conditions for the Mobility Transition? A Review and Evaluation of the Dutch Urban Mobility Policies,* Sustainability **13**, 22 (12736).

List of Supervised Master Theses

- **M. van Eijck**, *The Final Hurdles to Technical Implementation of Vehicle-to-Grid*, TU Delft Master Thesis CoSEM, 2024.
- **A. Patro**, *Enhancing Public Charging Network CPOs' Business Models Through Vehicle-to-Grid Integration in the Netherlands*, TU Delft Master Thesis SET, 2023.
- **D. Koopman**, *Drivers of Electric Vehicle Adoption: a Case Study at Public Chargers in the Netherlands*, TU Delft Master Thesis EPA, 2022.
- **W. Hofmans**, *Dutch public EV charging infrastructure design: a Multi-Criteria Decision Analysis*, TU Delft Master Thesis CoSEM, 2021 .