The future of public charging infrastructure in the Netherlands

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Abstract

The Dutch Energy agreement was implemented in 2013, with the goal to provide a basis for the future Dutch energy and climate policies. It sets targets for several sectors, including mobility and transport. The sector has the ambition to reduce greenhouse gas emissions with at least 60 percent, compared to 1990 (Sociaal-Economische Raad, 2013). One of the ways to reduce greenhouse gas emissions from transport is by transitioning to a passenger car market consisting of electric vehicles (EVs). The Energy agreement aims at replacing all passenger vehicles with an EV, which equals 9.5 million EVs in 2050. However, it remains unclear how the (public) charging infrastructure will develop to supply the charging demand from these vehicles.

Therefore, this thesis has been performed to provide a view on the requirements for public charging infrastructure to supply the electricity demand for 9.5 million EVs in the Netherlands in 2050 and identify the impacts of this charging infrastructure. A reference scenario was developed alongside 4 alternative scenarios, which differed in terms of charging technique and vehicle range. The scenarios were analysed in terms of number of charging stations, percentage of electricity demand, costs and electricity grid impact.

The results showed that the scenarios with DC fast charging technology requires the least number of charging stations, while installation costs were higher. The vehicle to grid scenario, with AC charging technology, could decrease peak electricity demand by 1,100 MW. Electricity demand for charging was 2 percent of total current electricity demand in 2030 and 11 percent in 2050.

The preferred pathway for the development of public charging infrastructure depends on the demands of policy makers. However, the vehicle to grid system, with AC charging, seems the most beneficial overall, since it is cheaper to install and has other benefits, e.g. improving grid stability. This study recommends focusing on improving the occupancy rate of charging stations and increasing the charging power prevent the need to install extra public charging stations up to 2030. In the period 2030 to 2050, new public charging stations are required due to the increase in number of EVs and thereby charging demand. However, this does not require additional policy interventions, since the business case for public charging infrastructure will be positive by then.

1. Introduction

Since the beginning of the Industrial Revolution, fossil fuels provide a reliable source of cheap energy. Increasing energy consumption provided conditions for economic growth and population increase, but there are negative side effects: Anthropogenic greenhouse gas emissions, linked to fossil fuel use, are growing and accumulating in atmosphere and ocean. Currently, atmospheric concentrations of carbon dioxide, methane and nitrous oxide are unprecedented in the last 800,000 year. The resulting greenhouse effect contributes to climate change: warming atmosphere and oceans, melting snow and ice and sea level rise (IPCC, 2014).

To combat climate change, the international community, including the European Union, organised the Paris climate conference (COP21) in December 2015. 195 countries agreed on an action plan to limit the increase in global average temperature to below 2°C above pre-industrial levels, in order to reduce the risks and impacts of climate change. For achieving this goal, greenhouse gas emissions need to peak as soon as possible, with a rapid reduction afterward (European Commission, 2015).

The Netherlands already took action before the Paris agreement and implemented the "Energy agreement for sustainable growth" in 2013, aiming to increase the sustainability of the economy and society. This agreement is signed by over forty organisations, including employers, environmental organizations, financial institutions and governmental bodies, which discussed several topics in so-called "tafels" (Sociaal-Economische Raad, 2013). The goal of the Energy agreement is to boost the economy while transitioning to a climate neutral energy supply in 2050. Sub-targets are energy savings (1.5 percent per year), renewable energy use (14 percent in 2020, 16 percent in 2023) and over 15,000 full time jobs (Sociaal-Economische Raad, 2013).

A large contributor to greenhouse gas emissions is the sector mobility and transport. According to the IEA (2009, p. 29), "Transport accounts for about 19% of global energy use and 23% of energy-related carbon dioxide emissions and these shares will likely rise in the future. Given current trends, transport energy use and CO_2 emissions are projected to increase by nearly 50% by 2030 and more than 80% by 2050." The CO_2 emissions from mobility and transport arise mainly from the sector's dependency on fossil fuels. Structural change in the transport sector is required to reduce emissions for road transport: The climate goals will not be met without decarbonisation of road transport. This means that longer term development and deployment of new technologies is necessary (IEA, 2009). Therefore, the sector mobility and transport is included in the Energy agreement: The sector has the ambition to reduce greenhouse gas emissions with at least 60 percent, compared to 1990 (Sociaal-Economische Raad, 2013). The involved organisations will also develop a shared vision on the future fuel mix, called "Sustainable fuels vision". The ambition to equip all newly sold passenger cars with a zero-emission drivetrain in 2035 results from the goals in the Energy Agreement. In 2050, all passenger cars should have a zero-emission drivetrain (Sociaal-Economische Raad, 2013).

An alternative for fossil fuel driven vehicles is the electric vehicle (EV). EVs achieve higher energy efficiency compared to gasoline and diesel cars. A typical efficiency for a gasoline engine is 25 percent (Blok, 2007). Most energy disappears as heat, through the exhaust and cooling system. For Diesel engines the efficiency lies around 30 percent (Blok, 2007). The efficiency of an electric motor is significantly higher: For a motor with a power over 50 horse power the efficiency is at least 90 percent (The Engineering Toolbox, 2016), since less energy is converted into heat. An electric engine also has fewer moving parts and less friction than an internal combustion engine. Another factor in determining energy efficiency of an electric engine is the efficiency of electricity generation. The worst case scenario is electricity generated by a coal fired power plant, with a typical efficiency of 40 percent (Blok, 2007). The resulting total energy efficiency is 36 percent, which is higher than the efficiency of an internal combustion engine. Natural gas fired power plants operate with a typical efficiency of 55 percent, which results in an overall efficiency of 49.5 percent for the electric engine. Both EVs and internal fossil fuel powered vehicles suffer from losses in transmission and distribution of the fuels. However, these losses are relatively small compared to the heat losses described above. Moreover, the electric drivetrain operates more efficient compared to an internal combustion engine drivetrain. The electric motor isn’t running while the car is stationary and it can recover energy while braking: regenerative braking. Losses in transmission are smaller for an electric drivetrain (Chen, Taylor, & Kringos, 2015). Consequently, an EV is considered a more energy efficient way of transport, compared to a fossil fuel powered vehicle.

Another important advantage of an EV is the zero tailpipe emission of pollutants, e.g. NO_x and particulate matter. This is especially significant in urban areas with bad air quality. For countries depending on fossil fuel imports, replacing internal combustion engine vehicles with electric vehicles can contribute to reducing oil demand and increasing energy security (Rijksoverheid, 2011). These advantages of an EV are often more important for municipalities and other governments in the decision to stimulate zero emission transport. Summarising, electric vehicles are seen as a solution in reducing greenhouse gas emissions, emissions of NO_x and particulate matter, while increasing energy security by decreasing the dependency on fossil fuels imports. These factors contribute to increasing the sustainability of transport and mobility, which is part of the Energy Agreement.

However, there are a few important issues/barriers regarding EVs: Limited range and charging infrastructure. Limited range leads to range anxiety, which is “the fear of fully depleting a BEVs battery in the middle of a trip, leaving the driver stranded” (Neubauer & Wood, 2014). This anxiety lowers appreciation of EVs, potentially letting consumers choose alternative means of transportation. Range anxiety is enlarged by uncertainties in trip lengths and energy consumption, e.g. for heating/cooling. Range anxiety can be reduced with a well-developed network of charging stations, to provide EV drivers with the possibility to recharge their vehicle while away from home, increasing their maximum travel distance (Neubauer & Wood, 2014).

Electric vehicles differ fundamentally with conventional vehicles in the way they refuel. EVs require recharging of the batteries over longer periods of time, therefore the build-up of charging infrastructure is essential in the development of EVs. This is similar to the chicken or the egg problem: Vehicle users don't want to change to an electric vehicle due to the limited access to charging infrastructure, while installing a charging station network is not cost-effective without costumers: The business case for charging infrastructure is negative. Initiative from the public sector is required to stimulate the development of charging infrastructure (Viswanathan et al., 2016).

Another issue concerning charging infrastructure is that over 60 per cent of Dutch citizens park their car in public space (Ministerie van Infrastructuur en Milieu, 2014). Ideally, citizens park on their own property, where a charging station is easily installed, for charging overnight. The charger is added to the electrical system of the house, adding the possibility of charging with solar PV panels from the house, independent from the electricity grid, increasing self-sufficiency. This system is also optimal for governments, since it does not require involvement in providing public infrastructure, combined with investments in connecting charging stations to the electricity grid.

This option is not available for the majority of car owners, meaning they would rely on charging at chargers in public space. Therefore, the Netherlands investigates the implementation of new regulations ensuring the right of each EV driver on a charging station within acceptable distance of their home (Ministerie van Infrastructuur en Milieu, 2014). Summarising: EV drivers depend on adequate public charging infrastructure with sufficient convenience, while investors in public charging infrastructure should be able to earn profit on their investment (Dharmakeerthii, Mithulananthan, & Saha, 2015).

Currently, the market for electric vehicles is relatively small; the demand for charging stations is also relatively small. With increasing market penetration of EVs, and a positive business case for public charging infrastructure from 2018 onward, up scaling to a well-developed, nation-wide charging network becomes viable (Ministerie van Infrastructuur en Milieu, 2014).

1.1 Research aim

The Energy Agreement and Sustainable Fuels vision emphasise the ambition of the Dutch government to stimulate the uptake of EVs. This should result in a passenger vehicle fleet which consists solely of EVs in 2050. Concrete policy measures regarding EVs and charging infrastructure, proposed in the Sustainable fuels vision, range from 2015 to 2020. The aim of this study is to gain insight in the current situation regarding public charging infrastructure and analyse several development pathways to 2050. A scenario analysis is performed, to analyse the impact of several potential development pathways. The scenario methodology is elaborated on in section 3.2. This provides a long-term projection for the development of public charging infrastructure in the Netherlands.

The results can be used to formulate a strategy for the period after 2020, in order to guide the development of public charging infrastructure to a desired situation: Capable of supplying sufficient public charging infrastructure for the increase in EVs. Therefore, this research complements the Energy Agreement and the Sustainable fuels vision by addressing public charging infrastructure development in the period from 2020 to 2050.

This study focuses on the Netherlands. The reason for this geographical focus is fourfold. First, the Netherlands have a frontrunner position in EV sales and developing a public charging infrastructure network: 4 percent of new car sales was an EV in 2013, only exceeded by Norway with 6 percent (McKinsey, 2014). Second, the Netherlands stated the ambition to have a passenger vehicle fleet consisting solely of EVs in 2050. Third, the Netherlands is chosen to limit the scope of the research to fit in the time frame for the study. Finally, the author studies in the Netherlands, simplifying data collection, especially when reading Dutch literature. It is important to realise that the Netherlands is not an isolated system: The Netherlands is also dependent on developments abroad. This is elaborated on in the discussion. The focus on the Netherlands does not render the study useless for scientists in other countries, since the model can be applied to other countries by changing the values of the indicators to represent the situation in that country. In that case, the Netherlands serves as a case study for applying the model.

1.2 Research gap

After consulting literature, the author concluded that the absence of a strategy for guiding the development of public charging infrastructure in the Netherlands from 2020 onwards as a gap in literature. There is no study of potential ways of development of public charging infrastructure, when all passenger vehicles are EVs in 2050, in compliance with the goal of the Sustainable fuels vision. However, this is the societal knowledge gap. The scientific research gap lies in the absence of tools to analyse the required development of charging infrastructure to facilitate public charging in the future. This study provides a model which can be used to fill the research gap.

Other contributions in the area of charging infrastructure focus mainly on one component of the system, e.g. charging technology and modelling the optimal location of charging stations. Examples of previous studies are given below. Since developments and growth in the EV market has increased significantly in the last five years. Therefore, recent articles were preferred.

From previous work, the Sustainable fuels vision is the most important one. Although it is a vision and not a study, it provides the backbone of future Dutch policy on electric vehicles: The ambition that in 2050 all vehicles have a zero-emission drivetrain. But it doesn't provide a long-term view on public charging infrastructure, so it remains unclear how the charging requirements of all EVs in 2050 will be met.

Yong, Ramachandaramurthy, Tan, & Mithulananthan (2015) review developments in technology for EVs and impacts of EV rollout. The article covers battery and charging techniques, impacts on the power grid. The authors conclude that EV deployment will have negative impacts on the power grid, without charging management. Another conclusion is that an increase in EVs could be a good integration in a smart grid. But the article only describes the technology qualitative and does not consider future developments. Therefore, it is not suitable for making future projections on charging infrastructure.

Morrissey, Weldon, & O'Mahony (2016) analyse charging behaviour of EV owners: When they charge, how much they charge, for how long they charge, which type of infrastructure. This is done to understand demand for charging infrastructure, to aid in a successful rollout, where charging stations are placed where demand is high. This increases efficiency of public charging infrastructure, reducing costs. The authors conclude that EV owners prefer to charge their vehicle in the evening, leading to a peak in electricity demand. Public infrastructure is less popular, with a preference for car park locations and petrol stations for fast charging. The focus of the study is present and short-term developments.

Filho & Kotter (2015) describe challenges in the early public charging infrastructure market. They propose six models for investing in charging infrastructure and identify opportunities and weaknesses of these models. The models aim to develop an efficient funding strategy for public charging infrastructure. The models vary from governments paying the installation costs to individual companies invest in the infrastructure. An example is the Supercharger network from Tesla. Hybrid models include state governments supporting local initiatives and local governments investing in charging infrastructure. There is no best option: The outcomes of the models vary with regional context. The authors conclude that the models need refinement and testing in real-life conditions. The models are useful for determining a good way to invest in charging infrastructure, but they focus on the short term and are not tested yet.

Aditya & Williamson (2016) describe the inductive power transfer system for charging EVs. The paper comprises important design features to achieve high frequency operation for inductive power transfer (IPT) with high efficiency. The article provides a good overview on the technique of IPT, but it only describes the technique qualitatively.

(Chatterjee & Gordon, 2006) explore future scenarios for transport in Great Britain in 2030 and study the implications these scenarios have. Five scenarios are analysed and results for travel distance, congestion and emissions are shown. The scenarios are a good way to analyse different pathways to a desired future, which can be useful for the research on charging infrastructure as well. However, this study has a different focus: It focuses on all transport and includes economic growth, globalisation and consumerism. The topic of this study is different from this study, but the methodology is suitable.

Shahraki, Cai, Turkay, & Xu (2015) use real world vehicle travel patterns to model public charging demand and select optimal charging locations. The model is applied to Beijing, China for almost 12,000 electric taxis. This model can help in predicting the right location for charging infrastructure. However, the project is done on a small scale and does not help in projecting the future of charging infrastructure.

Summarising, most literature on charging infrastructure focuses on short term and investigate only a part of the system. To develop a long term model of development of charging infrastructure, the insights from other studies are combined and expanded.

1.3 Research question

The research question is formulated with the research aim and gap in literature in mind: How can public charging infrastructure in the Netherlands develop to supply the charging demand from EVs in 2050 and what are the impacts of this charging infrastructure?

1.4 Research outline

This report is structured in several sections. Section 1 is the introduction. Section 2 explains theories used in this study. The research method is described in section 3. The results are displayed in section 4. To structure the scenario analysis, the research question is complemented with sub questions, given below. Section 4.1 describes the current situation, in order to gain a starting point for the scenario study. Section 4.2 explores possible future developments, in terms of technical development and policy development. Section 4.3 describes a reference scenario for public charging infrastructure in the Netherlands. Section 4.4 presents the results for the alternative scenarios.

Section 4.1. Current situation

Sub question 1: What are important organisations and actors?
Sub question 2: How many electric vehicles and charging infrastructure units are there currently?
Sub question 3: What policies are in place?

Section 4.2. Future developments

Sub question 4: What are suitable indicators to describe the EV and EV charging system?

This is done to get an idea of the technological state of the system and explore areas where future development may take place.

Sub question 5: What expected developments in EV charging technologies?

This includes changes in battery technology (range) and charging technology (Conventional, slow charging and DC fast charging).

Sub question 6: What are expected developments in EV policies?

Another interesting point is the potential changing role of the government, from actively stimulating EVs to a more facilitating role, or completely outsourcing all aspects of electric mobility. Therefore, future policies are identified.

Section 4.3. Reference scenario

Sub question 7: How will public charging infrastructure develop in a reference scenario?

Here I will create a reference (or business-as-usual) scenario for the development of charging infrastructure towards 2050. This will depend on number of EVs, range, charging technique/speed and legislation.

Section 4.4. Alternative scenarios

Sub question 8: What are critical uncertainties in the future developments of the indicators?

The indicators which development is critical are chosen, based on uncertainty and importance. These are called the critical uncertainties.

Sub question 9: What are the demands for charging infrastructure for the alternative scenarios?

The alternative scenarios are constructed from the critical uncertainties. The scenarios can be compared with the reference scenario. Analysis of the results from these scenarios will provide an overview of the impacts from developments in charging infrastructure and will yield an overview of several pathways towards 2050 for achieving sufficient charging infrastructure for the increase in EVs in the Netherlands.

1.5 Relevance

First, the relevance for the study Sustainable Development is discussed: The focus of the track Energy & Materials lies on efficient and sustainable use of energy and materials. This study contributes to the understanding of implementation of charging infrastructure, which supports the upscaling and development of EVs in the Netherlands. Therefore it aligns with the focus of the Master programme, since EVs are a (more) sustainable and efficient way of transport compared to the dominant fossil fuel powered vehicles.

Second, the relevance for the gap in literature: With the scenario analysis, this study helps developing a vision on the future of EV charging infrastructure. This is useful for the government and other actors since it contributes to the gap in literature identified above (no national strategy for the large-scale rollout of charging infrastructure after 2020).

Third, the relevance for society: This study helps the development of electric vehicles through focussing on the development of charging infrastructure. Electric cars are relevant for society, since they contribute to better air quality (especially in cities) and efficient mobility.

2. Theory

This research is based on two theories: Diffusion of innovations and Strategic Niche Management. The theories and the link to this study are discussed below.

2.1 Diffusion of innovations

Diffusion is the process by which an innovation is communicated through certain channels over time among the members of a social system (Rogers, 1995). Rogers states that innovations are influenced by adopters, communication channels, time and the social system. The adopters of the innovation are divided in categories, based on their innovativeness: The degree to which an individual, or other unit of adoption, is relatively earlier in adopting new ideas than other members of a system (Rogers, 1995). The categories are: Innovators, early adopters, early majority, late majority and laggards. The relative shares are shown in Figure 1.

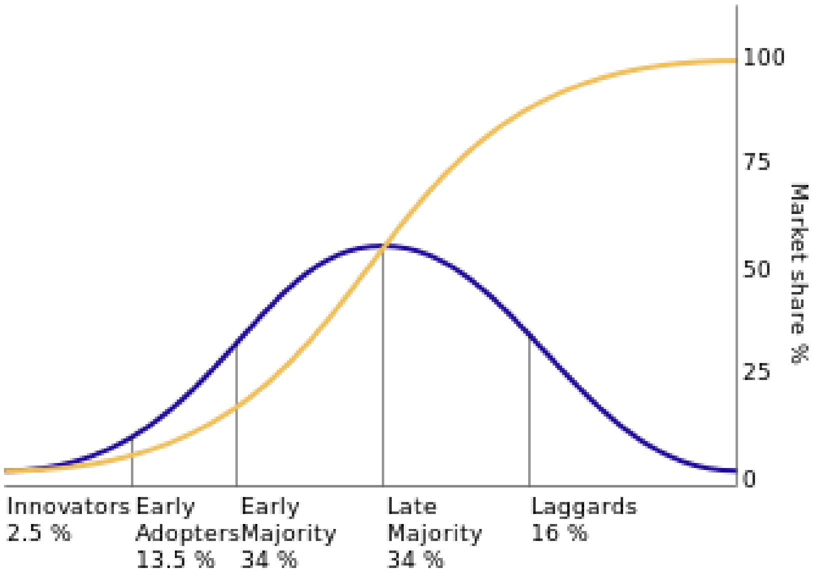


Figure 1. The shares of each adopter category and their cumulative share (Rogers, 1995)

The theory on diffusion of innovations describes how communication stimulates the uptake of innovations. Since the aim of this thesis is to analyse strategies to develop the rollout of charging infrastructure, the theory of Rogers is relevant for this research.

The main concepts in the diffusion theory are innovation, adopters, communication channels, time and the social system. An innovation is a new idea, practice or object, perceived by an individual or another unit of adoption (Rogers, 1995). An adopter is a unit that adopts the innovation. It is usually an individual, but it can be an organization, social network or a country as well (Rogers, 1995). Not all individuals adopt an innovation at the same time; therefore the adopters are categorized according to their innovativeness. The adopters are linked directly to the innovation, since they choose to adopt the innovation or not and will be the users of the innovation.

A communication channel is the means by which messages get from one individual to another. Diffusion of an innovation is the transfer of new ideas between individuals, through communication: We are influenced by peers which already adopted the innovation and communicate their experience with us. Therefore, the existence of a communication channel is a requirement for diffusion to occur (Rogers, 1995). When analysing a large group of individuals, the communication channel becomes a network of interconnected individuals communicating with each other.

Time is defined as the indefinite continued progress of existence and events in the past, present, and future regarded as a whole (Oxford Dictionaries, 2016). Innovations need time to be adopted, since some adopters are laggards, late adopters of the innovation. Laggards are often rather isolated in the communication network, meaning that communication between all possible adopters is not instantly, requiring time (Rogers, 1995).

The social system is the set of interrelated units that have a common goal/objective. The system includes external influences, e.g. media, and internal influences, e.g. social relationships. The members of the system can be individuals or groups/organisations (Rogers, 1995). Important in the social system are so-called ‘opinion leaders’. Opinion leaders stimulate the adoption of an innovation by influencing the opinion of other individuals. The steep increase in the S-shape in the adoption of the innovation in figure 1 is caused by opinion leaders adopting the innovation and influencing other individuals to do the same (Rogers, 1995). The theory predicts an S-shape development of market penetration of an innovation (figure 1). This fits the goal of the Sustainable fuels vision, to equip all passenger vehicles with an electric drivetrain in 2050. This study assumes that EV adoption develops in an S-shape, as predicted by Rogers, to meet the emission reduction targets from the Energy agreement. There are other ways of EV adoption, e.g. linear. However, the S-shape development is in line with the predictions from the sustainable fuels vision on the number of EVs in the Netherlands in 2030 and 2050 and is accepted as suitable development theory for this research.

Market penetration of EVs in the passenger vehicle market needs to increase from practically zero in 2010 to 100 percent in 2050. Therefore, the S-curve starts in 2010 and ends in 2050. This is a fundamental hypothesis and the basis for the development of electric passenger vehicles in the future scenarios.

2.2 Strategic Niche Management

The strategic niche management approach rises from the assumption that sustainable innovations can be stimulated by modulating of technological niches. Niches are areas protected from mainstream competition, e.g. a R&D programme (Schot & Geels, 2008). Inside the niches, innovations are tried out and developed. The innovations in the technological niche are not yet mature, but it is expected that they can be important for realising long-term societal goals. An example of such a goal is the reduction of greenhouse gas emissions. Therefore, governments and other actors are willing to invest and accept disadvantages of the innovation in the present (Schot & Geels, 2008). A reason for stimulating technological niches is that market niches and user demand are often lacking for innovations aiming at the long-term societal goals, because the innovations differ too much from the current situation (regarding infrastructure and regulations).

The overall goal of strategic niche management is that innovations develop in technological niches, transform into market niches and eventually change the system (Schot & Geels, 2008). This is shown in figure 2. This research aims to provide a strategy for the implementation of charging infrastructure, which fits the strategic niche management framework: Technological niches for charging infrastructure and electric vehicles develop and change the current fossil fuel transportation regime.

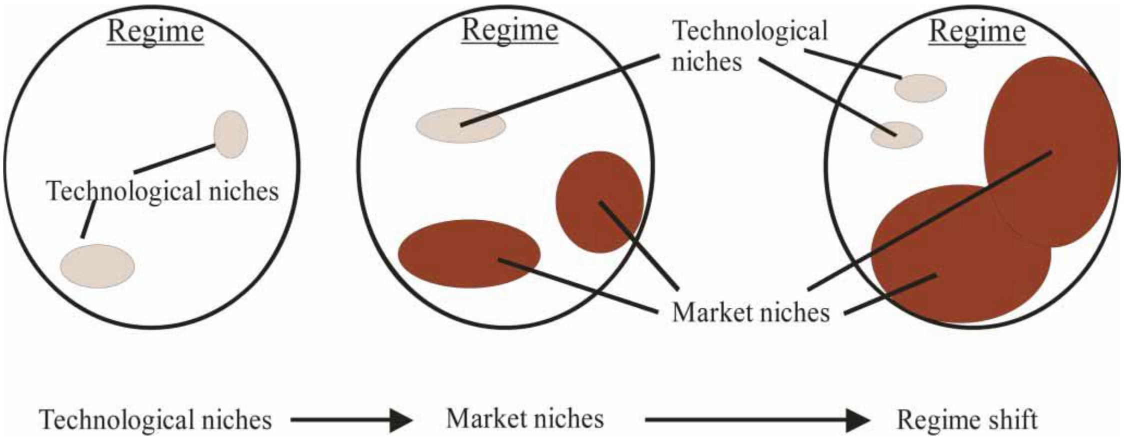


Figure 2. Three steps of strategic niche management (Schot & Geels, 2008)

The main concepts of the theory are technological niches, market niches and the regime.
A technological niche is a protected space where innovations are developed and tested. During development in the niche, time and money is spending on the innovation, often by companies through R&D programmes, or by governments through subsidy programmes.

Technological niches develop into market niches when the innovation is more mature and capable of withstanding some competition from the market. A market niche is less protected than a technological niche, the innovation is more mature and demand for the innovation is higher (Schot & Geels, 2008).

The regime is the way a certain topic is addressed and managed. For example, the transport regime is currently focused on fossil fuels. Every part of the system is optimised for fossil fuel powered vehicles. The goal of strategic niche management is to stimulate niches and enable these niches to change the regime, called a regime shift (Schot & Geels, 2008).

According to SNM, Successful development of a niche depends on 3 factors. The first factor is expectations and visions. These can be useful by attracting attention and steering the learning process. The second factor is the development of a broad social network. This gives the opportunity to broaden ‘cognitive frames’ and create legitimacy for the nice technology (Schot & Geels, 2008). The third factor is learning processes, in technical aspects, markets, infrastructure and regulations. Especially second-order learning is important.

Strategic Niche Management describes the importance of stimulating a technological niche to help the development into a market niche and change the regime. The scenario study identifies potential policies, which will manage and stimulate certain niches in EV charging infrastructure. The hypothesis is that strategically stimulating of promising technological niches, with policies, will guide the EV charging regime in the direction of that niche: That technology becomes dominant. By analysing several niches, multiple scenarios with different dominant charging techniques emerge for the development of charging infrastructure towards 2050.

3. Methods

To answer the research question and sub questions, two methods are used: A literature review and a scenario analysis.

3.1 Literature review

A literature review is necessary to provide the foundation of the scenarios, and answer the first sub questions. Government reports and documents are used to analyse the current situation (4.1), while scientific literature describing possible future developments, e.g. in charging techniques are applied in 4.2. Data sources are governmental web sites, statistics web sites, Scopus and Google Scholar. Two actors from organisations involved with EVs and charging infrastructure are interviewed. This provided an outside perspective on problems and developments in the field of charging infrastructure, and understands the position of different actors.

The actors which were interviewed are Suzan Reitsma, and Baerte de Brey. Suzan Reitsma is project leader electric mobility at the The Netherlands Enterprise Agency (RVO). She is responsible for the implementation of government policies on electric mobility. Baerte de Brey is involved with electric mobility as part of the management team at foundation ElaadNL and as manager electric mobility at grid operator Stedin.

3.2 Scenarios

The research aim of this thesis is to provide a long-term projection for the development of public charging infrastructure in the Netherlands, in order to determine a suitable strategy for providing sufficient public charging infrastructure for the increase in EVs in 2050. To make future projections, several methods can be used (see figure 3).

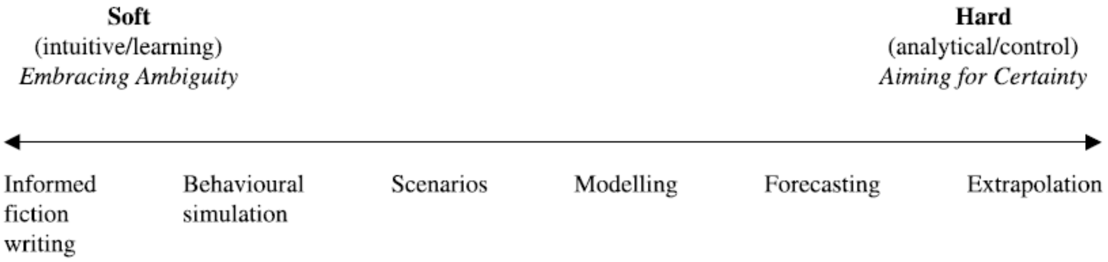


Figure 3. Methods used to make predictions for the future (Chatterjee & Gordon, 2006).

For uncomplicated and predictable topics, extrapolation, forecasting and modelling are suitable methods (Chatterjee & Gordon, 2006). For long-term projections, many assumptions and estimations need to be made, varying from economic, social, environmental, technological and political developments in that period (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006). This leads to large uncertainties in the outcomes of the projection. Therefore, these methods were considered to be unsuitable for this research, and the focus was shifted to scenarios. Scenarios are future studies that 'explore possible, probable and/or preferable futures' (Börjeson et al., 2006, p. 724). Scenario development is usually divided in three stages, with each three steps (Jager, Rothman, Anastasi, Kartha, & van Notten, 2008):

1. Clarifying the purpose and structure of the scenario exercise
    a. Establishing the nature and scope of the scenarios
    b. Identifying stakeholders and selecting participants
    c. Identifying themes, targets, potential policies
2. Laying the Foundation for the Scenarios
    d. Identifying indicators
    e. Selecting critical uncertainties.
    f. Creating a scenario framework
3. Developing and Testing the Scenarios
    g. Elaborating the scenario narratives
    h. Undertaking the quantitative analysis
    i. Exploring policy

This research follows that structure, but the different steps are divided over the sub chapters in the result section, as described in the research outline section.

Clarifying the purpose and structure of the scenario exercise is done to provide an introduction for the scenario process. Step a, establishing the nature and scope of the scenarios, is undertaken to identify the type of scenario and time horizon. Key questions are *what are the issues addressed in the scenario project?* And *are there specific targets or an end vision for the scenarios?* The main issue is the challenge to satisfy demand for public charging infrastructure with increasing number of EVs towards 2050.

A normative scenario answers the question *how can a specific target be reached?* The scenario has a known starting point and focuses on how a desired future situation can be realised (Börjeson et al., 2006). This method is called backcasting: It identifies an end vision and the scenario tells the story from the present situation to the end point (Jager et al., 2008). Since the De Tafel Wegvervoer Duurzaam Elektrisch (2014), as part of the Sustainable fuels vision, stated an expected increase towards of 9.5 million EVs in the Netherlands in 2050, this is used the end vision (target)in developing the scenarios. A normative, back casting scenario method is used in this research to reach this target. The time horizon for the scenarios follows directly from the target set in the Sustainable fuels vision: 2050.

Step b identifies important stakeholders in the field the scenarios focus on. These stakeholders influence the future of the charging infrastructure system, therefore their view on the subject and plans are useful to analyse. Important stakeholders will be described in chapter 4.1.

Themes, targets and potential policies for the scenarios are indentified in step c. The theme of the scenarios is straightforward: electric passenger transport. Part of identifying a theme is analysing the past: What are the numbers on EVs and charging infrastructure? And what policies are in place? Analysing the current situation can provide valuable insights for developments in the future by providing a background. This includes important topics and developments. This is covered in chapter 4.1. The target of the scenarios is to provide sufficient public charging infrastructure to accommodate the increase in EVs towards 2050. The scenarios are restricted to the development of EVs, according to the Sustainable fuels vision, to 9.5 million EVs in 2050.

The key question in analysing policies which interact with the scenarios is *what are (existing or potential) policies that can be explored as part of the scenario exercise?* These policies can be implemented to directly steer the direction of the scenarios, e.g. tax exemptions for fuel efficient cars, or policies which are implemented due to autonomous developments in a scenario, e.g. population growth or technological development. The feasibility and effectiveness of potential policies is examined by developing scenarios that differ only in terms of the implementation of the policies considered. Existing policies can be tested for effectiveness by analysing the results of several scenarios that differ in terms of external factors and developments (Jager et al., 2008).

Stage two of the scenario methodology aims at laying a foundation by identifying indicators, critical uncertainties and creating a scenario framework. After these steps, the outline of the scenario exercise is clear. Decisions on how many scenarios and fundamental distinctions are explained.
It starts with step d, identifying indicators. Indicators are used to describe the system. Common, general indicators are influenced by population, economy, environment, equity, technology and governance (Jager et al., 2008). In this research, the system of interest is passenger transport, including car owners, the government, all (electric) passenger cars in the Netherlands in 2050 and the public charging infrastructure to charge these passenger vehicles. The indicators are chosen so that they contribute to the quantitative analysis of the scenarios. They follow from an analysis on how the electricity demand for charging is built up: What influences the charging demand? Examples are the number of vehicles and electric mileage, in terms of kilometres driven per day per vehicle. A prediction of the possible development over time of each indicator is performed in section 4.2. The indicators are influenced by drivers. A driver is a trend which will influence the future of the system of interest, which is measured by the indicators, e.g. growing population, globalizing economy, urbanization, technological advancement, increasing environmental stress and increasing global governance (Jager et al., 2008).

The next step, step e, is to create a reference scenario and derive critical uncertainties. First, a reference scenario is created, to determine the requirements for charging infrastructure in 2030 and 2050. A reference scenario provides a pathway to the future following current trends. It takes expected (technological) developments into account, as well as policy measures which are already planned and/or implemented. The reference scenario does not include changes in policies in the future, if these changes are not already planned (International Energy Agency, 2010). The reference scenario will serve as a baseline to compare alternative scenarios with. It will predict the required amount of public charging stations to comply with the goal of 9.5 million EVs in 2050.

Second, the indicators which uncertainty is critical are identified: The future development of the indicator is unpredictable and unsure, but it is crucial in determining the future of the system. To select the critical uncertainty in indicator, each indicator is scored on degree of uncertainty in development: *How large is the variation in the range of future developments for this indicator?* Only indicators with a high degree of uncertainty are eligible for critical uncertainty. Next, each indicator is scored on importance. Indicators with high importance lead to large differences in the overall system. The key question here is: *Does the range in development of the indicator lead to large differences in the development of the overall system?*

After determining uncertainty and importance, each indicator is plotted in a chart of uncertainty versus importance. Indicators with high uncertainty in future development are found more upward and indicators with large impact on the development of the system are found further to the right in the chart. The critical uncertainties are the indicators in the right top quadrant of the chart: Indicators with high importance and high uncertainty. Indicators with low importance will often be excluded from the scenarios, since the little influence on the end result does not justify large modelling efforts. Indicators with high importance and low uncertainty are included in the scenarios, but these drivers will not differ significantly between the scenarios (Jager et al., 2008).

The critical uncertainties are the input in step f, creating a scenario framework. The scenario framework leads to four alternative scenarios, which represent four different ways the system can develop in the future. The scenario framework consists of a combination of four possible scenarios, with the critical uncertainties ranging from low development to high development, see figure 4. A third critical uncertainty can be introduced, leading to 12 different scenarios. This is usually avoided, since it complicates the scenario exercise significantly (Jager et al., 2008). This study also excludes a third critical uncertainty, since the uncertainty was significantly higher for 2 indicators. This is explained in section 4.4.1. Another reason for analysing 2 critical uncertainties is that the goal of this study is to provide a clear overview of the future. It is difficult for outsiders to deduct clear conclusions from 12 different scenarios.

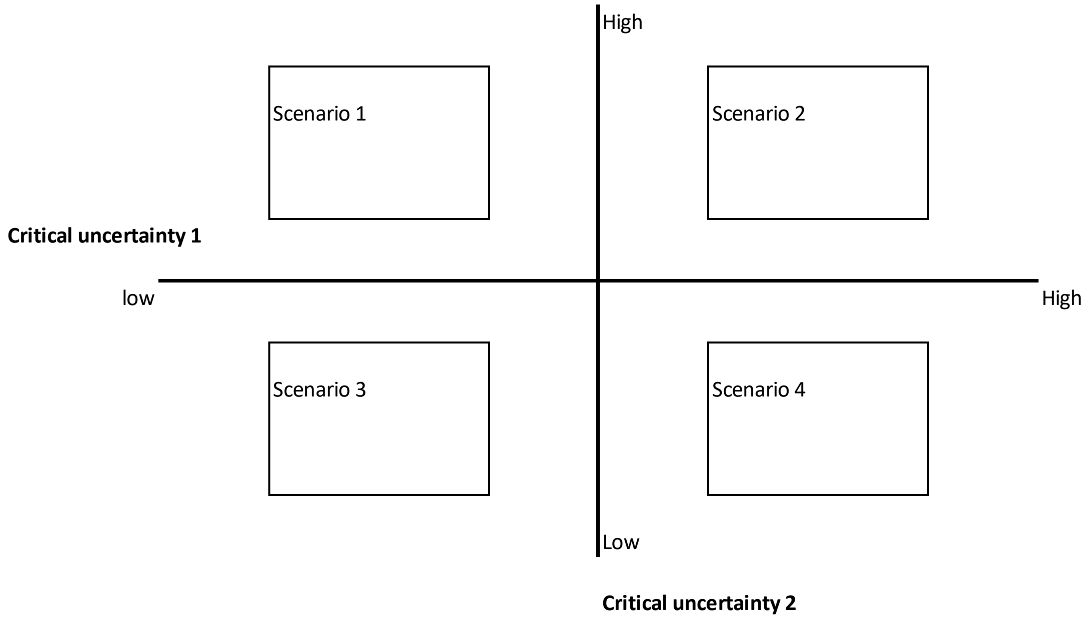


Figure 4. The four alternative scenarios

The foundation from stage two is elaborated with a narrative and qualitative analysis in stage three.

In step g, each scenario is provided with a narrative. This is a detailed description of the scenario. The current situation and trends are analysed to check for characteristics which fit a particular scenario. This will provide a plausible pathway from the current situation to the scenario future. When the starting situation is clear, the focus is shifted to the desired end situation of each scenario. *What would the system look like when the critical uncertainties are developed according to that scenario?* The development of each indicator under that scenario is described. Moreover, the challenges that had to be overcome to come to the end situation are identified.

After the start and end situation are clear, the intermediate time is described by a plausible route, which is converted into a coherent storyline: The narrative.

The narratives of each scenario can be linked by introducing shocks in the system: Events from where two scenarios diverge due to developments in the critical uncertainties. The last step of completing the narratives is assigning a name to each scenario. The name should specify clearly the main assumptions underlying the scenario (Jager et al., 2008).

The qualitative narratives are complemented by a quantitative analysis in step h. The quantitative analysis will provide the data and results on which defensible conclusions can be drawn. The quantitative analysis gives an overview of the magnitude of the required development, making it relevant for policy makers. Therefore it is often a major component of a scenario exercise (Jager et al., 2008). First, the approach to quantify the results from the narratives is chosen. Several tools and methods are available, but these models mainly focus on scenarios regarding climate change, e.g. IMAGE. After establishing an approach, the needed data and relationships between indicators is mapped. This can be done with a boxes-and-arrows scheme, where the drivers and indicators are displayed in boxes, with connecting arrows representing the relationships between indicators. After setting all the values and data on indicators, varying per scenario, the quantitative analysis is produced. The results are a required number of public charging stations in each scenario.

During step i, which is optional, policy options are considered, with the results of the quantitative analysis. For some scenario exercises policies are included in the uncertainties, while for other scenarios there is a lack of policy measures. For the both cases, additional policies are analysed in terms of feasibility, effectiveness and robustness, aimed at arriving at the desired situation. Suitable policies are listed in the policy recommendations in the Discussion section.

The construction of the scenarios involves making assumptions. Therefore, a sensitivity analysis will be performed to determine how the scenarios react on changes in the estimations on the drivers. This is done to test the results of the scenarios.

4. Results

This section presents the results of this research. First, the current situation is analysed in section 4.1. Section 4.2 describes plausible trends in future development of technology and policy. A reference scenario is developed in section 4.3, while the alternative scenarios are elaborated on in section 4.4.

4.1 Current situation

When analysing scenarios for the future, a logical starting point is the development towards the current situation. This section aims at understanding the current situation which is done in four parts. Relevant organisations and actors are introduced in 4.1.1. The numbers on growth of EV sales and charging infrastructure are shown in 4.1.2. Finally, section 4.1.3 describes the policy package which is currently implemented. This is a mix of policies from higher and lower governments.

4.1.1 Organisations and actors

There are many relevant actors in the field of EVs and charging infrastructure. One can think of policy makers, business, NGOs, EV drivers, electricity producers and municipalities. These actors often have conflicting interests, so coming to a long-term agreement on the development of public charging infrastructure can be challenging. Therefore, it is useful to analyse the different actors and their interest in public charging infrastructure, which is done below.

The Ministry of Economic Affairs

The aim of the Ministry of Economic Affairs is to assist the Netherlands in becoming a sustainable and enterprising society. Therefore, the Ministry promotes innovation and growth, to create a healthy business climate and improve the international competitiveness of the Netherlands. Another focus point is the environment. The economic activities should limit stress on nature and the environment. The Ministry helps the Netherlands continuing the front running position in agriculture industry, services and energy, contributing to a powerful and sustainable Netherlands (Rijksoverheid, 2016b). The Ministry and the minister of Economic Affairs, Henk Kamp, are responsible for legislation involving EVs and charging infrastructure on a national level. The interest of the Ministry is to create the right circumstances to stimulate green growth and chances for entrepreneurs in the field of public charging infrastructure.

The Ministry of Infrastructure and the Environment

The ministry of Infrastructure and the Environment is responsible for the accessibility and liveability of the Netherlands. This is achieved by stimulating a smooth traffic flow in a well appointed, clean and safe environment. The ministry improves and maintains a connected network of road, rail, water and airways. Extra attention is given to fit the infrastructure in the landscape, while safe and sustainable use is guaranteed. Other objectives are monitoring and improving air and water quality, and protection against flooding. This is done to ensure a safe and healthy environment.

The ministry develops laws, performs policies and inspects compliance with these laws and policies. This results in the development of a safe, liveable, accessible and competitive delta: the Netherlands (Rijksoverheid, 2016c). The Ministry's contribution in the field of EVs is that it works together with the Ministry of Economic Affairs to develop and implement measures that stimulate the uptake of EVs and charging infrastructure. Its ambition is to stimulate electric mobility, to increase air quality (and consequently liveability), especially in urban areas.

RVO

The Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland) originates from the fusion of Agentschap NL and Dienst Regelingen in 2014. It is a part of the Ministry of Economic Affairs. The Agency works with governments, knowledge centres, international organisations and entrepreneurs. It provides information, communication and advice to encourage entrepreneurs in sustainable, agrarian, innovative and international business. The RVO helps with grants, networking for business partners, knowledge and compliance with laws and regulations. Therefore, RVO helps businesses in providing sustainable ways of transport for their employees, i.e. an EV. RVO publishes information on the numbers on electric mobility in the Netherlands (RVO, 2016a). The interest of the RVO is similar to that of the Ministry of Economic Affairs.

Formula E-team

In 2009, the Dutch government wanted to obtain a front runner role in the field of electric mobility. Therefore, the Formula E-team (FET) was founded with the intention of stimulating the market for electric vehicles; make sure the Netherlands stays in line with developments abroad and to stimulate "Green growth". The FET is a public-private co-operation among business, research institutions and government. Members of the FET are ANWB, BOVAG, Energie-Nederland, and Ministry for Economic Affairs, Ministry for Infrastructure and the Environment, Foundation Natuur&Milieu, RAI, VNG and VNA (Association Dutch Car lease companies). The FET gives advice, provides a useful network, aims at knowledge transfer and supports projects with several working groups (Formula E-team, 2016). The working groups are PHEV, communication, safety, batteries, Light Electric Vehicles (LEV) and consumer market EV.

The FET also contributed to the "Sustainable fuels vision", by helping with the part report "Road transport Sustainable Electric" (Formula E-team, 2016). The "Sustainable fuels vision" and the part report are elaborated on in section 4.1.3. The Formula E-team was also involved in developing several Green Deals, which will also be treated in section 4.1.3.

Finally, the FET stimulates the development of charging infrastructure, by funding placement of charging infrastructure and assisting in certification and examination of new charging stations (Formula E-team, 2016).

Foundation E-laad

The foundation was an initiative from several electricity transmission system operators: Alliander, Cogas, Endinet, Enexis, Stedin and Westland Infra (EVnetNL, 2016). The goal was to facilitate the rollout of public charging stations, while gathering information on charging behaviour. E-laad worked together with approximately 350 Dutch municipalities to install public charging stations. E-laad supplied and installed the chargers for free and took care of maintenance and breakdowns. This resulted in almost 3000 public charging stations in 2014.

However, there were some issues with the involvement of electricity transmission system operators in supplying public charging infrastructure. Since the Dutch state is owner of the electricity transmission system operators, their role excludes commercial activities such as operating public charging infrastructure. Therefore, at the 6th of August 2014, E-laad was divided into two new foundations: ElaadNL and EvnetNL (ElaadNL, 2016). ElaadNL became a knowledge and innovation institute, helping governments and market players in safe and efficient placement of charging infrastructure. ElaadNL takes care of registration and reviewing permits. Another goal of ElaadNL is to stimulate the development of charging infrastructure towards a smaller and cheaper charging station and more efficient regulating. Therefore the National Knowledge platform Charging Infrastructure (NKL) was founded by ElaadNL in 2014. NKL aims to link organisations in the quest to decrease costs for public charging. These efforts should lead to a 40 percent decrease in costs for installing and exploiting public charging infrastructure, with a positive business case in 2018 (NKL, 2016a).

EvnetNL is responsible for management and maintenance of the 3000 currently installed charging stations of E-laad. Furthermore, EvnetNL converts these charging stations to smart charging. Smart charging can help with utilizing the renewable electricity at the moment it is produced. Another advantage of smart charging is peak shaving, reducing the peak demand for electricity, often in the morning and during the evening. EvnetNL allows researchers and market parties to test new technology regarding smart charging (EVnetNL, 2016).

After Elaad was divided, it stopped providing public charging infrastructure to municipalities. From that moment each municipality became responsible for managing and installing new charging infrastructure in their area. New policies were implemented to help municipalities, which are discussed in section 4.1.3.

Another relevant actor is the electricity transmission system operator, TenneT. It is responsible for the construction and maintenance of the high-voltage, 110 kV and higher, electricity system that is used to transport electricity. TenneT ensures that the supply and demand are in balance continuously, to prevent power outages. Finally, TenneT facilitates the electricity market and supports the inclusion of large scale renewable electricity into the grid. The high-voltage grid is linked to regional distribution grids, which are operated by smaller distribution system operators. Stedin is such an operator. Stedin transports electricity from the grid to consumers. It maintains the low- and medium-voltage grid and connects houses to this grid. The main interest of the transmission and distribution system operators is to balance the grid. With an increasing share of EVs, charging demand could lead to higher peaks in demand, requiring major investments from the operators to ensure net balance.

Other relevant actors are the suppliers of charging infrastructure and the suppliers of electricity at those charging stations. A supplier of charging infrastructure is called a Charge Point Operator (CPO). It takes care of supply, installation and maintenance of charging stations. An example of a CPO is Allego. The supplier of electricity to the owner of the EV is called a Mobility Service Provider (MSP). The MSP sells a mobility service: it provides a card to identify yourself at a charging station. The CPO charges the MSP for the electricity provided to the consumer. The MSP charges the consumer with for the electricity provided. The market model behind this is explained in 4.1.3. The interests of these actors focus on a positive business case for public charging infrastructure, to ensure sufficient profits.

4.1.2 Numbers

This section analyses the growth of EVs and charging infrastructure in the Netherlands so far. This is useful in determining the starting point for the scenario exercise. The amount of EVs and public charging infrastructure is displayed, combined with information on important characteristics of the system and its components, i.e. properties of an EV. The distribution of public charging infrastructure over the country is also discussed.

The RVO publishes data on the number of EVs and charging stations in the Netherlands (RVO, 2016a). The data distinguishes Battery Electric Vehicles (BEVs) from Plug-in Hybrid Electric Vehicles (PHEVs). The drivetrain of a BEV consists of an electric motor which is powered by a battery. The main advantage of a BEV is that it always drives with zero tailgate emissions, which is beneficial for local air quality. Furthermore, the electric drivetrain is more energy efficient then a combustion engine drivetrain, since it has less moving parts and wastes less energy that is converted into heat instead of power.

A PHEV is a hybrid car with a conventional internal combustion engine and an electric engine. Plug-in technology means that the car can be connected to the electricity grid to charge the battery. The battery is relatively small, so the electric range of a PHEV tends to be rather small, less than 50 kilometres. A PHEV can be seen as a compromise between sustainability and ease of use: The electrical drivetrain can be used for short trips, while it can assist the combustion engine on longer trips, improving overall fuel efficiency of the car. A PHEV tackles the main disadvantages of a BEV, since the conventional drivetrain ensures increased range and quick refuelling. However, the combustion engine also increases emissions and decreases energy efficiency of the vehicle.

Table 1 shows the data on the amount of BEVs and PHEVs in the Netherlands from 2009 to 2016. It can be seen that 2011 was the first year that PHEVs became available in the Netherlands, combined with a larger increase in the amount of BEVs. In 2012 the number of PHEVs surpassed that of BEVs.

Table 1. The amount of EVs in the Netherlands from 2009 to 2016 (RVO, 2016a)

Type	dec-09	dec-10	dec-11	dec-12	dec-13	dec-14	dec-15	okt-16
BEV	146	266	1124	1910	4161	6825	9368	11986
PHEV	0	0	17	4348	24512	36937	78163	84730
Total	146	266	1141	6258	28673	43762	87531	96716

The data is converted into a graph, see figure 5. The graph displays the growth trend of BEVs and PHEVs. The amount of BEVs grows almost linearly over the years, while the growth of number of PHEVs is more similar to exponential growth. Therefore, the total number of PHEVs is approximately 7 times larger than the total number of BEVs in October 2016.

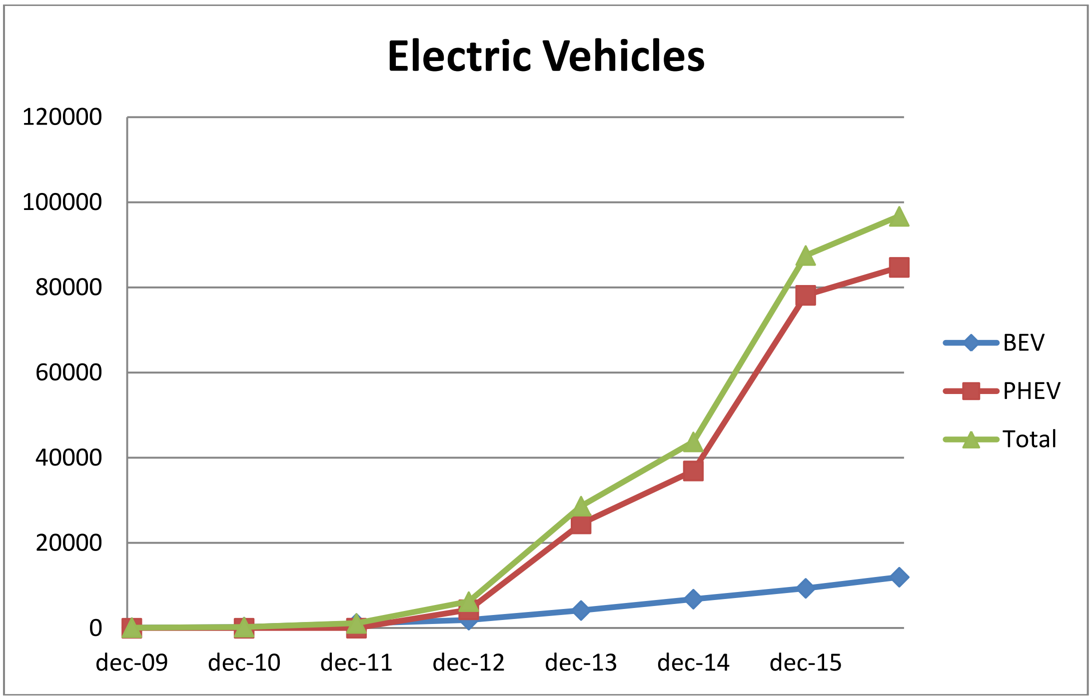


Figure 5. The amount of EVs in the Netherlands from December 2009 to October 2016 (RVO, 2016a)

The total number of passenger vehicles is approximately 8.1 million on January 1st 2016 (CBS Statline, 2016b). This means that the number of EVs is only 1.08 percent of total passenger vehicles in the Netherlands in January 2016. The share of BEVs was only 0.12 percent. Therefore, both total EV adoption and BEV adoption fit in the innovators category in Rogers diffusion of innovation, which is the first 2.5 percent of the market (Rogers, 1995).

Statistics on specific car models are also published by RVO (2016). Table 2 lists the five most popular BEVs by October 2016. Over one in two BEVs in the Netherlands is currently a Tesla model S: 5622 out of 11986. A possible explanation can be that the Tesla has a larger range compared to other BEVs, which will be elaborated on in section 4.2.

Table 2. The five most popular Battery Electric Vehicles by October 2016 in the Netherlands (RVO, 2016a)

Model	Number
Tesla Model S	5622
Nissan Leaf	1614
Renault Zoë	1325
BMW i3	814
Smart ForTwo	477

Additionally, the five most popular PHEVs are listed in table 3. Almost 30 percent of all PHEV in the Netherlands is a Mitsubishi Outlander PHEV. Another 15 percent is the Volvo V60 Plug-in Hybrid. These cars are rather large: The Mitsubishi is a SUV, almost 5 metres long and 1,8 metres wide, weighing 1820 kilograms (Mitsubishi Motors, 2016). The Volvo is a station wagon model, weighing

1880 kilograms. The Volvo is 4,6 metres long and 1,9 metres wide (Volvo cars, 2016). The consequences of these large dimensions for fuel efficiency are analysed in section 4.2.

Table 3. The five most popular Plug-In Hybrid Electric Vehicles by October 2016 in the Netherlands (RVO, 2016a)

Model	Number
Mitsubishi Outlander PHEV	24765
Volvo V60 Plug-in Hybrid	14917
Volkswagen Golf	9530
Audi A3 Sportback e-tron	5098
Mercedes Benz C 350 E	4986

RVO also distributes data on charging infrastructure (RVO, 2016a). Figure 6 displays the amount of public charging infrastructure installed in the Netherlands. The infrastructure is divided in public charging infrastructure, semi-public charging infrastructure and fast charging infrastructure. Public charging infrastructure is situated on public ground and is accessible 24/7. The infrastructure is installed with public money. An example is a charging station at a parking spot in public space.

Semi-public charging infrastructure is privately installed on private property. However, the charging infrastructure is publicly accessible. An example is a charging station at the parking lot of a company, or at a multi-story car park location, i.e. a park and ride (P+R). Fast charging infrastructure is a different category since the technology is different from conventional charging. The technological differences will be analysed in section 4.2. The RVO also analysed the amount of private charging stations in the Netherlands, it estimated that there were 55,000 private chargers installed in December 2015.

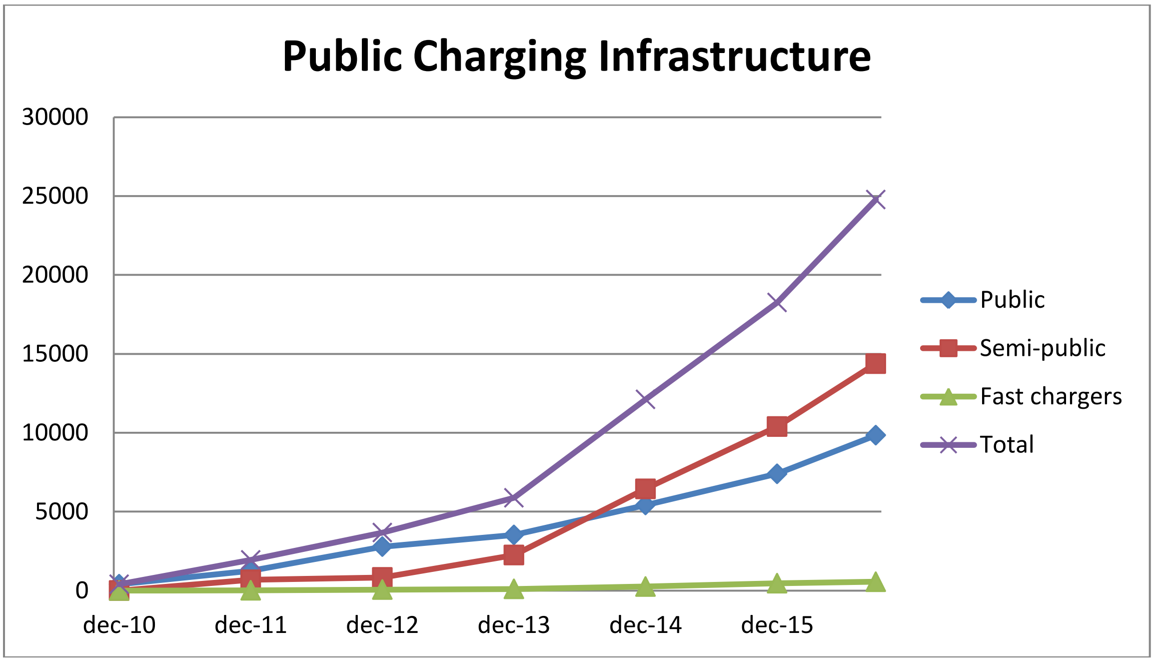
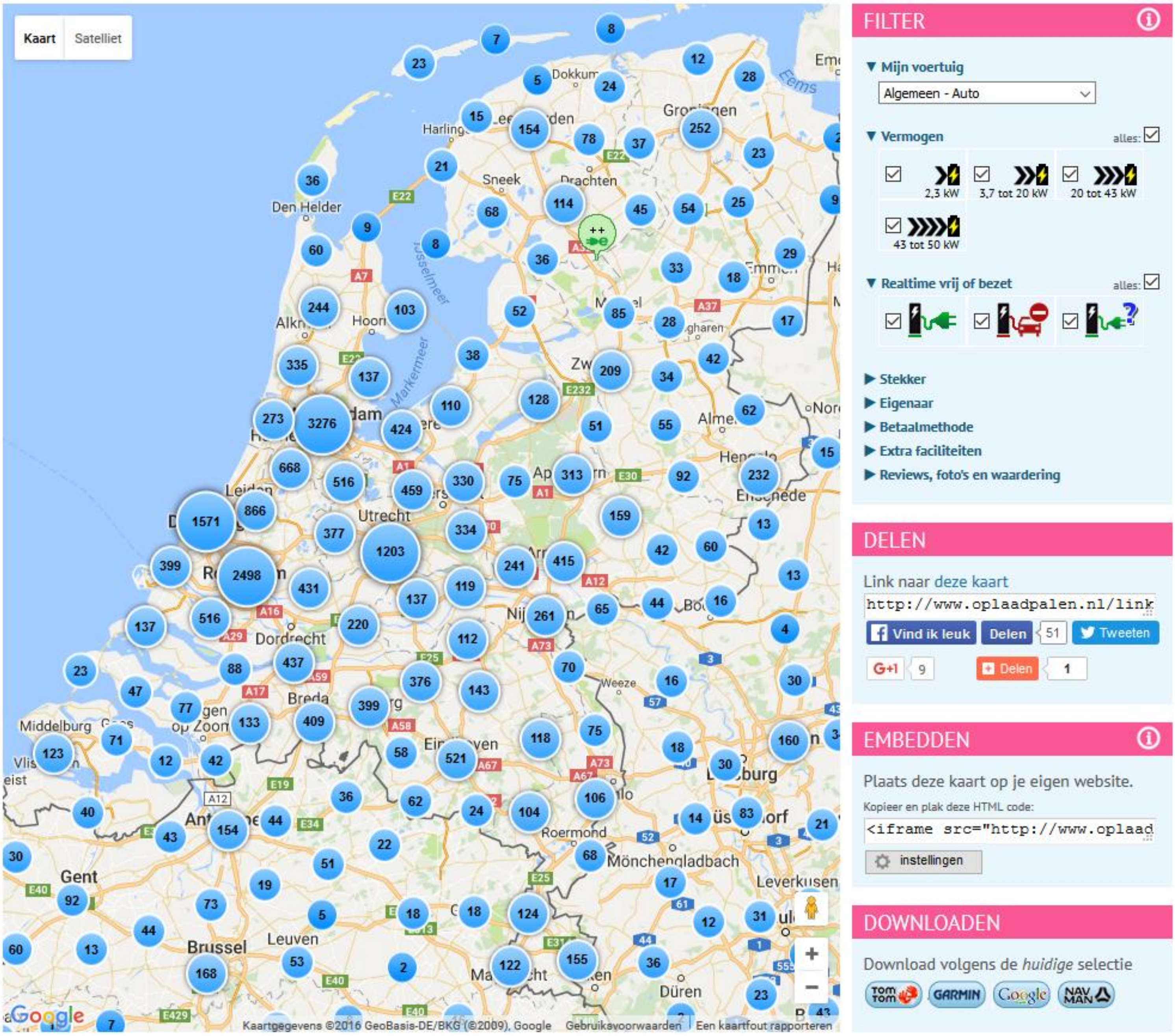


Figure 6. The amount of public charging infrastructure in the Netherlands from December 2010 to September 2016 (RVO, 2016a)

The website oplaadpalen.nl provides an overview of the geographical distribution of public charging infrastructure (figure 7). The web site was launched in 2012 to provide real-time information on the location of available public charging stations. Another feature is to search for the closest charger near your destination. Noteworthy is the high concentration of charging infrastructure in the four large cities in the ‘Randstad’: Amsterdam, Rotterdam, The Hague and Utrecht. This is likely to be caused by a higher population density in this area: Public charging infrastructure is placed where demand for charging is relatively high.



Link naar deze kaart

http://www.oplaadpalen.nl/link

Plaats deze kaart op je eigen website.

Kopieer en plak deze HTML code:

<iframe src="http://www.oplaad

Download volgens de *huidige* selectie

Figure 7. Screenshot of the web site oplaadpalen.nl

4.1.3 Policies in place

This section explores the various policies regarding charging and charging infrastructure. First overarching policies on mobility and EVs are analysed. Furthermore, national charging infrastructure policies are discussed. After that, a few local policies on charging infrastructure, implemented by municipalities, are highlighted.

Energy agreement

The Energy agreement for sustainable growth was implemented in 2013. The plan involved a large coalition of stakeholders with different backgrounds in government, business and NGO. A few parties are Rijksoverheid, Natuur&Milieu, Greenpeace, NS, ANWB, FNV and MKB Nederland.

The Energy agreement provides the basis for future proof, sustainable energy and climate policy. The plan has a long term perspective, but it also includes short term agreements and goals. The main goals of the Energy agreement are (Sociaal-Economische Raad, 2013):

-Reducing final energy use with 1.5 percent per year, with an intermediate goal of 100 Petajoule energy savings by 2020.

-Increase the share of renewable energy technologies to 14 percent in 2020 and 16 percent in 2023.

-Create at least 15,000 full time jobs

The Energy agreement is divided in plans for 10 pillars. This is done to include all important disciplines and stakeholders. One of those pillars is mobility and transport. The aim of the pillar is to increase efficiency and sustainability in mobility and transport. The aim is translated in several concrete goals (Sociaal-Economische Raad, 2013):

-A reduction in CO_2 emissions of 60 percent in 2050 relative to 1990 levels. An intermediate goal is a reduction of 25 Mtonne CO_2 in 2030, which equals a 17 percent reduction compared to 1990. Alongside a reduction in CO_2 emissions, other adverse environmental pressures will be reduced where possible.

-The coalition develops a vision on sustainable fuels for transport. The vision will result in an effective, efficient use of available fuels. This depends on availability, emission reduction potential, alternatives for each modality.

Action plan ‘Electric mobility gets up to speed’

Even before the Energy agreement was worked out, the Dutch government stimulated the uptake of electrical vehicles. The action plan ‘Electric mobility gets up to speed’ was implemented in 2011. The aim of the action plan was to achieve 200,000 EVs on the road in 2020, followed by 1 million in 2015. Conditions for this growth are sufficient charging infrastructure, a competitive market and good safety measures. The effect of 200,000 EVs will be an energy saving of 0.5 PJ, a reduction in CO_2

emissions of 0.5 Mtonne, improving urban air quality by reducing NO_x and particulate matter and energy security through less dependence on fossil fuel imports (Rijksoverheid, 2011). The action plan consists of three pillars. The first one is to concentrate on focus areas. Electric mobility is stimulated in areas where it is most promising, i.e. in cities with local air quality issues or places with links to research. The idea is to create a snowball effect: Other regions will follow after successful implementation in the focus areas. The focus areas are region Amsterdam, region Rotterdam, Utrecht and the provinces of Brabant and Friesland. Other regions with interesting experiments are supported, i.e. region Arnhem/Nijmegen (Rijksoverheid, 2011). Common features of the focus areas are the ambition towards a certain number of EVs and the stimulation the rollout of charging infrastructure. The second pillar is the stimulation of promising market segments. Since Electric mobility is not attractive for everyone, the action plan focuses on promising market segments to achieve a positive business case in these segments in terms of Total Costs of Ownership of the vehicle. An example is a vehicle with a high yearly mileage, since EVs have high investment costs and low costs per kilometre. Another segment is vehicles for companies with affinity for Sustainable Entrepreneurship. This could be companies in logistics and distribution, business commuting, public transport and company and governmental vehicles. The third pillar is the stimulation of earning potential of electric mobility. Electric mobility can contribute to sustainable economic growth. Supporting Dutch businesses and research institutes will improve their competitive position, leading to an impulse for employment and increased sales.

The main instrument in the action plan for stimulating the sales of EVs in the Netherlands is fiscal measures. These measures will incentivize citizens to choose for an EV. Tax addition for business vehicles with a CO_2 emission lower than 50 grams per kilometre is set to 0 percent. This limit ensures that only BEVs and PHEVs are eligible for this 0 percent rate. The yearly road tax exemption is continued until 2016 for efficient vehicles with an emission below 50 grams per kilometre. The exemption from a purchase tax is tightened to vehicles with an emission below 83 grams per kilometre, so BEVs and PHEVs are eligible for the exemption until 2018 (Rijksoverheid, 2011).

Other results of the action plan are the development of a market model for charging an electric vehicle, research on the possibilities of smart charging to ensure power grid balance and increasing cooperation in the EU. The market model is described below. It needs to ensure the availability of charging infrastructure and create a competitive market. Both are required for the large scale rollout of EVs (Rijksoverheid, 2011). The government's vision on charging infrastructure is that its rollout follows the rollout of EVs. In the focus areas the rollout of charging infrastructure will go ahead of the rollout of EVs, to prevent the chicken or the egg problem. Additionally, charging infrastructure will be placed on private and public space, with a large role for public charging, since almost 70 percent of Dutch citizens parks on a public car park. Promising new charging techniques will be tested, i.e. fast charging, induction charging and battery swap. The policies in the action plan are implemented in the period 2011 to 2015. After that, the policies are evaluated (Rijksoverheid, 2011).

Sustainable fuels vision

As planned in the Energy agreement, in June 2014 the Sustainable fuels vision was presented. The authors describe the vision as an ambitious but realistic future for the Netherlands, which will make the Netherlands a front runner in sustainable mobility (Ministerie van Infrastructuur en Milieu, 2014). The Sustainable fuels vision describes the potential of sustainable fuels in CO_2 emission, improving the local environment and achieving green growth. The vision is shared by the stakeholders involved in the Energy agreement, divided in several 'tables': liquid fuels, gaseous fuels, electric, hydrogen, shipping, aviation and green growth. This research will focus on the part report on electric drivetrains, since for passenger vehicles, the most suitable fuels in 2050 will be electric and hydrogen. The desired 60 percent CO_2 reduction in 2050 will not be achieved without the implementation of EVs, since battery-powered EVs are the most energy-efficient type of mobility (Ministerie van Infrastructuur en Milieu, 2014). Another advantage is that the energy carriers for electric and hydrogen drivetrains can be obtained sustainably by utilizing solar and wind energy. Electric drivetrains also contribute to improving local air quality, especially in urban areas. A final reason for promoting electric drivetrains in passenger transport is that the availability of sustainable biomass for biofuels and renewable gas may be limited, due to competition with other sectors. Therefore, the main statement of the authors is a vision of the future where passenger vehicles are equipped with an electric or hydrogen powered drivetrain. The liquid and gaseous (bio)fuels are reserved for transport modalities which cannot benefit from these two techniques, i.e. aviation, logistics and shipping (Ministerie van Infrastructuur en Milieu, 2014).

According to the authors of the Sustainable fuels vision, there will be approximately 700,000 BEVs and 1,570,000 PHEVs in the Netherlands in 2030. This will increase to 7,700,000 BEVs and 3,000,000 PHEVs in 2050. There are however a few barriers that need to be addressed. The main barriers are insufficient battery capacity, which leads to low range, insufficient public charging infrastructure, costs of an EV and behaviour. The authors propose to offset the public charging infrastructure barrier by a set of Green Deals, to reduce the investment costs and stimulate a positive business case for public charging infrastructure. It is expected that this will be the case in 2018 and market parties will install sufficient public charging infrastructure after that period. Another measure could be the implementation of a 'right to a charging point'. This means that each EV driver can demand a public charging point at reasonable distance from his house. This will increase demand for an EV for people with no private parking spot. A well developed network of fast charging stations can help reducing range anxiety in EV drivers. This will be developed simultaneously to the conventional charging infrastructure (De Tafel Wegvervoer Duurzaam Elektrisch, 2014).

The measures proposed in the Sustainable fuels vision regarding EVs range from 2015 to 2030.

Market model and charging technique

In 2012, the Dutch government implemented a market model for supplying and paying for electricity from public charging infrastructure (Agentschap NL, 2012). This involves several types of businesses, i.e. energy companies. Two key affairs are standardised: Interoperability and the ability to charge the consumer for the electricity provided.

Interoperability guarantees the ability of an EV owner to charge at any charger, regardless of the chargers location, the type of EV and the charging infrastructure provider. The Netherlands is the only country in the world where operability is guaranteed at a national level. The Open Charge Point Interface (OCPI) provides consumers and business with a way to transfer data easily. It contains information on charger specifications, charger availability and charging costs (NKL, 2016b).

The market model is shown in figure 8. The transaction start at the consumer (left top of the figure). A consumer can identify itself with a card to start the charging procedure. The card is provided by the Mobility Service Provider (MSP, left bottom in the figure). A MSP administrates the identity of the charging EV and amount of electricity transferred. Usually, the consumer pays the MSP for the electricity provided, combined with a small fee for the identification card. Since each EV owner has only one identification card, they only have one MSP. The interoperability principle guarantees that the EV owner can charge at any charging station with their identification card (Agentschap NL, 2012).

The infra provider (right bottom in the figure) is responsible for the supply and installation of a charging station. It is also responsible for the maintenance of the charging stations. The Charge Point Operator (CPO, right top in the figure) ensures that the charging station is available and ready to supply electricity. The CPO charges the MSP for the electricity supplied by its charging infrastructure. This is done for each charging station and for each Charge Point Operator where a consumer uses a charging station. The MSP receives an overview where and how much the consumer charged. The MSP combines these charging sessions and chargers the consumer (Agentschap NL, 2012).

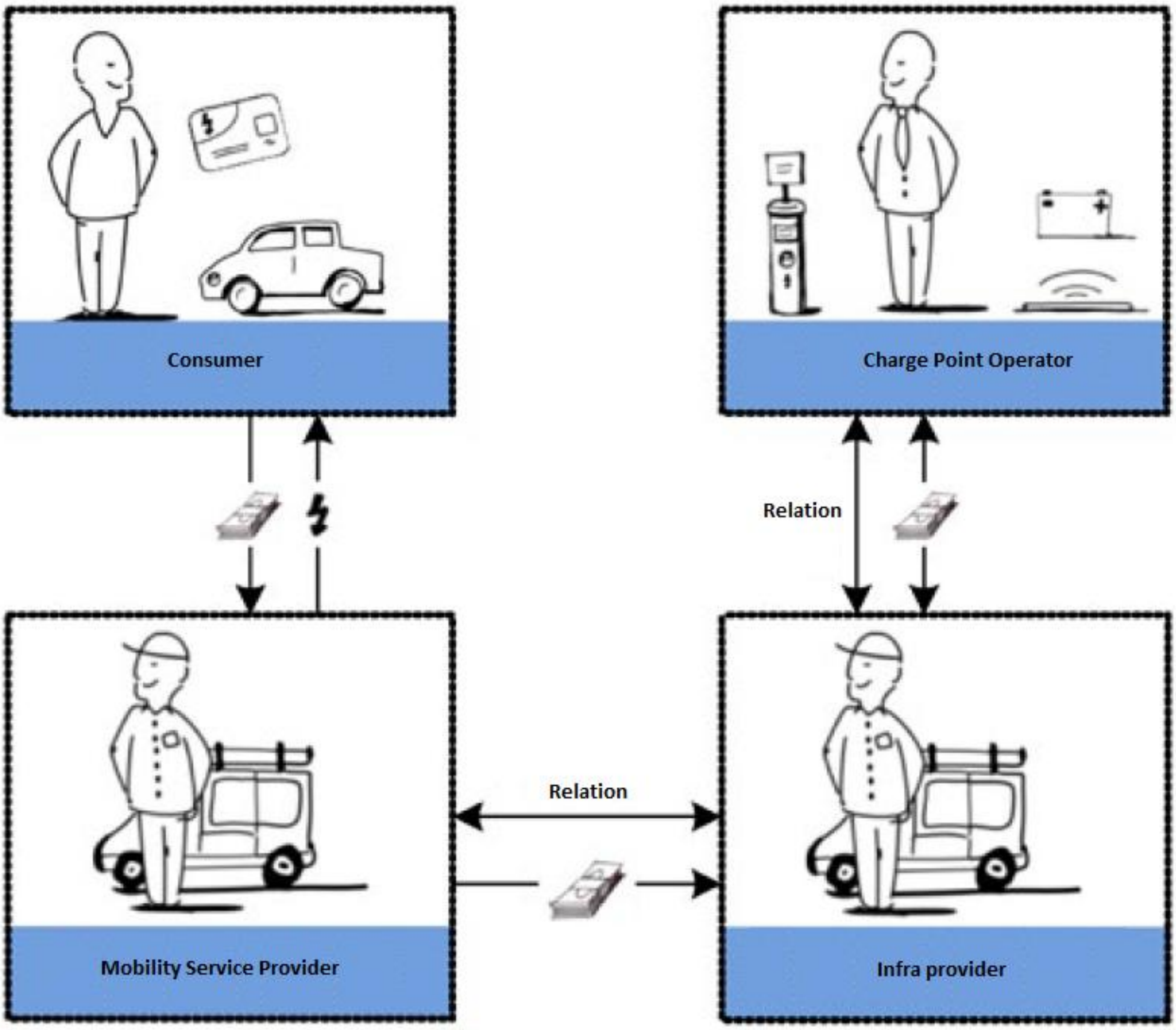


Figure 8. The market model for public charging in the Netherlands

The market model with separation of charging infrastructure and electricity supply provides freedom of choice for consumers in choosing the origin and costs of the electricity used to charge their car. It provides a level playing field for suppliers, since it guarantees open access to the infrastructure and data. This leads to more competition, increasing the quality of charging services.

Charging technique is also standardised. There are four modes of charging mode 1 to 4. Charging can be done with alternating current (AC) and direct current (DC). Mode 1 is charging from a regular socket with 220-230 Volts AC current and a maximum of 10 Amperes. This results in a maximum charging power of 230 V * 10 A = 2300 W = 2.3 kW (Nederland Elektrisch, 2016). Mode 2 is charging with a current limiter, often incorporated in the charging cable. Mode 2 can utilize single phase as well as 3-phase AC current. This results in a maximum charging power of 230 V * 16 A = 3.7 kW for single phase current and 230 V * 32 A * 3 phases = 22 kW (eMAP, 2015). Mode 3 is called controlled charging. The car communicates with the charger and a suitable charging power is set before charging. Similar to mode 2, mode 3 is compliant with single phase and 3-phase AC current. Maximum charging power is 230 V * 16 A = 3.7 kW for single phase current and 230 V * 63 A * 3 =

43.6 kW (eMAP, 2015). For mode 1 to 3 the conversion from AC current from the grid to DC current to the battery is done by an onboard converter in the car (Nederland Elektrisch, 2016). Mode 4 is charging with direct current. The fast charger utilizes its own converter to convert the AC current from the electricity grid to direct current. It connects directly to the car battery, without interference from the car: The charger controls the charging process (Nederland Elektrisch, 2016). Maximum mode 4 charging power is typically 50 kW or more, but it depends on the charging infrastructure and grid connection.

Besides the four charging modes, several different connectors exist. A connector connects the car to the charging station. Connector type 1 is a standard Schuko power plug. This connector is used with charging mode 1. Type 2 is called a Mennekes plug. Since it is capable of charging single phase current and 3-phase current, it is compatible with mode 2 and 3 charging. The type 2 connector is set as the standard for AC charging in the Netherlands, combined with charging mode 3 (Nederland Elektrisch, 2016). Type 1 and 2 connectors are shown in figure 9.

Figure 9. A type 1 Schuko connector (left) and a type 2 Mennekes connector (right)

DC fast charging also uses multiple types of connectors. The CHAdeMO plug was developed in Japan by Japanese car manufacturers. The maximum charging power of a CHAdeMO plug is 500 V * 125 A = 62.5 kW (Kane, 2016). The Tesla supercharger only works with Tesla cars and is capable of charging at 120 kW (Kane, 2016). The combo CCS type connector was developed by CharIN e.V., an initiative of a coalition of car manufacturers and other parties involved in charging infrastructure. The CCS connector is capable of charging both AC and DC current. AC charging is done with a type 2 Mennekes compatible plug, at a maximum of 43 kW, while DC charging can be done with up to 107 kW: 850 V * 125 A (CharIN e.v., 2016). The CHAdeMO and Combo CCS connectors are shown in figure 10.

Figure 10. A CHAdeMO type connector (left) and a Combo CCS type connector (right)

An overview of the combination of charging modes and connector types is given in figure 11(eMAP, 2015).

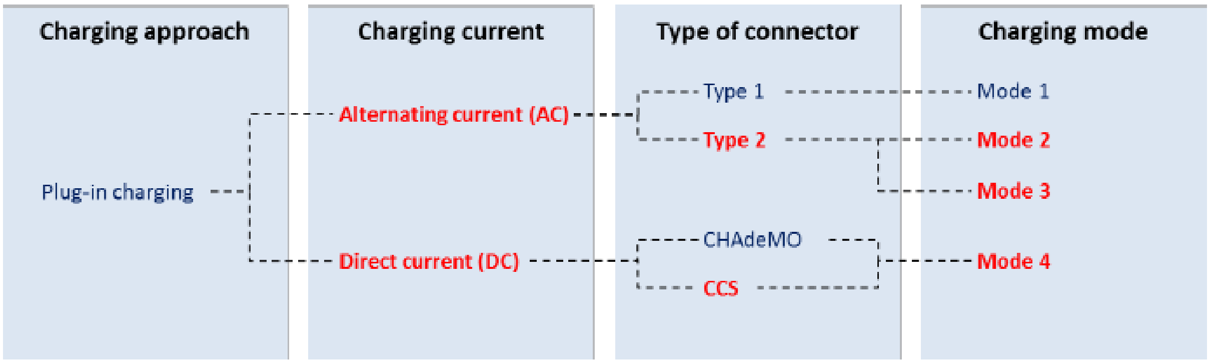


Figure 11. An overview of the combination of charging modes and connector types (eMAP, 2015)

Green Deals

The Netherlands implemented several Green Deals to stimulate the development of public charging infrastructure. A Green Deal is an agreement between the government and other stakeholders to reduce barriers for successful implementation of a sustainable initiative. Common areas for Green Deals are energy, climate, water, resources, biodiversity, mobility, building and food (Rijksoverheid, 2016a). The government can adjust law and regulations, for instance to reduce bureaucracy. The government can also bring relevant actors together to mediate in negotiations and help explore new markets by implementing supporting regulations.

The first Green Deal on charging infrastructure is implemented in 2011. The Green Deal electric mobility was an agreement between the government, car sector organisations, NGOs and lower governments (RVO, 2016b). The deal ensured the continuation of the Formule E-team, stimulation of EV sales, development of the focus areas and the realisation of a public charging network. The government provided sufficient freedom for start ups on charging infrastructure coupled to smart grid applications. Another result was the removal of barriers in law and regulations for permits for parking, charging infrastructure and environmental zones with limited access. This Green Deal fits in with the action plan from 2011.

The next Green Deal was the Green Deal infrastructure for electric mobility in 2011. The New Motion, in cooperation with car manufacturers, Alliander, foundation E-laad and several Ministries signed the deal with the aim to develop a large scale, intelligent public charging network for EVs (RVO, 2016b). This network would provide a charging service, combined with the ability to balance the grid with smart charging and supply. The New Motion installed 15,000 public, semi-public and private charging stations. The government stressed the importance adequate authorisation of public charging infrastructure to municipalities. This resulted in brochures for municipalities in 2012 and 2013. The first brochure informed on the necessity of stimulating EVs on a municipal level and provided general information on EVs and charging infrastructure. It contains suggestions for pathways for a municipality to get started with EVs (Agentschap NL, 2012). The second brochure focuses on solutions for municipalities to incorporate charging infrastructure in public space. It specified the solutions for charging in different situations. In the case of self-sufficient EV drivers, who park on private terrain and charge with a private charger, little involvement in required. A subsidy on the charging station can be considered. In the case an EV driver parks on a public parking space but charges with a private charger, involvement is limited to setting up a suitable parking policy and a potential subsidy on the charging station. The final case requires more municipal involvement: Public parking combined with public charging. The municipality can supply and maintenance the charging station and implement the market model for public charging (Agentschap NL, 2013).

The Green Deal publicly accessible electric charging infrastructure from 2015 involved grid operators, ElaadNL and EvnetNL, National Knowledge Platform Charging Infrastructure (NKL), VNG and several governmental bodies. They deemed is necessary to extend the development of charging infrastructure, to stimulate sales of EVs. However, charging infrastructure supply and maintained is not cost effective yet. Therefore, the national government supplies € 5.7 million to municipalities for the realisation of public charging infrastructure, with a maximum of € 900 per station in the first year, € 600 in the second year and € 300 in the final year (RVO, 2016b). The subsidy is only available if municipalities also contribute on average € 500 per station and if at least ten charging stations are installed. Additionally the agreement aims at reducing costs for charging infrastructure by 2017 with 70 percent compared to 2013. This is done by increasing knowledge and innovation. The National Knowledge Platform Charging Infrastructure (NKL) is a result of that ambition. The lower costs should lead to a positive business case for public charging infrastructure.

In December 2016, the Dutch minister of Economic Affairs, Henk Kamp, increased the funding with 1.5 million euros to facilitate the installation of an additional 3,000 public charging stations (ANP, 2016). This is done to stimulate the uptake of EVs in the Netherlands, since the Minister believes that the number of charging stations and their location are important conditions for consumers in purchasing an EV (Kamp, 2016). Research showed that a purchase subsidy and other stimulation policies would mostly benefit consumers who would also purchase an EV without these policies. Therefore, the Minister identifies that the best long term growth strategy for EVs lies in increasing the number of sustainable vehicles in European car production and the development of a public charging infrastructure network (Kamp, 2016).

The Green Deal Electric Mobility 2016-2020 was signed in 2016. It aims extend the front runner role of the Netherlands and to bundle the activities on EVs until 2020 so that after that time the market has matured and needs no further support to grow. This includes developing a consumer market, next to the business market which occurs currently, improving charging infrastructure, initiate Living Labs for smart charging and electricity storage in EVs. This should lead to a share of 50 percent EVs in newly sold passenger cars in 2025, of which 30 percent of newly sold cars BEV. Before 2020 10 percent of newly sold passenger vehicles should have an electric drivetrain, so that in 2020 75,000 individuals drive an EV, including 50,000 second hand EVs. The national government aims at reducing the uncertainty on the market for public charging (RVO, 2016b).

Other policies

The final national policy concerns fast charging stations in service areas along the motorways. The Dutch government first assumed that fast charging stations could be incorporated into existing gas stations and restaurants. This would be the easiest solution, since these already operate service areas. However, interest was low, due to the limited amount of EVs. So the government allowed new market players to bid on a concession for fast charging stations by changing the policy at 20th of December 2011 (Fastned, 2015). The Netherlands became the first European country to develop a nationwide fast charging network. Six new parties gained concessions to supply electricity at 249 service areas for a total of 459 connections. A major player is Fastned with 55 stations spread all over the country.

Besides the national government, local governments also implemented policies and set up ambitions on electric mobility. The region Amsterdam works together in Metropole Region Amsterdam Electric (MRA Electric) to expand the charging network and stimulate EV sales, by cooperation and knowledge sharing between governments and businesses (MRA Electric, 2016). MRA Electric organised a public procurement for charging stations. All municipalities in the region could join the procurement. A market player installs, maintains and exploits the charging stations. The regional governments contributed financially to the procurement, since the business case was negative. The national government, the EU and market parties invested. Therefore, individual municipalities were charged only € 1000 per charging station.

The municipality of Utrecht set up an action plan on Sustainable Transport (Gemeente Utrecht, 2015). It aims at improving the sustainability of all transport. An important point is increasing electric mobility. Therefore, Utrecht stimulates EVs for light and heavy transport, expand the public charging infrastructure network, improving efficient use of this charging network and incentivise private charging points at businesses and citizens. Utrecht aims at the realisation of 400 pubic charging stations in 2020 (Gemeente Utrecht, 2015).

Another large municipality, Rotterdam, wrote a report on the placement of public charging infrastructure (Gemeente Rotterdam, 2015). Rotterdam changes its role from stimulating to facilitating the expansion of public charging infrastructure. Therefore, earlier subsidy measures are removed. A limited budget remains for compensating the financial gap in a procurement that is expected to remain until 2018. This also means a shift to installing demand driven infrastructure: EV owners can apply for a public charging station in their area when there are no alternatives in a 250 metre radius and the expected charging demand is over 2000 kWh per year (Gemeente Rotterdam, 2015). Another measure is the introduction of a rate for parking on a charging spot, regardless whether the car is charging or not. This is done to stimulate owners to remove their car when the battery is fully charged. Finally, Rotterdam analyses the possibility to install ‘charging squares’, with a high density of chargers, where charging demand is high and growing.

Summarising, public charging infrastructure is not profitable in the current situation. The market model guarantees optimal freedom of choice for consumers, but governments often aid market parties by subsidising the financial gap in the procurement. A reason for the negative business case for public charging is that the share of EVs is only 1.04 percent. A large portion consists of PHEVs, which require limited charging. The share of BEVs is only 0.12 percent. Therefore, EV technology falls in the innovator category in the theory of diffusion of innovations from Rogers.

The government set up several Green Deals to stimulate the development of public charging infrastructure and reducing the installation costs, aiming to achieve a positive business case for public charging in the future.

There are many different actors involved in the field of EVs and charging infrastructure. These actors often have different interests. EV owners want to charge their vehicle with high power so the battery is charged quickly, while electricity grid operators strive for a low electricity demand peak. The federal government wants an abundant network of public charging infrastructure to stimulate the rollout of EVs, while local governments, such as municipalities, which are responsible for the layout of municipal public space, often want as few objects in public space as possible. However, some municipalities have additional policies in place, i.e. Utrecht and Rotterdam.

4.2 Future developments

This section maps expected future developments in the field of EVs and charging infrastructure. Suitable indicators are identified in section 4.2.1 to analyse the current EV and charging infrastructure system. This is done to get an idea of the technological state of the system and explore areas where future development may take place.

Technological advancements are discussed in section 4.2.2. This includes changes in battery technology (range) and charging technology. Possible new policies are discussed in section 4.2.3. The critical uncertainties in the future developments are identified in section 4.2.4.

4.2.1 Indicators

The various indicators used to describe the technological state of EVs and charging infrastructure are described here. An indicator is a variable that represents the state or quantity of something. In this research, indicators are used to quantify important components of the EV and charging infrastructure system. These indicators are car ownership, mileage, energy efficiency, battery capacity and charging power.

Car ownership is measured by the number of electric vehicles in the Netherlands. Several drivers are influential when analysing this indicator: The total population, the state of the economy, the level of governance and technological progress. A larger population, with the same lifestyle, will increase the demand for mobility, leading to an increase in vehicles on the road. Since part of this increase will consist of EVs, the number of EVs in the Netherlands will increase with increasing population (with a constant lifestyle). With a growing economy, the demand for mobility increases, therefore the number of EVs increases. The government can increase demand for an electric vehicle with strategically policy packages. Technological progress can decrease costs of an EV, increasing demand.

Mileage is measured by the indicator kilometres per vehicle per day. This equals the average daily mileage of a Dutch passenger car. This indicator depends on the state of the economy and level of governance. A growing economy increases demand for mobility, increasing the average kilometres per vehicle per year. Road taxes can increase the costs of mobility, thereby reducing demand for mobility, reducing the average kilometres per vehicle per year.

Energy efficiency is expressed as the fuel input divided by the useful output. In the case of an EV, this is represented by the amount of kWh used per km driven: kWh / km. This mainly depends on the efficiency of the electric drivetrain and overall car technology.

The battery capacity is mainly determined by the specific energy of the battery cells. It is expressed in terms of the amount of energy per kilogramme of battery cell weight: kWh / kg. It depends on the battery technology implemented. The total battery capacity (in kWh) is defined as the specific energy of the battery material times the total weight of the battery material (kWh / kg) * kg. Currently, EV batteries consist of Lithium-ion cells, while this technology might be replaced by a new technology with higher specific energy.

Charging power is represented by the maximum amount of electricity that an onboard converter or fast charging station can put in the battery. Power is expressed in W, although kW is more convenient for the high power levels used for EV charging. The power depends on technology and governance. The technology inside the vehicle and the charging technology determine the maximum charging power, while government legislation can require a certain power level to be standardised.

The charging infrastructure system is displayed as a boxes and arrows diagram in figure 12. The relations between the indicators and the effects on charging infrastructure are displayed.

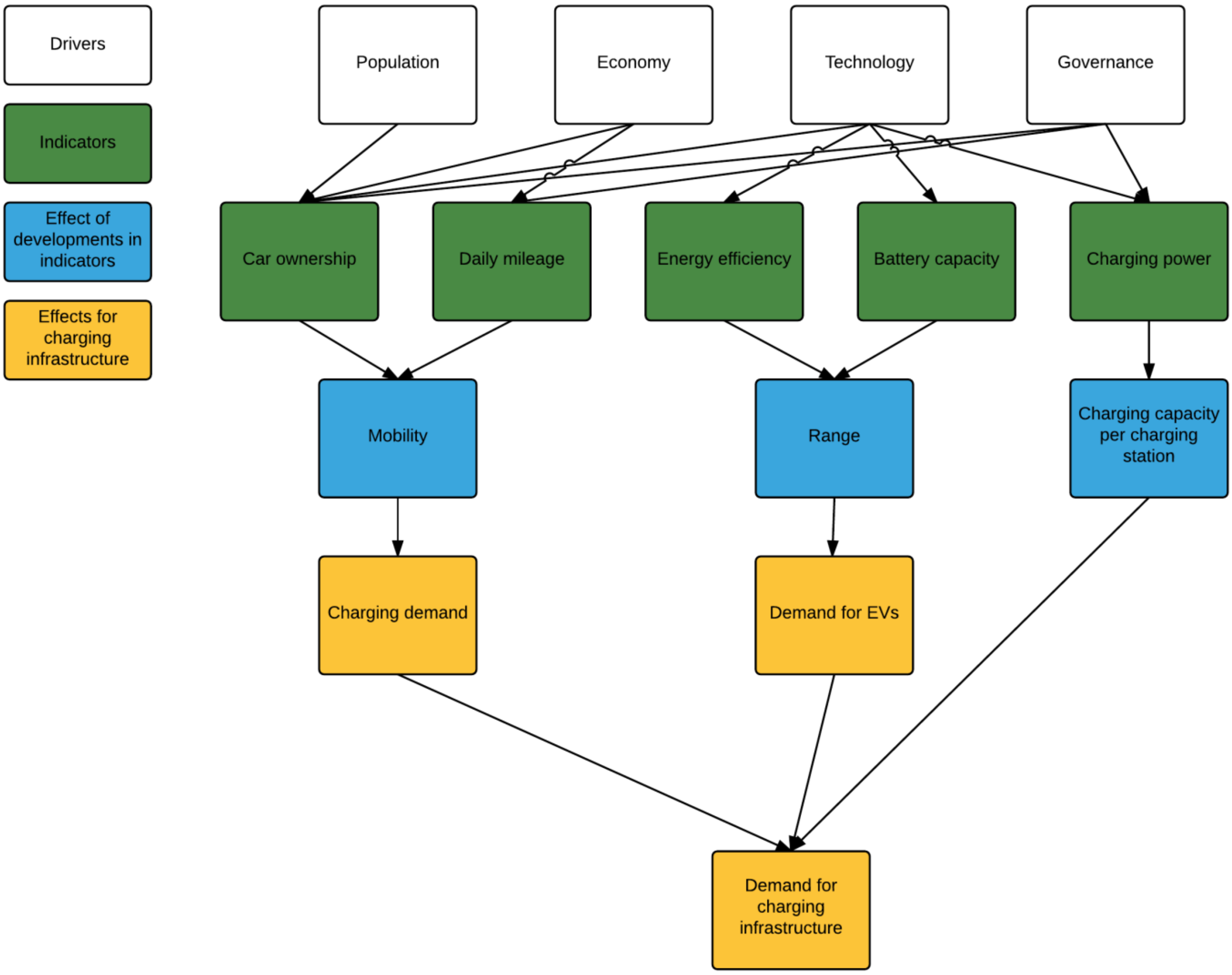


Figure 12.The boxes and arrows diagram for the charging infrastructure system

4.2.2 Technology

This section explores technological developments regarding energy efficiency, battery technology and charging technology. For battery technology, a distinction is made between current lithium-ion battery cells and future designs regarding lithium-sulphur and lithium-air.

Energy efficiency

The energy efficiency of the BEV drivetrain is expressed as the efficiency of the electric motor * the efficiency of the electric drivetrain * the efficiency of the battery (Hill, Varma, James, Norris, & Kay, 2012). Since electric motors are applied on a large scale, performance standards are introduced. The required efficiency for electric motors over 50 horsepower is 90.2 percent. For electric motors over 125 horsepower, the required efficiency increases to 92.4 percent (The Engineering Toolbox, 2016). The efficiency of en electric motor can increase to 95 percent in 2050 (Hill et al., 2012). The electric drivetrain operates at 95 percent efficiency. This is thought to remain 95 percent towards 2050 (Hill et al., 2012). The efficiency of the battery is a combination of charger efficiency and battery efficiency. Currently, the efficiency is 75 percent. This can potentially increase to 90 percent in 2050 (Hill et al., 2012). The combined efficiency is 92 % * 95 % * 75 % = 65 % currently. This increases to 95 % * 95 % * 90 % = 81 % in 2050, a 24 percent increase. This is the technical potential for increase, the real increase in energy efficiency will probably be lower, since the technical potential does not take into account the limitations at the supply side, e.g. market growth and replace rate of existing technology (Harmsen, 2014).

Battery technology

Developments in battery technology can facilitate a higher range for EVs in the future. Battery capacity increases if the specific energy increases with constant battery weight. Today's generation of Lithium-ion batteries have a specific energy of 100-180 Wh / kg (Cluzel & Douglas, 2012). Improvement of this specific energy is researched and focuses on new chemistries: Electrodes with higher capacity, which is measured in mAh / g. Another field of research is developing new battery cells with a higher voltage (Cluzel & Douglas, 2012). Proposed materials are nickel cobalt manganese and composite cathodes. This could potentially increase the specific energy of Li-ion batteries to 300 Wh / kg in 2030 (Cluzel & Douglas, 2012).

Alternatives for Li-ion batteries could provide an even higher specific energy and better performance. The most well-known options are lithium-sulphur (Li-S) batteries and lithium-air (Li-air) batteries. The Li-S concept was discovered in the 1960s but the expectations on high energy density and low costs are still not reality. Li-S suffers from low power output, due to a relative low voltage of 2.2 V. Another issue is that the self-discharge rate is high. This is caused by the loss of sulphur which forms soluble polysulphides. Finally, H_2S can be formed if water leaks into the battery cell (Cluzel & Douglas, 2012).

The lithium-air battery cell differs fundamental from other technologies. Lithium is reduced at the anode, flows to the cathode and forms Li_2O_2 with oxygen from the air. This means that the battery cell is lighter, since part of the cathode material is outside the cell. In a Li-ion cell the cathode consists of relative heavy metal elements and other non-reactive components. Li-air battery cells have a higher specific energy compared to Li-ion cells, because the amount of lithium per cell mass is higher due to the absence of excess cathode material (Cluzel & Douglas, 2012). However, there are some issues with the Li-Air battery cells. The battery depends on oxygen from its surrounding, requiring a sufficient airflow passing the cathode to allow operation. The battery pack needs a membrane that allows oxygen to enter the cathode but keeps water, dust and other gases such as CO_2 out. Impurities in the air flow can damage battery components and decrease lifetime (Sapunkov, Pande, Khetan, Choomwattana, & Viswanathan, 2015). Charging releases oxygen from the battery, this requires an environment where elevated oxygen levels are acceptable. There is also a challenge in cathode design. Small pores are required to achieve a high surface area, while simultaneously these pores need to be large enough to prevent clogging by the deposition of Li_2O_2. The final drawback is the potential safety hazard of the pure lithium anode. When lithium is exposed to air during an accident, risk of an explosion occurs (Cluzel & Douglas, 2012).

Both new battery technologies have a potential specific energy of 2,500 Wh / kg (Cluzel & Douglas, 2012). However, the theoretical specific energy tends to be an overestimation of the realistic specific energy, since the theoretical value is based on the lithium anode and oxygen cathode mass, excluding other cell components, i.e. electrolyte and other cathode materials (Rahman, Wang, & Wen, 2014). Furthermore, these technologies are in development and face several barriers before they can be introduced successfully: The lithium air battery is far more complex, compared to the lithium-ion battery. Li-air requires a complex porous (carbon) cathode, impermeable to CO_2, while Li-ion contains a metal oxide cathode. The anode is also more complex, Li-air requires reactive lithium metal, while Li-ion uses carbon. The electrolyte is also more complex. Finally the Li-air battery requires an air management system, to ensure sufficient and clean supply of air to the anode. Therefore it is likely that practical automotive applications of the Li-air and other new technologies will be after 2030 (Cluzel & Douglas, 2012).

Conventional charging technology

Most PHEVs can charge with a maximum power of 3.7 kW, since their onboard converter is designed to support the single phase 230 V times 16 A input from a typical private charging station which is connected to the home's electrical system. Since PHEV battery capacity is relatively small, this power is sufficient for charging. BEVs, with a higher battery capacity, are often equipped with an onboard converter which maximum charging power is 11 kW. This way, it can deal with 3-phase 230 V times 16 A power connection in an owner's home. 11 kW is also the charging power of a public charging station. Normally these operate at 3 phase 230 V times 32 A, which equals 22 kW. However, one charging station supplies two parking spots, halving the charging power per parking spot.

The maximum AC charging power is 43 kW, with the Mennekes type 2 connector from the combo CSS plug (CharIN e.v., 2016). The Renault Zoe, available from January 2017, is the only car to support this type of charging (Elektrische voertuigen database, 2016).

B. M. H. de Brey (personal communication, November 4, 2016) expects future AC charging power to increase to 44 kW (3-phase * 230 V * 63A) for public charging stations. However, this will develop only in the case of a smart charging system, which needs high charging power to allow maximum flexibility. For non smart charging systems, lower charging powers are sufficient.

Another development is the introduction of induction charging. Inductive power transfer is obtained by using a primary coil to produce an electromagnetic field. This field is aimed at the secondary coil (in the car), which converts it to electricity by electromagnetic induction (Aditya & Williamson, 2016). The result is wireless power transfer from the charging station to the vehicle. This increases convenience, and this option is therefore preferred by car owners. However, the efficiency of the power transfer is lower compared to conductive power transfer, which means through a cable. When the technology develops, it potentially can replace conductive power transfer. However, for the way of power transfer does not influence the results of this study. Conductive and inductive power transfer both can be implemented in AC charging infrastructure.

Fast charging technology

Currently, all popular BEV models are capable of fast charging. Most models support DC charging up to 50 kW, but Tesla cars can charge with 120 kW DC at Tesla Supercharger stations. For PHEVs, only the Mitsubishi Outlander PHEV supports fast charging, up to 22 kW DC (Elektrische voertuigen database, 2016). This makes sense, since the small battery of a PHEV is quickly recharged by conventional AC charging through the onboard converter.

As mentioned in section 4.1.3, there are 2 types of DC fast charging connectors, CHAdeMO and CCS. CHAdeMo can charge up to 62.5 kW and CCS up to 107 kW. Car manufacturers are planning to introduce new models which support higher charging power to fully utilize the potential of both charging techniques. The Kia Soul EV will support up to 100 kW with CHAdemo, while BMW, Nissan, Volkswagen, Ford and Opel plan to upgrade their electric models to support 80 kW charging with CCS (Fastned, 2016b). The organisation behind CCS, CharIN, plans to upgrade the CCS standard to allow 150 kW charging by increasing the current (Amperage). The charging power can increase even further to 350 kW by increasing the voltage (CharIN e.v., 2016). The CHAdeMO standard is also being upgraded. The association plans to increase the current to 350 A, resulting in a charging power over 150 kW. Long term development could be increasing the voltage to 1000 V, resulting in 350 kW charging power. However, this is dependent on market demand (CHAdeMO Association Europe, 2016).

Another development is dynamic induction charging. This is similar to inductive charging described above. The charging equipment is installed in the roads and the vehicles are charged while they drive on these roads. Tests with this technology already achieved a charging power of 100 kW (Chen et al., 2015). The technology can be an alternative for DC fast charging, but it is still in development and suffers from high investment costs (Highways England, 2015). As with the inductive charging, the technology does not influence the results of the scenarios, if the charging power is similar to that of DC fast charging stations.

Summarising, DC charging power technique is expected to increase to 150 kW in the near future, with long term development towards 350 kW when market demand is there. However, current public fast charging stations are designed for 50 kW, compatible with current electric vehicles. The majority of Fastned charging stations have grid connections that allow 4 cars to simultaneously charge at 150 kW. This means that the stations can be upgraded to 4 * 150 kW. The company is planning to install the first 150 kW fast chargers in 2017, however only if there is demand from new car models which are capable of charging at 150 kW (Fastned, 2016b). Increasing charging power is beneficial for companies, since it allows for a larger electricity sales volume, leading to economies of scale. This means that the fixed costs for installing the infrastructure, connection to the grid, permits and maintenance are spread out over a larger sales volume, decreasing costs for the operator and for customers. Therefore it is concluded that fast charging infrastructure suppliers are willing to increase the charging power when market demand is sufficient.

4.2.3 Future policies

This section explores (potential) future policies aimed at EVs and charging infrastructure. When the EV market matures and reaches the early majority stage, subsidy schemes may be scrapped. An example of that is the addition tax ("bijtelling") for vehicles with a CO_2 emission between 1 and 50 grams per kilometre, i.e. PHEVs. Their addition tax will increase to levels of conventional cars with an internal combustion engine. Zero-emission vehicles will become the only exception to the 22 percent rate, as shown in table 4 (Rijksoverheid, 2015).

Table 4. Changes in 'bijtelling' from 2016 to 2020 (Rijksoverheid, 2015)

	2016	2017	2018	2019	2020
Zero-emission	4%	4%	4%	4%	4%

PHEV (1-50 gram/km)	15%	17%	19%	22%	22%
Efficient (51-106 gram/km)	21%	22%	22%	22%	22%
Other (> 106 gram/km)	25%	22%	22%	22%	22%

Other tax exemptions for PHEVs, i.e. BPM and MRB, are also equalised with conventional cars. With these measures, the government hopes to stimulate BEVs and fix the flaws in the current system, where Dutch citizens adopt mainly PHEVs and not BEVs, since the financial advantages are similar and the practicality of a PHEV is higher (Rijksoverheid, 2015).

Although the (PH)EV market is maturing and may need less support, the business case for public charging infrastructure is still negative. One issue is the tax on electricity supplied. The ministry of Finance argues that the tax costs per kilometre are lower for EVs compared to internal combustion engines. The calculation is shown in table 5 (Ministerie van Financiën, 2016). The tax rate on electricity is divided in steps. The tax rate for the first 10,000 kWh is € 0.1007. For 10,001 to 50,000 kWh the tax rate is € 0.04996, more than halve of the first step. The tax rate for the third step, 50,001 to 10 million kWh is € 0.01331. For individual users with an electricity consumption over 10 million kWh, the tax rate is € 0.00107, for businesses the rate is € 0.00053 (Belastingdienst, 2016). A public charging station has its own connection to the electricity grid and falls within the first step. Therefore the tax rate for electricity supplied through a public charging station is the highest rate.

Table 5. The tax costs per kilometre for EVs and internal combustion engine vehicles(Ministerie van Financiën, 2016)

Fuel	Efficiency	Unit	Tax rate	Unit	Costs per km
Electricity	18	kWh / 100 km	€ 0.101	€ / kWh	€ 0.018
Gasoline	6.33	Litre / 100 km	€ 0.770	€ / litre	€ 0.049
Diesel	5.66	Litre / 100 km	€ 0.484	€ / litre	€ 0.027
LPG	7.60	Litre / 100 km	€ 0.195	€ / litre	€ 0.015

From table 5 follows that the tax rate per kilometre is lower for EVs compared to gasoline, diesel and LPG powered vehicles. However, if the tax rate per unit of energy (MJ) is calculated, it becomes clear that the tax rate on electricity is higher. Per MJ of electricity, the tax rate is 117 percent higher than per MJ of gasoline, see table 6. This increase is striking, since other fuels which are more efficient than gasoline in terms of CO_2 emissions per kilometre, i.e. diesel and LPG, have a lower tax rate: 54 percent and 29 percent lower respectively, compared to gasoline. The reason the costs per kilometre are lower is because EVs have higher fuel efficiency and require less energy input per kilometre.

Table 6. The tax rate per unit of energy for electricity, gasoline, diesel and LPG (Ministerie van Financiën, 2016)

Fuel	Tax rate	Conversion to MJ	Tax rate (€ / MJ)	Relative to gasoline
Electricity	€ 0.101 / kWh	1 kWh = 3.6 MJ	0.028	117 %
Gasoline	€ 0.770 / litre	1 litre = 32 MJ	0.024	100 %
Diesel	€ 0.484 / litre	1 litre = 36 MJ	0.013	54 %
LPG	€ 0.195 / litre	1 litre = 27 MJ	0.007	29 %

The high tax rate which MSPs have to pay over the electricity they supply through public charging infrastructure is (partially) passed on to the consumer. This leads to higher prices, limiting demand. To stimulate public charging infrastructure, the government implemented regulations that resulted in halving the tax rate for public charging infrastructure in the period 2017 to 2020 (Ministerie van Financiën, 2016). This is achieved by applying the tax rate of the second step to public charging infrastructure. Since the government assumes no further stimulation is needed for the rollout of electric mobility after 2020, the measure is stopped at that time.

B. M. H. de Brey (personal communication, November 4, 2016) also identified the tax rate for electricity as a barrier for the profitability of charging infrastructure. Especially in combination with a vehicle to grid system, this involves bidirectional charging: The EV owner pays the electricity tax up to three times. The tax is paid after production of surplus electricity which is delivered to the grid, i.e. by solar panels on the roof of the house of an EV driver. The second time the EV owner pays the tax is by charging the car through public charging infrastructure. The third time the electricity tax is paid is when the car supplies electricity to the grid. Therefore, lowering the electricity tax leads to increasing profitability of bidirectional charging.

Another potential policy measure regarding charging infrastructure is the ‘right to a charging station’. This right is a proposed policy from the sustainable fuels vision (De Tafel Wegvervoer Duurzaam Elektrisch, 2014). The thought behind it is that it stimulates governments, building owners and businesses to install charging infrastructure on their property. This can be public and private. The authority in charge of public space, including road construction and maintenance, should implement public charging stations when an EV driver files a request. The measure can be implemented in the period 2015 to 2020 (De Tafel Wegvervoer Duurzaam Elektrisch, 2014).

The final possible policy measure deals with the problem of fast charging at service areas. Currently, providers of fast charging at these areas are not allowed to sell additional services: no food, no drinks and no toilets. These services are part of the auctions for gas stations at service areas, addressed in the Gasoline law (“Benzinewet”), which does not apply for providers of fast charging infrastructure (Fastned, 2015).

However, these additional services are also a source of income for the providers. This limits the competitive position of providers of fast charging infrastructure compared to gas station providers. Potential policies to level the playing field include an equal treatment of fast charging providers and gas station providers. This could be done by allowing both to sell any service they with: selling petrol, electricity, food, drinks and providing toilets. Another option could be to allow both gas station providers and fast charging providers to sell additional services. By allowing fast charging providers to sell additional services, fast charging at service areas becomes more convenient for consumers and therefore more attractive.

4.3 Reference scenario

A reference scenario is constructed in this section. The narrative explains qualitative how the scenario developed over time: What important developments took place. The quantitative analysis converts these developments in numerical changes in the indicators that describe the system. From the indicators, the public charging station demand is calculated.

4.3.1 Narrative

The reference scenario shows how charging infrastructure develops following current trends, with no additional interventions. The results of the reference scenario provide a basis of comparison to compare the alternative scenarios to. The starting condition is that the EV market develops as predicted by the sustainable fuels vision. This means 595,000 BEVs and 1,470,000 PHEVs in 2030, and 7,100,000 BEVs and 2,360,000 PHEVs in 2050 (Ministerie van Infrastructuur en Milieu, 2014). The other indicators follow current trends, with the addition of current and future policy measures which are already planned. Mileage will continue to increase due to economic growth. Energy efficiency will increase slightly through technological development. Battery technology improves, leading to improved versions of Li-ion batteries in 2030 and Li-air technology in 2050. Charging technology is similar to today; conventional AC charging is combined with DC fast charging.

4.3.2 Quantitative analysis

The quantitative analysis aims at quantifying the scenario. This is done by assessing the quantitative development of each indicator. The indicators are assigned a value based on the development following current trends, as described in the narrative. The development of each indicator is calculated and explained below.

Car ownership

To estimate the indicator car ownership in 2030 and 2050, the current trend in car ownership in the period 1990-2016 is analysed. The results are shown in table 7 (CBS Statline, 2016b). The average annual growth is 1.78 percent. Extrapolating to 2030 and 2050, the number of passenger vehicles increases to 10,527,611 and 14,996,638 respectively. The Planbureau voor de Leefomgeving reported that the number of passenger cars is likely to be 10 to 20 percent smaller in the case of an all EV market, compared to internal combustion vehicles (Nijland, Hoen, Snellen, & Zondag, 2012). Multiplying the numbers from the current trends with 0.8, car ownership in 2030 is 8,422,089 and in 2050 11,997,311. The predictions on car ownership by extrapolating the current trend seem unlikely. Car ownership is influenced by population growth: A higher population leads to more passenger cars, assuming that the lifestyle (including car usage) remains constant. The Planbureau voor de

Leefomgeving (2016) foresees a continuing population growth in the Netherlands; however the growth rate will reduce. Another reason for rejecting the current trend is that an EV has high investment costs and low running costs, compared to a vehicle with an internal combustion engine (Nijland et al., 2012). It can be expected that the growth of passenger vehicles will slow down due to these higher investment costs, while the lower running costs stimulate a higher yearly mileage, which is elaborated on below. These two factors combined are estimated to lead to a decrease in growth of number of passenger vehicles, while each vehicle drives more kilometres per year (Nijland et al., 2012). Therefore the numbers extrapolated from the trend are probably still an overestimation.

Table 7. The number of passenger vehicles in the Netherlands in the period 1990 to 2016 and the annual increase (CBS Statline, 2016b)

Year	Number of passenger vehicles	Change
1990	5,118,429	
1991	5,204,604	1.68%
1992	5,246,568	0.81%
1993	5,340,858	1.80%
1994	5,455,733	2.15%
1995	5,580,818	2.29%
1996	5,664,408	1.50%
1997	5,810,228	2.57%
1998	5,931,387	2.09%
1999	6,119,581	3.17%
2000	6,343,164	3.65%
2001	6,539,040	3.09%
2002	6,710,595	2.62%
2003	6,854,947	2.15%
2004	6,908,890	0.79%
2005	6,991,974	1.20%
2006	7,092,293	1.43%
2007	7,230,178	1.94%
2008	7,391,903	2.24%
2009	7,542,331	2.04%
2010	7,622,353	1.06%
2011	7,735,547	1.49%
2012	7,858,712	1.59%
2013	7,915,613	0.72%
2014	7,932,290	0.21%
2015	7,979,083	0.59%
2016	8,100,864	1.53%

Instead, the reference scenario follows the projection of the sustainable fuels vision: all passenger vehicles have an electric drivetrain in 2050. There will be a total of 9.1 million passenger vehicles in 2030, including 595,000 BEVs and 1,470,000 PHEVs. This increases to almost 9.5 million passenger vehicles in 2050, consisting of 7,100,000 BEVs and 2,360,000 PHEVs (De Tafel Wegvervoer Duurzaam Elektrisch, 2014). These numbers are obtained by estimating the potential of a Product Market Combination. In this case, it is the combination of an electric vehicle for the passenger transport market. The estimations require sufficient development of electric mobility, including vehicles, battery technology and charging infrastructure. The results are analysed on robustness, i.e. the percentage in newly sold vehicles and turnover rates of the passenger vehicle market. The values for the indicator car ownership in 2050 in the reference scenario are shown in table 8.

Table 8. The number of passenger vehicles in the Netherlands in 2030 and 2050 and the percentage EVs (Ministerie van Infrastructuur en Milieu, 2014)

Year	Number of passenger vehicles	percentage EVs
2030	9,100,000	23
2050	9,460,000	100

The sustainable fuels vision also distinguishes several types of passenger vehicles. In the Netherlands a class system is used to describe the typical size of a vehicle (Wikipedia, 2016). The classes range from small cars, type A, up to large SUVs, type M. The relevant passenger car classes and some representative models are shown in table 9. It also shows the expected number of cars for each class (De Tafel Wegvervoer Duurzaam Elektrisch, 2014).

Table 9. The number of passenger vehicles in the Netherlands in 2030 and 2050 per vehicle class (De Tafel Wegvervoer Duurzaam Elektrisch, 2014)

Class		Model	2030	2050
Mini class	A	VW e-Up	317,692	1,873,267
Compact class	B	Renault Zoë, BMW i3	555,962	2,809,901
Compact middle class	C	Nissan Leaf, VW e-Golf	714,808	2,809,901
Middle class	D	Volvo V60	158,846	655,644
Higher middle class	E	Tesla Model S	158,856	655,644
SUV	L	Mitsubishi Outlander PHEV	158,846	655,644
Total			2,065,010	9,460,000

Unfortunately, the numbers do not provide the exact division between BEVs and PHEVs. Several estimations are made to provide this division. In 2030, 29 percent of all EVs are a BEV and 71 percent a PHEV. This changes to 75 percent BEV and 25% PHEV in 2050 (De Tafel Wegvervoer Duurzaam Elektrisch, 2014). The author assumes that all small class A vehicles are a BEV, since there are currently no PHEVs in this vehicle class. Also, the author believes that there will be no demand for a class A PHEV in the future, since the range will increase and these types of vehicles are often used to drive only small distances. Vehicles of class E are assumed to be 50 percent BEV and 50 percent PHEV, since both BEV and PHEV have successful models in this vehicle class, e.g. Tesla model S and Mercedes E hybrid. The author also assumes that all SUVs are PHEV, since there are currently no BEV SUV models on the market. All other vehicles are a combination of BEVs and PHEVs. The ratio between BEVs and PHEVs is assumed to be constant for class B to D. The ratio is determined by subtracting the number of class A, E and L vehicles from the total number of BEVs and PHEVs, originating from the sustainable fuels vision. The remaining number of vehicles is divided over class B to D. This results in the number of passenger vehicles in per vehicle class, divided in BEV and PHEV (Table 10).

Table 10. The number of passenger vehicles in the Netherlands in 2030 and 2050 per vehicle class, divided in BEV and PHEV

Class		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	317,692	0	1,873,267	0
Compact class	B	76,953	479,009	2,193,542	616,359
Compact middle class	C	98,940	615,868	2,193,542	616,359
Middle class	D	21,987	136,859	511,826	143,817
Higher middle class	E	79,428	79,428	327,822	327,822
SUV	L	0	158,846	0	655,644
Total		595,000	1,470,010	7,100,000	2,360,000

Mileage

The second indicator, mileage, is expressed as kilometres per vehicle per day. Population and economic growth generally lead to increasing mobility (Moorman & Kansen, 2011). Mileage is calculated by dividing the total number of kilometres driven by passenger vehicles in the Netherlands by the number of passenger vehicles in the Netherlands. The data on kilometres driven are obtained from CBS Statline (2016b). The trend is an average increase of 1.23 percent per year in kilometres driven. The data on number of vehicles is shown in table 7. Since the total kilometres driven increase slower than the number of vehicles, the trend in kilometres per car per year is decreasing. The current trend in mileage is shown in table 11. The average annual decrease is 0.55 percent.

An EV is characterised by high investment costs but low costs per kilometre (Nijland et al., 2012): An EV becomes more beneficial with high yearly mileages. This leads to the assumption that with an increasing share of EVs in the total passenger car fleet, the yearly mileage per vehicle will increase, opposite to the current trend. Therefore, the current trend is dismissed. Alternatively, it is calculated from predictions for the increase in total kilometres driven in 2050. Moorman & Kansen (2011) foresee an increase in this mobility to 119 percent of the 2010 level in 2030 and 134 percent in 2050, based on a study by PBL and ECN, combined with European data from the TREMOVE model. This results in 133,742 million kilometres driven in 2030 and 150,600 million kilometres driven in 2050. Combined with the number of vehicles in 2030 and 2050, mentioned above, the number of kilometres driven per car per day in 2030 and 2050 becomes 40.3 and 43.6 respectively, shown in table 12. This is a small increase from the mileage in 2015, which was 39.6 km per car per day.

Table 11. Mobility in the Netherlands in the period 1990 to 2015 and the annual change(CBS Statline, 2016c)

Year	Mobility (km per car per year)	Change (%)
1990	16,632	
1991	16,556	-0,46%
1992	16,979	2,56%
1993	16,709	-1,59%
1994	16,848	0,83%
1995	16,642	-1,22%
1996	16,406	-1,42%
1997	16,639	1,42%
1998	16,346	-1,77%
1999	16,512	1,02%
2000	16,132	-2,30%
2001	15,768	-2,26%
2002	15,527	-1,53%
2003	15,333	-1,25%
2004	15,455	0,79%
2005	15,392	-0,41%
2006	15,418	0,17%
2007	15,440	0,14%
2008	15,296	-0,93%
2009	14,968	-2,14%
2010	14,745	-1,49%
2011	14,807	0,42%
2012	14,471	-2,27%
2013	14,379	-0,63%
2014	14,436	0,39%
2015	14,450	0,10%

Table 12 Kilometres driven, number of vehicles and mobility in the Netherlands in 2030 and 2050

Year	Kilometres driven (million km)	Number of vehicles (million)	Mileage (km per car per day)
2030	133,742	9.1	40.3
2050	150,600	9.46	43.6

Energy efficiency

Energy efficiency is defined as kWh used per 100 kilometres driven. The energy efficiency of current models is calculated by dividing the useful battery capacity by the real range of that EV. The useful battery capacity is the amount of kWh that is available. Total battery capacity is larger, since the car battery is not completely discharged to avoid damage to the battery cells. The surplus capacity is usually in the order of a few kWh. The useful capacity of a battery pack is usually expressed in a State of Charge (SoC) value: The percentage of the whole battery that is available when the battery is fully charged. Due to aging of the battery, which leads to lower battery capacity, the SoC value will decrease when the battery ages, since the available capacity decreases. The range of a PHEV or BEV is determined during the New European Driving Cycle (NEDC). The NEDC is a standardised test of light vehicles and is required for type approval of a new car model (Verband die Automobilindustrie, 2016). Fuel consumption and emissions are measured in a laboratory while imitating a real driving profile. For EVs, fuel consumption is expressed in kWh per 100 km. However, real driving conditions differ from the test environment and car manufacturers are known to prepare the cars for the test by removing side mirrors and taping seams to improve aerodynamics (Verband die Automobilindustrie, 2016). The range of an EV in real conditions is provided by the Electric Vehicle Database, a site aimed at comparing EVs and PHEVs (Elektrische voertuigen database, 2016). The real range is 65 to 80 percent of the NEDC range. The battery capacity, range and resulting energy efficiencies of popular BEV models are shown in table 13. As can be expected, a smaller car has higher energy efficiency: The Renault Zoë uses 13.33 kWh per 100 kilometres, while a Tesla model S uses almost 20 kWh per 100 kilometres.

Table 14 displays the battery capacity, range and resulting energy efficiencies of popular PHEV models. The same trend in efficiency is observed: The compact middle class type VW Golf GTE uses 16 kWh per 100 kilometres, while the large SUV Mitsubishi Outlander PHEV uses 23 kWh per 100 kilometres. What also stands out in the table is that the energy efficiency of a PHEV is lower compared to a BEV. This can be explained by the size of a PHEV, which is usually larger than a BEV. Another explanation is the presence of an internal combustion engine. When a PHEV drives fully electric, the internal combustion engine is dead weight which is driven around, resulting in extra energy consumption.

Table 13.Battery capacity, range and energy efficiency for popular BEV models(Elektrische voertuigen database, 2016)

Model	Version	Battery capacity (kWh)	Useful battery capacity (kWh)	Range (km)	Real range (km)	Efficiency (kWh / 100 km)	Real efficiency (kWh / 100 km)
Tesla Model S	60	75	60	400	320	15.00	18.75
	60D	75	60	408	330	14.71	18.18
	75	75	72	480	385	15.00	18.70
	75D	75	72	490	395	14.69	18.23
	90D	90	87	557	450	15.62	19.33
	P100D	100	98	613	500	15.99	19.60
Nissan Leaf	24 kWh	24	21.4	199	139	10.75	15.40
	30 kWh	30	26.7	250	175	10.68	15.26
Renault Zoë	R90 Entry	25.9	22	240	165	9.17	13.33
	Q90	41	40	370	280	10.81	14.29
	R90	41	40	403	300	9.93	13.33
BMW i3		21.6	18.8	190	130	9.89	14.46
	94 Ah	33.2	27.2	312	200	8.72	13.60
Smart ForTwo		17.6	17.6	135	100	13.04	17.60
VW e-Up		19	16.2	160	115	10.13	14.09
VW e-Golf		24.2	20.6	190	125	10.84	16.48

Table 14. Battery capacity, range and energy efficiency for popular PHEV models (Elektrische voertuigen database, 2016)

Model	Battery capacity (kWh)	Useful battery capacity (kWh)	Range (km)	Real range (km)	Efficiency (kWh / 100 km)	Real efficiency (kWh / 100 km)
Mitsubishi Outlander PHEV	12	9	52	39	17.31	23.08
Volvo V60 Plug-in Hybrid	11.2	8	50	38	16.00	21.05
Volkswagen Golf GTE	8.7	7.4	50	38	14.80	19.47
Audi A3 Sportback e-tron	8.8	7.5	50	35	15.00	21.43
Mercedes C350 E	6.2	5.0	31	23	16.13	21.74
Opel Ampera	16	11	83	57	13.25	19.30
Toyota Prius PHEV	4.4	3.4	23	17	14.78	20.00

Due to the differences between vehicle classes, the energy efficiency is categorised per vehicle class and EV type. The results are shown in table 15. The efficiencies are averaged for the different car models in that class. When looking at the number of EVs in 2030 and 2050 (table 10), it can be noticed that in those years also BEVs from middle class and PHEVs from compact class and higher middle class exist. The efficiencies of those classes are derived from comparing with the other efficiencies and are shown in italic.

Table 15. Energy efficiency per vehicle class

Class		Model	BEV efficiency (kWh / 100 km)	PHEV efficiency (kWh / 100 km)
Mini class	A	VW e-Up	14.09	
Compact class	B	Renault Zoë, BMW i3	13.85	*18.5*
Compact middle class	C	Nissan Leaf, VW e-Golf	15.71	20.45
Middle class	D	Volvo V60, Mercedes C350 E	*15.75*	20.52
Higher middle class	E	Tesla Model S	18.80	*22.00*
SUV	L	Mitsubishi Outlander PHEV		23.08

As described in 4.2.2, the energy efficiency of an EV can increase with a maximum of 24 percent. However, the real efficiency increase will be lower than this potential increase. This study assumes that 40 percent of the technical potential is achieved (Cluzel & Douglas, 2012). Therefore, the efficiency of EVs improves with 5 percent in 2030 and with 10 percent in 2050, compared to 2016. The resulting efficiencies are shown in table 16.

Table 16. Energy efficiency in 2030 and 2050 for each vehicle class

Class		2030		2050	
		BEV efficiency (kWh / 100 km	PHEV efficiency (kWh / 100 km	BEV efficiency (kWh / 100 km	PHEV efficiency (kWh / 100 km
Mini class	A	13.38		12.68	
Compact class	B	13.16	17.58	12.47	16.65
Compact middle class	C	14.93	19.43	14.14	18.41
Middle class	D	14.96	19.50	14.18	18.47
Higher middle class	E	17.86	20.90	16.92	19.80
SUV	L		21.92		20.77

Battery capacity

The capacity of a battery is mainly determined by the specific energy of the battery cells. Battery specific energy is expressed in terms of the amount of energy per kilogramme of battery weight: Wh / kg. Current batteries are made with lithium-ion cells. However, the cell chemistry can vary and accordingly the specific energy of the cell. Popular Li-ion cells for use in EVs are lithium nickel manganese, nickel cobalt aluminium oxide (used by Tesla) and lithium titanate. These cells have a specific energy of 150-220 Wh / kg, 200-260 Wh / kg and 70-80 Wh / kg (Battery University, 2016b). This is similar to the range in specific energy of 100 to 180 Wh / kg mentioned by Cluzel & Douglas (2012) and 90 to 190 Wh / kg by (Diouf & Pode, 2015). For this study, it is assumed that the average specific energy of current Li-ion cells is 180 Wh / kg. The total weight of all Li-ion cells in the battery can be calculated with the useful battery capacity (in kWh) from table 14 and the specific energy of 180 Wh / kg. The results are shown in table 17. For each class, the model with the largest battery capacity is chosen. Since there are numbers for BEVs class D and PHEVs class B and E, these are estimated. The number for class C is increased, since class B cars, i.e. the Renault Zoë, are smaller while having a larger battery. Therefore, it is assumed that the total cell weight in a class C battery is slightly larger.

Table 17.The total cell weight in the car battery for each vehicle class

Class		Model	Total cell weight (kg)		Estimated cell weight (kg)	
			BEV	PHEV	BEV	PHEV
Mini class	A	VW e-Up	90,0		100	
Compact class	B	Renault Zoë	222,2		225	35
Compact middle class	C	Nissan Leaf, VW Golf GTE	166,7	41,7	250	40
Middle class	D	Volvo V60		44,4	400	45
Higher middle class	E	Tesla Model S P100D	544,4		550	50
SUV	L	Mitsubishi Outlander PHEV		50,0		50

To determine the battery capacity in the future, the future specific energy (in Wh / kg) is multiplied with the future total cell weight in the battery (in kg). The total cell weight is assumed to remain equal to the values listed in table 17, since the battery pack of current EVs already takes up all the available space underneath the floor of a vehicle (Arcus, 2016).

The future specific energy depends on the development of battery technology. Lithium-ion technologies are currently the standard, but new technologies are being developed, i.e. Li-air and Li-S. Each innovation needs R&D and time to mature into a market technology. This can be visualised in a hype chart, see figure 13. The hype chart starts with an innovation trigger, when the technology is discovered. The hype for promising innovations increases in the peak of inflated expectations. However, the hype deceases after occurring problems, to the trough of disillusionment. If these barriers are overcome, the innovation matures via the slope of enlightenment to the plateau of productivity (Sapunkov et al., 2015). The figure shows he position in this process for the battery technologies. Li-ion is the best alternative for now, but Li-air can be the next technology.

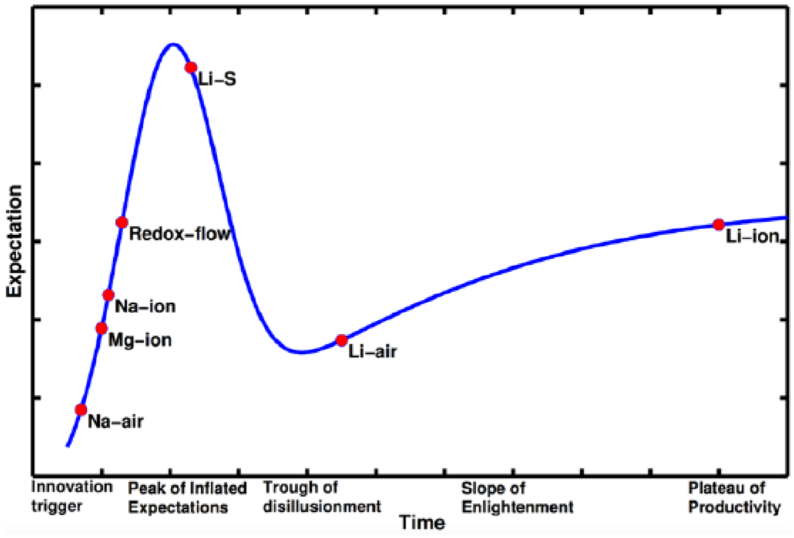


Figure 13. The hype chart for battery technologies(Sapunkov et al., 2015)

In the reference scenario, Li-ion is developed to 2030. The specific energy is expected to increase to 290 Wh / kg (Cluzel & Douglas, 2012). In the period 2030 to 2050, Based on the hype chart, Li-air matures and becomes the new standard in EV battery technology in 2050. The theoretical specific energy of Li-air is 13,000 Wh / kg (Battery University, 2016a). The practical specific energy will be lower, since the reactive element lithium might be combined with heavier elements, required for reversing the discharging process. This reduces the potential specific energy to around 2,500 Wh / kg. The observed ratio of practical to potential specific energy for other battery chemistries is 20 to 40 percent (Cluzel & Douglas, 2012). This would mean that the practical specific energy of Li-air ranges between 500 to 1000 Wh / kg, which is in line with academic predictions (Cluzel & Douglas, 2012). The reference scenario uses a moderate development of Li-air to 500 Wh / kg in 2050. The resulting battery capacity for each vehicle class is shown in table 18.

Table 18. Battery capacity (kWh) of each car class in 2030 and 2050

Class		Model	2030		2050	
			BEV	PHEV	BEV	PHEV
Mini class	A	VW e-Up	29.0		50	
Compact class	B	Renault Zoë	65.3	10.2	113	18
Compact middle class	C	Nissan Leaf, VW Golf GTE	72.5	11.6	125	20
Middle class	D	Volvo V60	116.0	13.1	200	23
Higher middle class	E	Tesla Model S P100D	159.5	14.5	275	25
SUV	L	Mitsubishi Outlander PHEV		14.5		25

The range of the car classes is obtained by multiplying the battery capacity with the energy efficiency. The results are shown in table 19. The average range in 2030 is 408 km for a BEV and 61 km for a PHEV. In 2050, the average range is 833 km for a BEV and 114 km for a PHEV.

Table 19. Range (km) of each car class in 2030 and 2050

Class		Model	2030		2050	
			BEV	PHEV	BEV	PHEV
Mini class	A	VW e-Up	217		394	
Compact class	B	Renault Zoë	496	58	902	105
Compact middle class	C	Nissan Leaf, VW Golf GTE	486	60	884	109
Middle class	D	Volvo V60	775	67	1411	122
Higher middle class	E	Tesla Model S P100D	893	69	1625	126
SUV	L	Mitsubishi Outlander PHEV		66		120

Charging technology

The charging technology develops in a moderate way in the reference scenario. AC charging through public charging infrastructure is often limited by the onboard converter. With increasing battery capacity, the charging power should also increase to prevent long charging times. Therefore, AC charging power is increased from 11 kW currently to 22 kW in 2030 and 2050: The 3-phase 16 A connection is upgraded to a 3-phase 32 A connection. This means that all PHEVs, with a maximum battery capacity of 25 kWh in 2050 (table 18) can recharge in little over an hour. BEVs require longer recharging, at 22 kW a class A BEV with typical battery capacity of 50 kWh in 2050 takes 2 hours and 15 minutes. The larger class D BEVs take 9 hours, while the class E BEVs take 12 hours and 30 minutes to recharge.

The charging capacity per day is calculated from the charging power. Unfortunately, public charging stations are not used to their full potential: In 2015 the public chargers of EVNetNL had a occupancy rate of only 14 percent (Energeia, 2016). On average the cars were connected to the charging stations for 7 hours, including 2 hours and 30 minutes of charging. The average load profile is shown in figure 14. Interestingly, the charging demand is low during the night, while it peaks in the morning and during the evening. Most charging sessions start at 8.51 in the morning and end at 17.12 in the afternoon, this corresponds with a typical working day (Energeia, 2016). The dip in the afternoon is caused by fully charged batteries of cars that plugged in at 9 am, while the dip during the night is caused by fully charged batteries of cars that plugged in the evening. The peak in the evening is caused by people who come home from work and plug their EV in the charger. During the weekend the peak shifts to the afternoon. The peaks show two types of public chargers, charging at work locations and charging at home locations. At work the charging starts around 9 am and lasts until 5 pm, 8 hours in total. At home the charging starts around 7 pm and ends when leaving for work the next day. It is important to realise that both types of chargers will only be used for a part of the day: The charger at work locations is abandoned after work while the charger at home locations is likely to remain inactive during the day. The reference scenario assumes that the charging time will increase, since EVs will have increased range. Currently, an EV driver plugs their vehicle in after each trip, to ensure that the battery is fully charged when he leaves again. Larger range will remove the need to charge every time: The EV owner can make multiple trips before recharging is required without risking emptying the battery. So instead of plugging in always, the EV owner will plug in when the battery is almost empty. With charging times under 9 hours for almost all vehicle classes, this fits in a working day or during night time. Therefore, the effective charging time per charging point is set to 8 hours a day. At 22 kW, an average public charging station provides 176 kWh per day in the reference scenario.

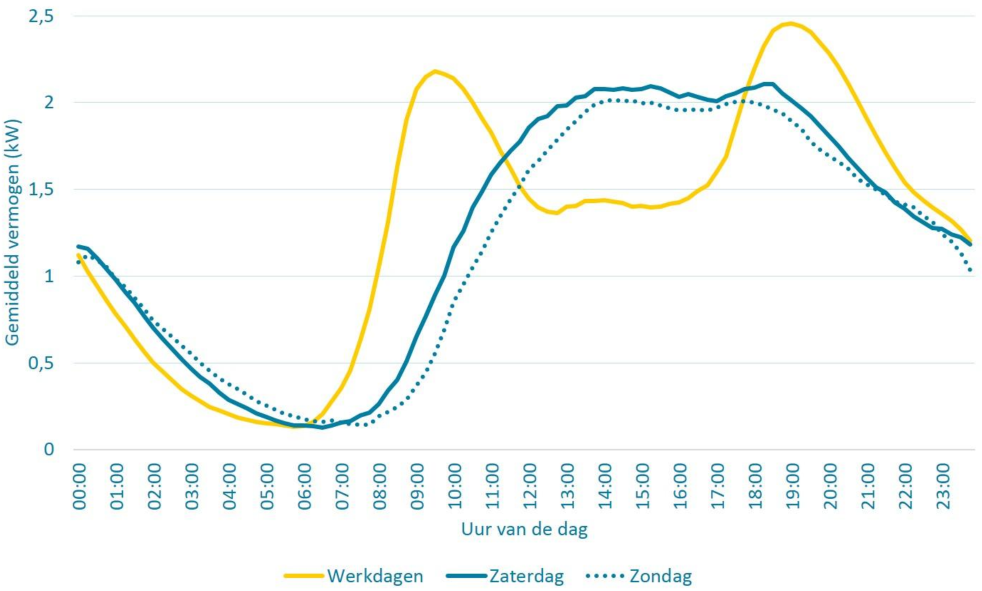


Figure 14.Charging load profile on a public charging station in 2015 (Energeia, 2016)

DC fast chargers develop from 50 kW currently to 150 kW in 2030 and 2050. The increase in charging power is already planned and therefore incorporated in the reference scenario. A further increase to 350 kW is not applied. As a consequence, fast charging times go up. Fast charging time is often expressed as the time it takes to charge the battery from 0 to 80 percent, because above 80 percent the charging power must be reduced to prevent overheating of the battery. The class A BEV models with a battery capacity of 29 kWh in 2030 and 50 kWh in 2050 will be charged from 0 to 80 percent in 16 minutes and 32 minutes respectively. For class E BEVs, with a battery capacity of 160 kWh in 2030 and 275 kWh in 2050, fast charging takes 51 and 88 minutes. This is considerably longer than current fast charging times, this is caused by the battery capacity, which is increased as well. There are three main assumptions when considering the charging capacity of a fast charging station: Window of operation, occupancy rate and charging power. The window of operation of a Fastned fast charger is from 7 am and 11 pm, 16 hours a day. The occupancy rate is approximately 50 percent during the hours of use. The charging power is on average 70 percent (Fastned, 2016a). This is caused by the slowing down to prevent overheating. With these assumptions, the charging capacity of a 150 kW charging station is 840 kWh / day.

The ratio between AC and DC public charging infrastructure is assumed to stay constant in the reference scenario. In September 2016 there were 24,220 AC charging stations and 556 DC charging stations (RVO, 2016a). This brings the ratio AC conventional: DC fast to 43.56 : 1.

Charging demand

Now the development of the indicators is specified, the next step is to calculate the charging demand in the reference scenario. First, the mileage indicator is converted to kilometres per day. The charging demand is only influenced by the kilometres which are driven with an electric drivetrain. For BEVs, this is the total mileage, but for PHEVs the percentage electrically driven kilometres is only 26.1 percent in 2015 (Smokers & Ligterink, 2015). This is assumed to continue to 2050. The amount of electric kilometres per day is shown in table 20.

Table 20. The amount of kilometres per year, kilometres per day and electric kilometres per day

Year	km per year	km per day	PHEV electric km per day
2014	14,436	39.6	10.3
2030	14,697	40.3	10.5
2050	15,920	43.6	11.4

With an average range of 408 km for a BEV and 61 km for a PHEV in 2030, recharging the battery is only required every once in 10 and 6 days respectively. In 2050 this is increased to once in 19 days for a BEV and once every 10 days for a PHEV.

The average kilometres driven electrically per day are combined with the vehicle efficiency (table 13 and 14) to determine the required amount of electricity for charging. Due to differences in efficiency, the electricity demand is divided per vehicle class, which is shown in table 21.

Table 21. The electricity per day per vehicle class (in kWh) in 2030 and 2050

Class		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	5.4		5.5	
Compact class	B	5.3	1.8	5.4	1.9
Compact middle class	C	6.0	2.0	6.2	2.1
Middle class	D	6.0	2.0	6.2	2.1
Higher middle class	E	7.2	2.2	7.4	2.3
SUV	L		2.3		2.4

Combined with the number of vehicles in each class in 2030 and 2050 (table 10), and the fact that 65 percent of car owners parks in public space, the total electricity demand per day at public charging stations is calculated (table 22). The total electricity demand at public charging stations is 4,147,664kWh per day in 2030 and 30,192,354 kWh per day in 2050.

Table 22. The total electricity demand per day in 2030 and 2050 at public charging stations

		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	1,112,741		6,733,093	
Compact class	B	265,068	575,077	7,753,587	759,353
Compact middle class	C	386,496	817,365	8,793,181	839,439
Middle class	D	86,101	182,270	2,056,843	196,553
Higher middle class	E	371,262	113,399	1,572,432	480,285
SUV	L		237,884		1,007,590
total		2,221,668	1,925,996	26,909,135	3,283,220

The total number of public charging stations required to provide this electricity is calculated by dividing the electricity demand by the electricity supply per charging station. On average, each AC charging station provides 176 kWh per day and a DC charging station 840 kWh per day. Applying the ratio of 43.56 to 1 for AC : DC charging stations, the total number of AC public charging stations is 21,239 in 2030 and 154,608 in 2050. The total number of DC public charging stations is 488 in 2030 and 3,549 in 2050, shown in figure 15. The most interesting aspect of the graph is that the required amount of charging stations in 2030 is lower than the number of charging stations installed currently, which are also shown in figure 15. This can be explained by an increased occupancy rate of the public charging stations. This means that one charging station can supply the electricity for several EVs. In 2016, there were approximately 100,000 EVs and 25,000 public charging stations (figure 6), 1 charging station per 4 EVs. In 2030, the number of EVs increases to approximately 2 million, while the required number of public charging stations is approximately 22,000: 1 charging stations for 62 EVs. To put this number into perspective, it is compared to the number of gas stations. There were 4198 gas stations in the Netherlands in 2015 (Rabobank, 2016). Assuming that an average gas station has 6 refuelling stations and there were 7,979,083 passenger cars in the Netherlands in 2015, there is one refuelling station per 316 cars. If an average gas station has 8 refuelling stations, there is one refuelling station per 238 cars. This means that there are more public charging stations required, compared to gas stations. Another explanation for the decrease in number of public charging stations is that charging power increased from 11 kW AC to 22 kW AC and from 50 kW DC to 150 kW DC.

The figure also shows a significant increase in demand for public charging stations towards 2050. This is caused by the increase in EVs from 2 million in 2030 to 9.5 million in 2050. Table 10 shows that the number of BEVs increases from 595,000 to 7,100,000, while only 900,000 extra PHEVs are on the road. BEVs drive fully electric and PHEVs only partially. Therefore the electricity demand for charging increases harder with increasing number of BEVs, compared to an increasing number of PHEVs, which was the case before 2030. In 2050 there are 158,157 public charging stations, see figure 15. Combined with the 9,460,000 EVs in 2050, of which 65 percent uses public charging infrastructure. This results in one charging station per 39 vehicles. This can be explained by the increasing share of BEVs, which require more electricity per day, because the percentage of electrically driven kilometres is higher.

The main outcome of the reference scenario is that there is sufficient public charging infrastructure installed to satisfy the charging demand in the reference scenario up to 2030. However, this is only the case when charging power is increased to 22 kW AC and 150 kW DC and occupancy rate increases to 8 hours of charging per day. After 2030, increasing number of EVs and no further increase in charging power require more charging infrastructure.

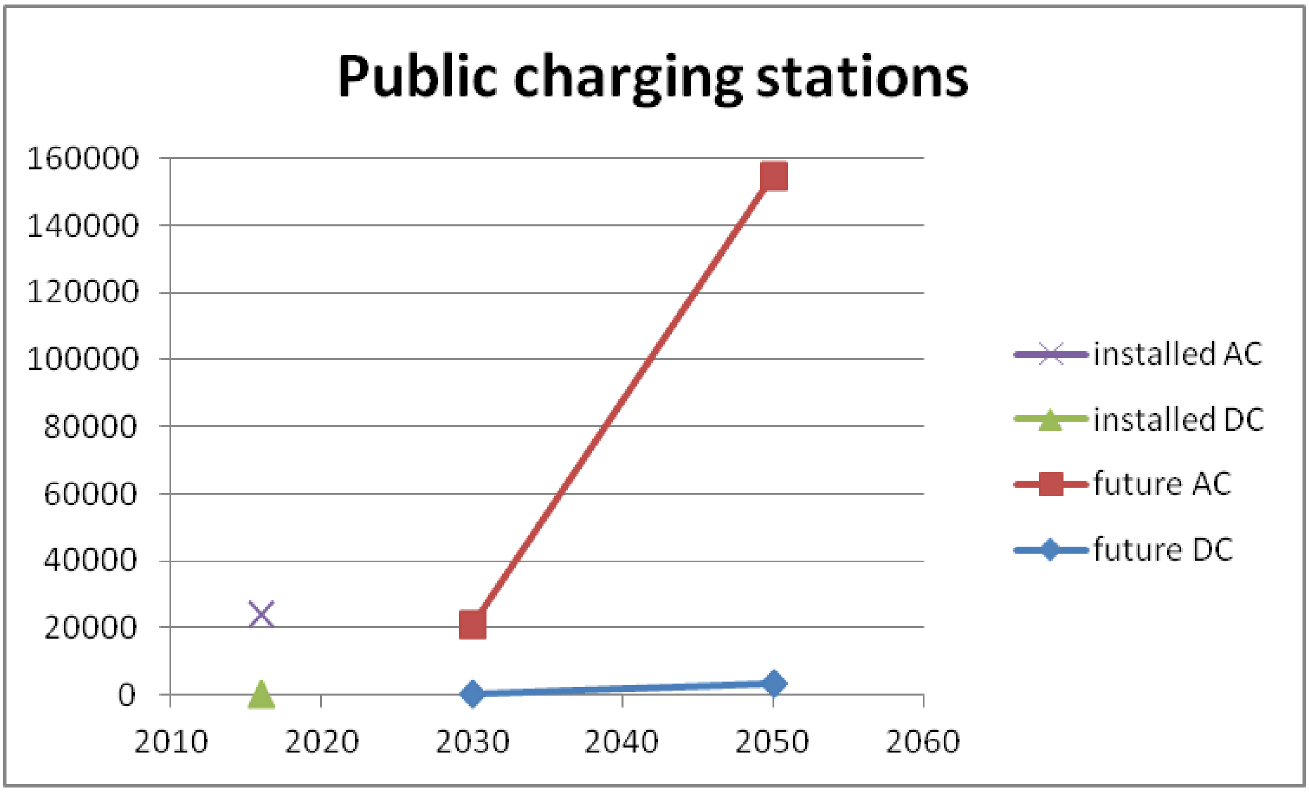


Figure 15. The development in number of public charging stations in the Netherlands in the reference scenario

4.4 Alternative scenarios

This section will explore and elaborate on the alternative scenarios. The first step is to identify critical uncertainties. The scenario framework is constructed by varying the development of the critical uncertainties. Finally, the narrative and quantitative analysis of each scenario is presented.

4.4.1 Critical uncertainties

In this section, the indicators are analysed on the degree of uncertainty in the future development and on the importance. The key questions are *How large is the variation in the range of future developments for this driver?* And *Does the range in development of the driver leads to large differences in the development of the overall system?* The degree of uncertainty is expressed as the difference between the low and high development estimate, in percentages. The author believes that high uncertainty is expressed as an uncertainty over 100 percent. An indicators scores moderate on uncertainty with an uncertainty between 25 and 50 percent, while low uncertainty is defined as an uncertainty lower than 24 percent.

Importance is expressed as the effects on charging infrastructure demand when the indicator fluctuates. According to the author, importance is labelled high when an increase in the indicator leads to an almost linear increase or decrease in charging demand, e.g. an increase in the indicator with 20 percent leads to an increase in charging demand higher than 15 percent. Importance is labelled moderate when an increase in the indicator leads to an increase or decrease in charging station demand, smaller than linear, e.g. and increase in the indicator of 20 percent leads to an increase in charging demand between 10 and 15 percent. The importance is labelled low when the effects are low, e.g. an increase of 20 percent in the indicator leads to an increase or decrease in charging station demand of less than 10 percent. The indicators, identified in section 4.2.1, are car ownership, mobility, energy efficiency, battery specific energy and charging power.

Car ownership scores low on uncertainty. Several models exist on future development of this indicator. The prediction of the sustainable fuels vision is used as a high estimate, while the current car ownership is taken as a low estimate. This would mean that car ownership does not grow towards 2050. The difference is 17 percent, which falls in the low category. The indicator scores low on importance. Less cars can lead to less kilometres driven, but it could also be that the annual mileage of the remaining cars goes up, resulting in the same mobility. In this case, the total charging demand would not decease as much as the number of vehicles declines: the relation is non-linear.

Mileage scores low on uncertainty. Again, several models exist on future development of mobility, including the PBL reference scenario (Nijland et al., 2012). This model estimates future mobility to increase to 134 percent of current levels. Combined with the number of cars, these results in a daily mileage of 43.6 km per day. The low estimate is the current mileage: 39.6 km per day. The difference is 10 percent. Mileage scores low on importance, since 10 percent more kilometres driven per day does not directly lead to 10 percent more charging demand, it could also mean that there are fewer cars and mobility remains constant, similar to the car ownership indicator.

Energy efficiency is scored moderate on uncertainty and high on importance. The high estimate is 81 percent efficiency of the overall drivetrain, while the low estimate is the current efficiency: 65 percent for the overall drivetrain. This is a difference of 25 percent, which falls close the border between the low and the moderate category. An increase in efficiency leads to linear decrease in electricity demand for charging and thus charging infrastructure demand.

Battery specific energy scores high on uncertainty. It is unclear which battery technology will develop to a successful market introduction in the future. The developments of Li-ion technology are also unsure. The low estimate is current specific energy of Li-ion cells, 180 Wh / kg. The high estimate is the potential specific energy of Li-air cells: 1,000 Wh / kg. This is a difference of 456 percent, which falls into the high category. The indicator also scores high on importance. Although the battery capacity does not influence the electricity demand, it determines the electricity demand per charging session: With a 10 percent higher specific energy of the battery, the vehicle has a 10 percent higher range. This means that it needs less frequent recharging. However, it will require more electricity to charge the battery to 100 percent. This means that battery capacity influences the preferred charging station type (fast or conventional charging). Therefore, the specific energy receives the label high on importance.

Charging power is rated high on uncertainty. It is unsure how the ratio between conventional AC charging and DC fast charging will be in 2050. It is also not sure how both technologies will develop. The importance of this indicator is high, since a 20 percent increase in charging power results in a 17 percent lower charging station demand. Moreover, the public charging system is completely different when conventional charging is the standard compared to when fast charging is dominant.

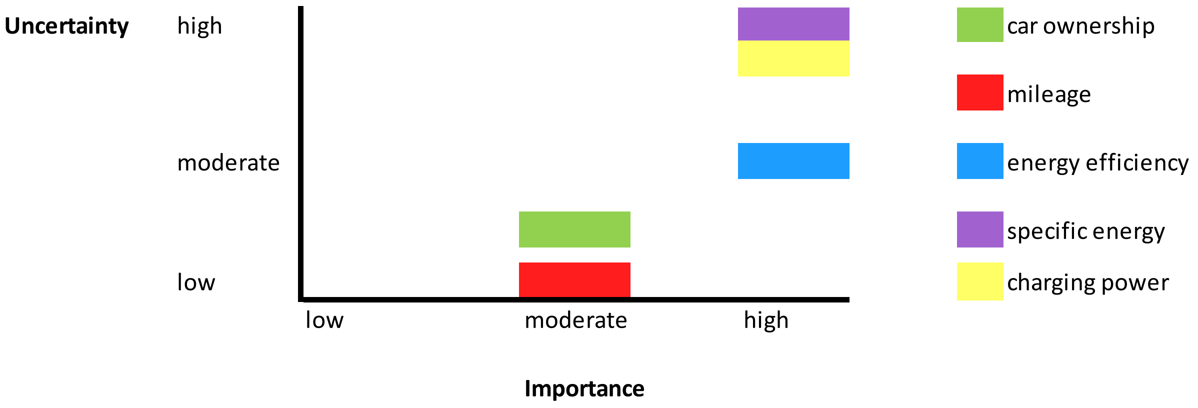


Figure 16. The degree of uncertainty and importance of each indicator

The two critical uncertainties are identified from figure 16: Battery specific energy and charging power.

4.4.2 Scenario framework

With these critical uncertainties, the scenario framework is constructed (figure 17). Battery specific energy can be expressed as the range of an EV and charging power can be expressed as the charging method used. This low range scenarios result from failures in development of Li-S and Li-air battery technologies. Therefore, the dominant technology in 2050 is Li-ion which developed only slightly after 2030, to 300 Wh / kg. The high range scenarios result from successful development of Li-air battery technology to 1,000 Wh / kg.

The charging method is varied from conventional AC (slow) charging to DC fast charging. The charging power depends on the battery capacity. Higher battery capacities require higher charging power, to prevent long charging times. Acceptable charging times are approximately 8 hours for AC charging and up to 30 min for fast charging. However, faster charging is preferred, around 10 minutes (S. Reitsma, personal communication, 18-11-2016). The resulting charging powers are 11 kW AC and 50 kW DC for low range scenarios and 44 kW AC and 350 kW DC for high range scenarios.

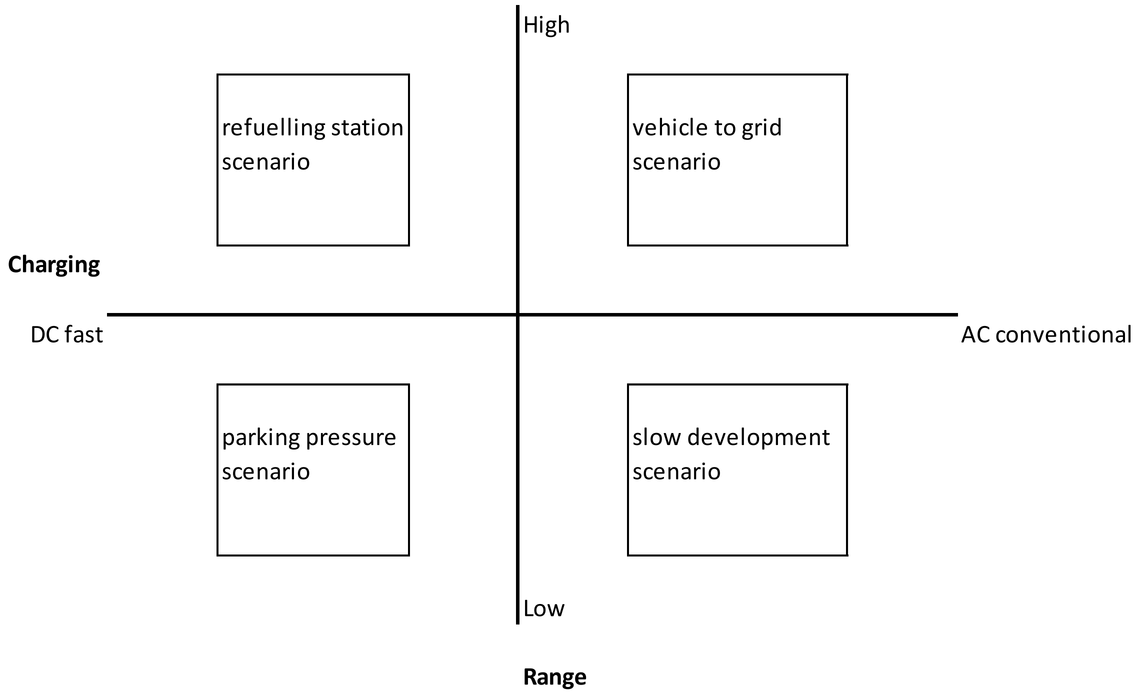


Figure 17. The scenario framework

The scenario with high range and DC fast charging is called the refuelling station scenario, since the EVs have high range, similar to internal combustion engine vehicles, and quickly recharge the battery at DC fast charging stations, similar to the gas station system currently in place. The scenario with high range and AC charging is called the vehicle to grid scenario. EVs have high range, so they have sufficient battery capacity to deliver electricity back to the grid through an AC charging station. The scenario with low range and DC fast charging is called the parking pressure scenario. The shortage in parking spaces emerged from the increasing number of cars in the Netherlands and increasing urbanisation. Therefore, AC charging technique was abandoned and a network of DC fast charging stations was installed to supply the electricity for charging. The slow development scenario is caused by slow development in battery technology, leading to low range. Charging power also remained low and mainly AC.

4.4.3 The refuelling station scenario

Narrative

The refuelling station scenario combines DC fast charging and high range. Battery capacity increased significantly due to successful implementation of lithium air batteries with a high specific energy. This facilitated an increase in average range to 1,600 kilometres. This is similar to current passenger vehicles with high range, e.g. 1,900 kilometres for the Mercedes E 300 Hybrid (ANWB, 2016).

The electric vehicles have a high range, so recharging every day is often not necessary. Recharging is done at a DC fast charging station at a strategically chosen locations, e.g. alongside motorways and around cities. This is similar to the current situation with gas stations. Therefore the scenario is called gas station scenario. DC charging became the dominant charging method for several reasons. AC charging power is limited, leading to high charging times for EVs with high range. Additionally, the Dutch government supplied fast charging infrastructure companies with additional permits, which allowed them to sell additional goods and services at the fast charging stations. Examples are food and drinks, toilets and resting places. This increased the attractiveness for consumers, leading to increasing usage and profits for DC charging companies. AC charging stations faded out, since the technology could not compete with DC charging stations. To ensure convenient charging time, charging power increased to 350 kW. Mobility developed similar to the reference scenario, therefore the number of passenger vehicles and the daily mileage were equal. Energy efficiency also developed as in the reference scenario.

The refuelling station scenario addresses several important challenges in the development of EVs. The high charging power reduces charging time to convenient levels, allowing competition with gasoline and diesel powered cars. The development of battery capacity increased consumer acceptance of EVs by removing range anxiety. However, there are also downsides on the scenario. The DC fast charging technique is disruptive within a smart grid, due to high power demand and limited smart charging possibilities (B. M. H. de Brey, personal communication, November 4, 2016). Therefore, the development of a smart grid was inhibited by the development of the DC fast charging network.

Quantitative analysis

The indicators are assigned a value according to the narrative and developments in the refuelling station scenario. The indicators car ownership, mileage and energy efficiency are equal to the development in the reference scenario, since the scenarios differ only in the critical uncertainties: The indicators battery capacity and charging technology. The development of the indicators car ownership and energy efficiency are shown in table 10 and 16. However, due to larger range of PHEVs, the electrically driven kilometres of PHEVs increases from 26 percent currently to 50 percent in 2030 and 65 percent in 2050. This is in line with estimations from the sustainable fuels vision (Ministerie van Infrastructuur en Milieu, 2014). The effect on the mileage, electrically driven kilometres per day for a PHEV, is shown in table 23.

Table 23. The amount of kilometres per year, kilometres per day and electric kilometres per day

Year	Km per year	Km per day	Electric km per day PHEV
2014	14,436	39.6	10.3
2030	14,697	40.3	20.1
2050	15,920	43.6	28.4

Battery capacity

The high range for EVs in this scenario is the result of battery technology developments which increase the specific energy of the battery cells. In 2030 the specific energy is set to 500 Wh / kg and for 2050 this increases to 1,000 Wh / kg (Cluzel & Douglas, 2012). This is a high development scenario for Li-air battery technology. The resulting average range is shown in table 24. The number of days to recharging is obtained by dividing the average range by the average daily mileage.

Table 24. The average range and days to recharging for BEVs and PHEVs in 2030 and 2050

	2030		2050	
	BEV	PHEV	BEV	PHEV
Average range (km)	704	105	1,665	228
Days to recharging	17	5	38	8

Charging technology

Charging power developed together with battery capacity. With higher battery capacity, higher charging power was required to reduce charging times to convenient levels. Only DC fast charging is used in the refuelling stations scenario. The charging power is 150 kW in 2030 and 350 kW in 2050. However, the higher power cannot prevent an increase in charging time. The charging time is determined by calculating the time it takes to charge the battery from 0 to 80 percent. The results are shown in table 25. The table illustrates that charging time for PHEVs is 8 minutes or less, comparable to the time it takes to refuel a gasoline or diesel car. For BEVs, the recharging time is longer. Type A, B and C BEVs will be charged in approximately half an hour, while larger BEVs require one hour or longer to recharge. However, these BEVs only need recharging every 17 and 38 days in 2030 and 2050, so multiple shorter charging sessions are a viable alternative. Therefore it is concluded that the chosen charging powers are sufficient in this scenario.

Table 25. The charging time (in minutes) for BEVs and PHEVs in 2030 and 2050

		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	16		14	
Compact class	B	36	6	31	5
Compact middle class	C	40	6	34	5
Middle class	D	64	7	55	6
Higher middle class	E	88	8	75	7
SUV	L		8		7

The charging demand per day in 2030 and 2050, in kWh per day, is calculated from the indicators. The results are shown in table 26. The required number of charging stations is determined by the charging capacity of a single charging station. The same assumptions as for the reference scenario are used. The window of operation is 16 hours a day, during which the occupancy rate is 50 percent. The average charging power is 70 percent of total power. The charging capacity for a DC fast charging station is 840 kWh / day in 2030 and 1,960 kWh / day in 2050. The resulting required number of charging stations is shown in table 26. The number of vehicles per charging station is 191 in 2030 and 344 in 2050. This is similar to the number of cars per refuelling station in the current situation, as mentioned in the reference scenario.

Table 26. The charging demand and number of charging stations in 2030 and 2050

	2030	2050
Charging demand (kWh / day)	5,911,316	35,085,735
Number of charging stations	7,037	17,901

4.4.4 The vehicle to grid scenario

Narrative

The vehicle to grid scenario combines AC charging with high range. The charging infrastructure and EVs are designed to be able to charge and discharge the vehicle, according to electricity demand. As with the previous scenario, range increased due to lithium air battery technology developments. The high range allowed for the development of a vehicle to grid system: EV owners have enough range to satisfy their own mobility and deliver electricity back during a peak in electricity demand. The development towards a smart grid was stimulated by new policies. The right to a charging space for

EV owners was implemented to provide EV owners with an easily accessible parking space with charging station. This resulted in a large network of AC charging stations at parking spaces. Another regulation implemented was the adaptation of tax rates on electricity. Currently, EV owners pay the electricity tax up to three times in the vehicle to grid system. The first time when they supply surplus electricity to the grid from their solar panels. The second time when they charge their EV with public charging infrastructure and the third time when the EV supplies the electricity back to the grid during peak hours. This limits the profitability and viability of a vehicle to grid network (B. M. H. de Brey, personal communication, November 4, 2016). The regulations were changed so that the electricity tax was only paid once and electricity prices for consumers were made flexible: High rates during peak hours and low rates during low electricity demand. A nationwide, profitable vehicle to grid network was developed with EV drivers willing to plug in their car at the charging station, especially during peak hours.

With increasing number of electric vehicles, the infrastructure changed to ‘charging squares’. One charger is connected to several parking spots and it divides the charging power between these cars. Depending on the wishes of the EV driver, the charging station would determine the charging power and the amount of electricity that the EV driver is willing to deliver back to the grid. The EV drivers are stimulated, e.g. by lower costs, to use low charging power and allow large deliveries back to the grid. This ensures a large flexibility and more options for grid balancing (S. Reitsma, personal communication, 18-11-2016). High charging power is required, to maximise the uptake op surplus electricity in the EVs during a peak of renewable electricity supply and to maximise the discharging capacity during electricity shortages.

The other indicators regarding mobility and energy efficiency developed in the same way as in the reference scenario.

Important barriers to the large uptake of EVs were tackled in the scenario. The vehicle to grid network provides additional tools to balance the electricity grid. This will be important in the future, when renewable energy will have a larger market share. Since the availability of renewable energy is fluctuating, larger peaks and shortages are likely to occur on the electricity grid. A vehicle to grid system could help stabilise the system, reducing extra investments in the rigidity of the electricity grid. Another barrier that was taken is the low range of EVs. The development of lithium air batteries provided EVs with a higher range, increasing consumer demand.

The downside of the vehicle to grid system is that fast charging is not available. The system benefits from charging stations where a car is plugged in without the need of charging. This is not the case at current gas station locations. Therefore, charging stations alongside motorways do not fit well into the scenario. This can be an issue on long trips where recharging on the road is necessary.

Quantitative analysis

The indicators are assigned a value based on the narrative and developments in the vehicle to grid scenario. As in all other scenarios, the indicators car ownership, mileage and energy efficiency are equal to the development in the reference scenario. This development of these indicators is shown in table 10, 12 and 16 respectively. However, due to larger range, the electrical mileage of PHEVs increases from 26 percent to 50 percent in 2030 and 65 percent in 2050. The effect on the electrical mileage per day for a PHEV is shown in table 23.

Battery capacity

The high range for EVs in this scenario is the result of battery technology developments which increase the specific energy of the battery cells. In 2030 the specific energy is set to 500 Wh / kg and for 2050 this increases to 1,000 Wh / kg (Cluzel & Douglas, 2012). This is a high development scenario for Li-air battery technology. The resulting average range is shown in table 24. The number of days to recharging is the number of days a car can drive with a single battery charge. It is obtained by dividing the average range by the average daily mileage, which is also shown in table 24.

Charging technology

Charging power developed together with battery capacity. Higher battery capacity requires higher charging power to keep charging times at convenient levels. Only AC charging is used in the vehicle to grid scenario. The charging power is 22 kW in 2030 and 44 kW in 2050, compared to a maximum of 11 kW today. This higher charging power reduces charging times. The time required to recharge an empty battery for each vehicle class is shown in table 27. As can be seen from the table, the charging times are equal for 2030 and 2050. This is caused by the doubling in battery capacity from 2030 to 2050, while the charging power also doubles from 22 kW to 44 kW, leading to equal charging times. Charging times for PHEVs are approximately 1 hour. The charging time for a BEV varies from 2 hours for a class A BEV to 12.5 hours for a class E BEV. This means that class A, B and C BEVs can recharge the battery overnight, while class D and E BEVs need longer timeframes. However, these BEVs only need recharging every 17 and 38 days in 2030 and 2050, so multiple shorter charging sessions are a viable alternative. Therefore it is concluded that the chosen charging powers are sufficient in this scenario.

Table 27. Charging time (in hours) for each vehicle class in 2030 and 2050

		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	2.3		2.3	
Compact class	B	5.1	0.8	5.1	0.8
Compact middle class	C	5.7	0.9	5.7	0.9
Middle class	D	9.1	1.0	9.1	1.0
Higher middle class	E	12.5	1.1	12.5	1.1
SUV	L		1.1		1.1

The charging demand per day in 2030 and 2050, in kWh per day, is calculated from the indicators. The results are shown in table 28. The required number of charging stations is determined by the charging capacity of a single charging station. The same assumptions as for the reference scenario are used. The occupancy rate is 33 percent: 8 hours a day. The charging capacity for an AC charging station is 176 kWh / day in 2030 and 352 kWh / day in 2050. The resulting required number of charging stations is shown in table 28. The number of vehicles per charging station is 40 in 2030 and 62 in 2050. This is significantly lower than the current situation, where one gasoline refuelling station serves approximately 200 to 300 vehicles (see the reference scenario for details). This is caused by the relatively low charging power. The results are that more space is required for recharging EVs compared to refuelling gasoline and diesel powered vehicles. This effect is mitigated by the possibility of installing a charging station next to a parking space, which is often not possible for a gasoline refuelling station, due to safety issues.

Table 28. The charging demand and number of charging stations in 2030 and 2050

	2030	2050
Charging demand (kWh / day)	5,911,316	35,085,735
Number of charging stations	33,587	99,675

4.4.5 The parking pressure scenario

Narrative

The scenario rises from the combination of DC fast charging and EVs with low range. Low range is caused by slow developments in battery technology. Alternative battery technologies failed to become competitive and reach the market, while lithium ion batteries developed only slightly after 2030.

The main reason for the preference of DC fast charging over AC charging is the limited availability of public parking places in this scenario. The increase in number of passenger vehicles in the Netherlands and increasing urbanisation caused high parking pressure in cities. The government and municipalities rearranged public space in urban areas, with less public parking space. This was done to increase the attractiveness of cities and improve liveability. The idea was that public parking space was an inefficient way of utilizing the available public space in cities. Charging is done at fast charging stations at strategically locations, e.g. outside urban areas, to prevent EVs occupying public parking space for charging. To facilitate fast charging stations, extra permits were issued to extend the services the charging stations could provide. Sales of foods and drinks and toilets services boosted the profit of fast charging stations, which developed quickly to a nationwide network. AC charging at public parking space was no longer necessary and disappeared. Since battery developments slowed down after 2030, increasing charging power was not required. Therefore the charging power was 150 kW in 2030 and 2050. The other indicators followed the same development as the reference scenario.

Challenges that were addressed in this scenario are the ‘pollution’ of public space by placing charging stations next to parking spaces. Increasing market penetration of EVs would lead to more objects in public space, contrasting with the desire of most municipalities to reduce the number of objects in public space (Ministerie van Infrastructuur en Milieu, 2014). The fast charging model is similar to the system which is used today for gasoline and diesel cars. Consumers can make the transition towards an EV without a major behavioural change in terms of refuelling the vehicle. A disadvantage of the scenario is that DC fast charging technique is disruptive within an electrical grid, due to high power demand and limited smart charging possibilities. This increases the challenge for grid operators to ensure grid balance at all times.

Quantitative analysis

As with the other two scenarios, the indicators car ownership, mileage and energy efficiency are equal to the reference scenario. However, since the range is limited in this scenario, PHEVs will drive less on the electric drivetrain, estimated at 50 percent of their mileage in 2030 and 2050. The development of the indicators car ownership and energy efficiency is shown in table 10 and 16. The electric mileage of a PHEV is shown in table 29.

Table 29. The amount of kilometres per year, kilometres per day and electric kilometres per day

Year	Km per year	Km per day	Electric km per day PHEV
2014	14,436	39.6	10.3
2030	14,697	40.3	20.1
2050	15,920	43.6	21.8

Battery capacity

The relatively low range for EVs in this scenario is the result of limited battery technology developments. The Li-air and Li-S technologies failed to reach the market, so Li-ion remained the dominant technology. In 2030 the specific energy is lower compared to the reference scenario, 250 Wh / kg. After 2030, battery technology only develops slightly, for 2050 the specific energy increases to 300 Wh / kg. This is a low development scenario for Li-ion battery technology. The resulting average range is shown in table 30. The number of days to recharging is obtained by dividing the average range by the average daily mileage.

Table 30. The average range and days to recharging for BEVs and PHEVs in 2030 and 2050

	2030		2050	
	BEV	PHEV	BEV	PHEV
Average range (km)	352	53	500	69
Days to refuelling	9	3	11	3

Charging technology

Due to high parking pressure and profitability of fast charging stations at service areas, the parking pressure scenario consists of DC fast charging stations. The low range of the EV does allow for relatively low charging power: 150 kW in 2030 and 2050. The charging time is measured as the time it takes to charge the battery from 0 to 80 percent of charge. The results are presented in table 31. From the table can be seen that charging times for a PHEV is 5 minutes or lower. A disadvantage is that these models need recharging every 3 days on average. Fast charging a BEV can be done in (under) half an hour for class A to D BEVs, for class E BEVs the charging time is 44 minutes in 2030 and 53 minutes in 2050. Since these models have a higher range, and therefore need less frequent recharging, multiple smaller charging sessions could be an alternative.

Table 31. Charging time (in minutes) for each vehicle class in 2030 and 2050

		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	8		10	
Compact class	B	18	3	22	3
Compact middle class	C	20	3	24	4
Middle class	D	32	4	38	4
Higher middle class	E	44	4	53	5
SUV	L		4		5

The indicators provide the information needed to obtain the charging demand. The charging demand (in kWh per day) in 2030 and 2050 is shown in table 32. The charging demand increases significantly from 2030 to 2050, mainly because a large increase in BEVs. The capacity of a single charging station is 840 kWh per day in 2030 and 2050. The resulting number of charging stations which provide this charging demand is also shown in table 32. The number of vehicles per charging station is 191 in 2030 and 156 in 2050.

Table 32.The charging demand and number of charging stations in 2030 and 2050

	2030	2050
Charging demand (kWh / day)	5,911,316	33,198,827
Number of charging stations	7,037	39,522

4.4.6 The slow development scenario

Narrative

The slow development scenario incorporates AC charging and low range. The low range is a consequence of slow development in battery technology: Lithium-ion technology fails to break through. AC charging became the preferred charging technique, since a policy which ensured the right on a charging point was implemented. The low range also made high charging power unnecessary. This lead to the disappearing of DC fast charging and low charging power of 11 kW.

Low range also prevented the successful rollout of a vehicle to grid network. EV owners needed the battery capacity to drive their vehicles. Supply of surplus electricity was too small to make a vehicle to grid network profitable. The electricity tax was also not changed, which also prevented vehicle to grid technology to become successful.

The challenge that this scenario tackled was to limit charging power to limit investments in infrastructure. A disadvantage of the slow development scenario is that the limited range of EVs and low charging power can be an issue on long trips.

Quantitative analysis

The indicators car ownership, mileage and energy efficiency are equal to the reference scenario. Range is limited in this scenario. Therefore PHEVs will drive less electric kilometres, estimated at 50 percent of their mileage in 2030 and 2050. The development of the indicators car ownership and energy efficiency is shown in table 10 and 16. The electric mileage of a PHEV is shown in table 29.

Battery capacity

The relatively low range for EVs in this scenario is the result of limited battery technology developments. The Li-air and Li-S technologies failed to reach the market, so Li-ion remained the dominant technology. In 2030 the specific energy is lower compared to the reference scenario, 250 Wh / kg. After 2030, battery technology only develops slightly, for 2050 the specific energy increases to 300 Wh / kg. This is a low development scenario for Li-ion battery technology. The resulting average range is shown in table 30. The number of days to recharging is obtained by dividing the average range by the average daily mileage.

Charging technology

Since battery capacity is limited in this scenario, a high charging power is not required. Charging power is set to 11 kW AC in 2030 and 2050. The resulting charging times are shown in table 33. In 2030, the charging time for a PHEV is approximately one hour. BEVs of class A to D can be charged overnight, while class E BEVs require 12.5 hours to recharge. In 2050, charging times increase. A PHEV can be charged in under 1.4 hours, while BEVs of class A to C recharge in less than 7 hours. Class D BEVs require 11 hours to recharge. This can be done during the evening and overnight. Class E BEVs require 15 hours to recharge. However, the range of these vehicles is sufficient to facilitate multiple shorter charging sessions.

Table 33.Charging time (in hours) for each vehicle class in 2030 and 2050

		2030		2050	
		BEV	PHEV	BEV	PHEV
Mini class	A	2.3		2.7	
Compact class	B	5.1	0.8	6.1	1.0
Compact middle class	C	5.7	0.9	6.8	1.1
Middle class	D	9.1	1.0	10.9	1.2
Higher middle class	E	12.5	1.1	15.0	1.4
SUV	L		1.1		1.4

The indicators provide the input for calculating the charging demand per day, see table 34. The capacity of a single charging station is 88 kWh per day in 2030 and 2050. The number of charging stations required to facilitate the charging demand is shown in table 34. The number of vehicles per charging station is 31 in 2030 and 25 in 2050.

Table 34. The charging demand and number of charging stations in 2030 and 2050

	2030	2050
Charging demand (kWh / day)	5,911,316	33,198,827
Number of charging stations	67,174	377,259

4.5 Implications

This section interprets the results of the scenarios. First the electricity demand for charging and the requirements for the total number of charging station per scenario are described. After that an indication of the costs for public charging infrastructure per scenario is provided. Another way of comparing the scenarios is analysing the impact on the electricity grid by reviewing the potential peak demand and the electricity demand for charging during the day.

Charging demand

Charging demand is similar for all scenarios, since the number of vehicles and daily mileage are equal. However, in the reference scenario, the parking pressure scenario and the slow development scenario, the PHEVs drive less kilometres with the electric drivetrain in 2050. Therefore, the electricity demand in these scenarios is slightly lower than that of the refuelling scenario and the vehicle to grid scenario. To illustrate the magnitude of the electricity demand for public charging, it is compared to the average electricity consumption in the Netherlands from 2010 to 2015, which was 119,696 million kWh per year (CBS Statline, 2016a). Table 35 shows the electricity demand for charging as the percentage of the total electricity consumption. The most interesting aspect of the table is that in 2030 the electricity demand for charging is only 2 percent of current total electricity consumption. In 2050 the percentage increases to a maximum of 10.7 percent of current total electricity consumption. Considering this is only for passenger vehicles, this is a significant amount.

Table 35. The electricity demand for charging in terms of the percentage of total electricity consumption in 2016

	Electricity demand for charging	
	2030	2050
Reference scenario	1.3%	9.2%
Refuelling station scenario	1.8%	10.7%
Vehicle to grid scenario	1.8%	10.7%
Parking pressure scenario	1.8%	10.1%
Slow development scenario	1.8%	10.1%

Number of charging stations

The required number of public charging stations follows from the electricity demand. It is shown for each scenario in figure 18. The increase from 2030 to 2050 is explained by the significant increase in BEV sales after 2030. Even though the refuelling station scenario has the highest electricity demand for charging, it requires the least number of charging stations: Almost 18,000. This is a consequence of the high charging power in the scenario. Each charger can supply the charging demand of more cars, compared to the other scenarios. The parking pressure scenario also requires relatively few public charging stations: almost 40,000. The vehicle to grid scenario requires more public charging stations, almost 100,000, since the system depends on AC charging stations instead of DC fast charging stations. The slow development scenario requires the most charging stations, since charging power is low in this scenario: Over 375,000 charging stations.

It is important to realise that the typical number of DC charging stations per fast charging refuelling station is 4 (Fastned, 2016a). This means that the total number of fast charging refuelling stations is one fourth of the total number of fast charging stations. For the refuelling station scenario, the required number of fast charging refuelling stations is 4,475 in 2050. This number is similar to the number of gas stations in the Netherlands, which is 4,200 (Rabobank, 2016). Consequently, in this scenario the charging demand can be met by reforming gas stations into fast charging stations. For the parking pressure scenario, the required number of fast charging refuelling stations is 9,881. This would require an increase in the number of refuelling station areas, or more charging stations per fast charging station.

For AC charging in the vehicle to grid scenario, one charging station has 4 charging connections: One charging station serves 4 EVs on 4 parking spaces. However, this means that the charging power is divided over these 4 connections. The total number of AC charging parking spaces in the vehicle to grid scenario is 4 times the number of charging stations: 398,702. For the slow development scenario, each charger serves 2 parking spots, similar to the current situation. Therefore the total number of AC charging parking spaces in the slow development scenario is 754,519.

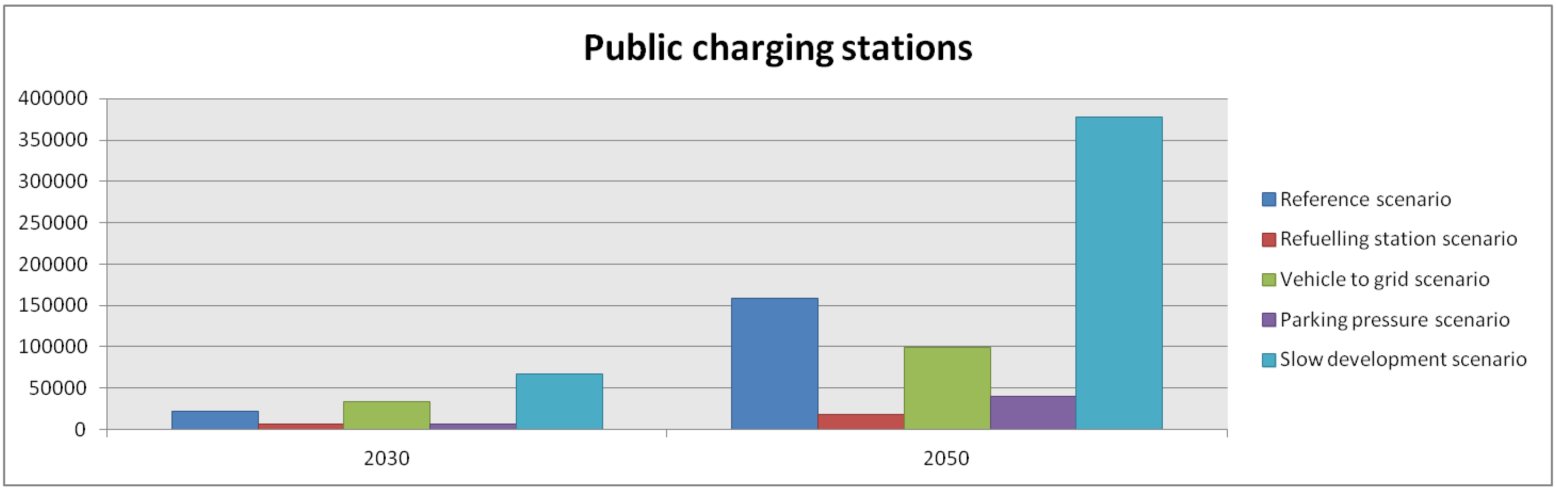


Figure 18. The required number of public charging stations in each scenario

The number of required charging stations in 2030 in the reference scenario is lower than the current installed number of charging stations (approximately 25,000). For the vehicle to grid scenario, the number of charging stations is only slightly higher with 33,500 charging stations. Thus although the number of EVs increases, the number of required charging stations is similar to the current installed capacity. This can be explained by the higher occupancy rate for the charging stations in the scenarios, compared to the current situation. The increase in number of EVs leads to the higher occupancy rate, since there are more EVs per charging station. Another factor is the increased charging power, which increases the capacity of a charging station. The results imply that it can be beneficial to focus on improving occupancy rate and increasing charging power of existing public charging infrastructure, rather than adding new public charging stations. In that case, the current installed charging stations can supply sufficient electricity for the near future, which removes the necessity to place more objects in public space. However, it is important to realise that when the occupancy rate does not increase, new public charging stations are required sooner.

After 2030, the increase in public charging infrastructure is inevitable with higher numbers of EVs on the road, particularly BEVs. However, the required number of DC fast charging stations can still be provided by converted gas stations. For the refuelling scenario, which requires almost 18,000 charging stations, 3,000 of the existing 4,200 gas stations can be converted to DC fast charging stations with 6 chargers each. The parking pressure scenario requires almost 40,000 DC fast charging stations. This can be achieved by converting 4,000 gas stations to fast charging stations with 10 chargers each.

Costs

The estimation of future costs of public charging infrastructure falls outside the scope of this research. However, it is useful to give an indication of the total costs. To do this, the current costs for charging infrastructure are analysed and used to calculate the total costs for public charging infrastructure in the scenarios. The costs for a public AC charging station depend on the costs for hardware and installation. Installation costs are determined by the distance to the breaker box (Rocky Mountains Institue, 2016). The average costs are € 2500 per charging point (Figenbaum, Assum, & Kolbenstvedt, 2015). This is confirmed by the estimation of $ 6,000 per two charging points from Rocky Mountains Institue (2016).

For DC fast charging stations, the costs range from € 60,000 to € 125,000 per charging station (Figenbaum et al., 2015). The Rocky Mountains Institue (2016) estimates the costs at $ 60,000. The costs increase by the necessity of a 480 V transformer, which costs $ 10,000 to $ 25,000. The costs per charger are lower when a fast charging station consists of multiple chargers, since planning, permit and labour costs are divided (Figenbaum et al., 2015). Since the scenarios in this study contain 4 chargers per fast charging station, the total costs per charging stations are estimated at € 70,000.

The total public charging infrastructure costs per scenario are displayed in table 36. From the table it becomes apparent that the total costs are lower for the AC charging scenarios than for the DC fast charging scenarios, when expressed in current costs. The costs are the lowest for the vehicle to grid scenario and the highest for the parking pressure scenario. This is explained by the differences the critical uncertainties: The scenario with high charging power and AC charging technology leads to lower costs, while the scenario with relatively low charging power and DC fast charging technology leads to higher costs. However, this is only an indication, since charging infrastructure costs will most likely decrease towards 2050.

Table 36. The total public charging infrastructure costs per scenario

	Costs	
	2030	2050
Reference scenario	€ 87,228,139	€ 634,965,302
Refuelling station scenario	€ 492,609,630	€ 1,253,061,970
Vehicle to grid scenario	€ 83,967,551	€ 249,188,460
Parking pressure scenario	€ 492,609,630	€ 2,766,568,949
Slow development scenario	€ 4,702,182,829	€ 943,148,505

Impact on the electricity grid

Another way to compare the scenarios is to determine the impact on the electrical grid. First the potential peak demand is calculated for the scenarios. The potential peak demand is obtained by multiplying the number of charging stations with the charging power. This presents the power demand when all chargers are in use simultaneously. The results are shown in table 37. The potential peak demand is equal for all scenarios in 2030: 739 MW. This is caused by the fact that electricity demand for charging is equal in all scenarios, as well as the charging time per charger per day (8 hours). 750 MW is similar to the production of a power plant in the Netherlands, e.g. the natural gas powered power plant in Moerdijk supplies 769 MW of electrical power. The extra peak demand can be met by installing one extra power plant. Another way of supplying this peak demand is by installing 300 extra 2.5 MW wind turbines. However, this solution might be less viable, since there might be a mismatch between demand for charging and electricity supply from the wind turbines, and the space to place these wind turbines might not be available.

The potential peak demand increases to 4,386 MW in 2050 for the refuelling stations scenario and the vehicle to grid scenario. The other scenarios score lower since the electricity demand for charging is lower in these scenarios, due to fewer kilometres driven electrically by PHEVs. The reference scenario also has a lower peak demand for the same reason.

Table 37. The number of charging stations, charging power and potential peak demand for each scenario

Scenario	Number of charging stations		Charging power (kW)		Potential peak demand (MW)	
	2030	2050	2030	2050	2030	2050
Reference scenario	21,727	158,157	24	24	518	3,774
Refuelling station scenario	7,037	17,901	105	245	739	4,386
Vehicle to grid scenario	33,587	99,675	22	44	739	4,386
Parking pressure scenario	7,037	39,522	105	105	739	4,150
Slow development scenario	67,174	37,7259	11	11	739	4,150

Charging demand

Even though the potential peak power is similar for the scenarios, the division of charging demand over the day is not. To understand why the moment of charging is important, the electricity demand in the Netherlands (in MW) is presented in figure 19, for four days in 2016: March 1st, June 1st, September 1st and December 1st (ENTSOE, 2016). During winter the electricity demand is higher, but the pattern over the day is similar for each day. Electricity demand peaks during 9 AM and 7 PM. The author expects the peak during the evening to be caused by turning on the lights, since the peak shifts during the seasons, similar to the sunset. The difference between the peak demand and lowest demand is around 6,000 MW.

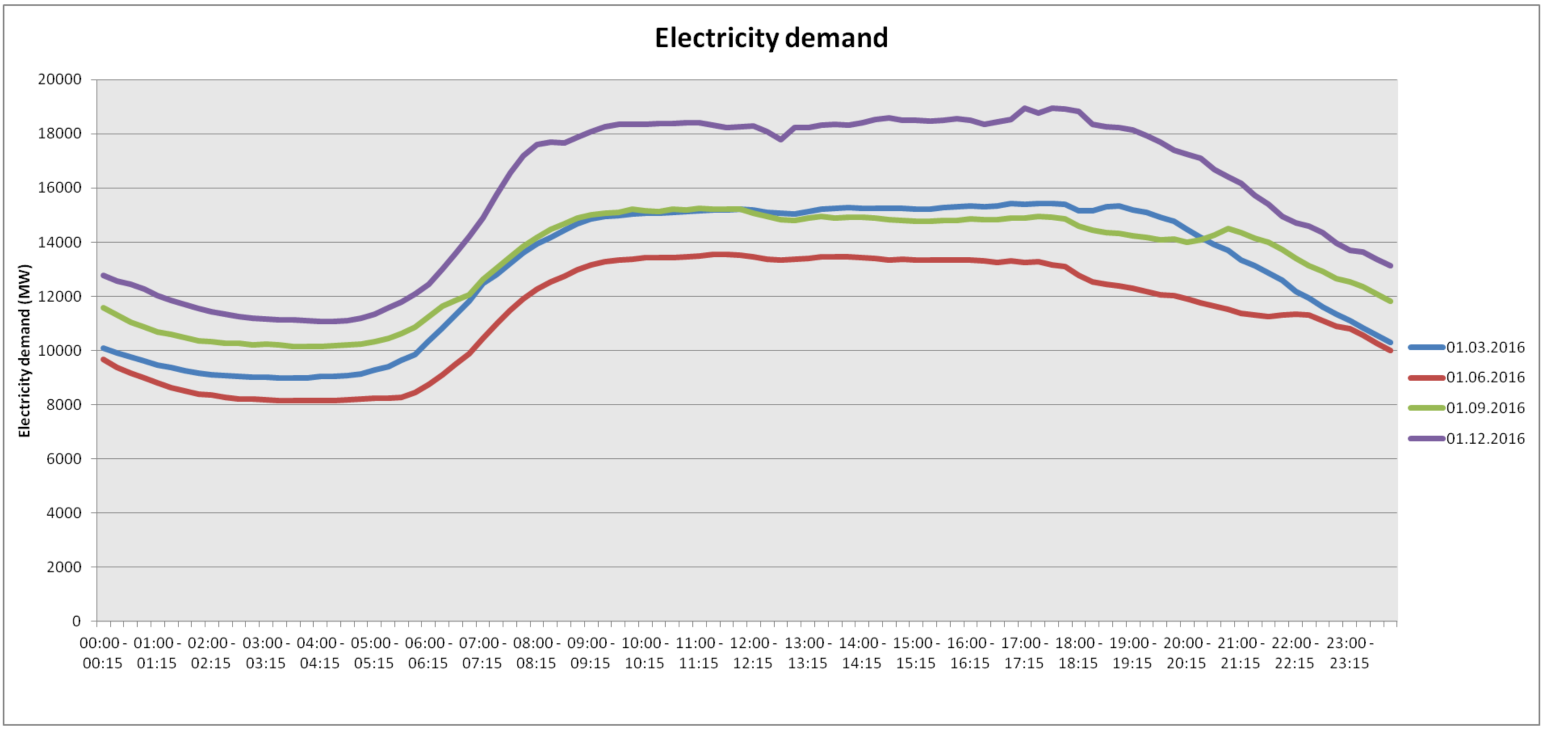


Figure 19. The electricity demand in the Netherlands for four different days in 2016 (ENTSOE, 2016)

AC charging infrastructure is used differently from DC charging infrastructure in the scenarios. The main assumptions are that half of the AC charging stations is used during the day, from 9.00 to 17.00, and the other half during the night, from 23.00 to 7.00. DC chargers are used from 7.00 to 23.00, where the occupancy rate is 50 percent.

The vehicle to grid scenario charging demand is expanded by giving electricity back to the grid during peak hours. To compensate, extra charging is done during low hours. The goal is to limit the peak of electricity demand during the day and limit the impact on the grid from charging EVs. The discharging during peak hours is done by the chargers at home locations, since these chargers are not used for charging during the day. The chargers at office locations are not used to discharge during peak hours, since these chargers are already charging during the day. At night, these chargers are abandoned. The discharging during peak hours must be compensated by charging during low hours. However, during 23.00 to 7.00 all chargers are used for charging already, so extra charging is done outside these hours: From 19.00 to 21.00 on half power, since total electricity demand is still relatively high during these hours. From 21.00 to 23.00, the chargers are used at full charging power to charge extra. The last period for charging extra is from 7.00 to 9.00, again at half power to prevent a peak in charging demand. In total, 4 hours of full power charging on half the number of AC charging stations can be supplied extra during low hours. This is the amount that can be discharged during peak hours. The peak hours are identified: From 9.00 to 17.00. This means that half of the home based charging stations can be used for discharging, since the discharged capacity must be equal to the extra capacity charged during low hours.

The chosen method of discharging during peak hours results in the discharging of 176 kWh per day per charger. In the vehicle to grid scenario, each charger is connected to 4 parking spots. Therefore, the discharging is 44 kWh per car per day. The average battery capacity is 227 kWh in 2050, so each day 19.4 percent of the average battery capacity is discharged and delivered back to the grid. This leaves sufficient battery capacity to drive the daily mileage of 43.6 km per day per car. The system does not require each car to participate. Assuming only BEV owners will be interested in delivering electricity back to the grid, and the number of charging stations is 99,675, the total number of cars which van participate in the vehicle to grid system is 398,702. This is only 5.6 percent of all BEVs in 2050. In the vehicle to grid scenario, the discharging of EVs reduces electricity demand by 1,100 MW from 9.00 to 17.00. However, this capacity can be expanded by changing the charging patterns in such a way that no charging is done during the day. This makes all charging stations available for discharging. In that case, the discharging capacity of the system is equal to the potential peak demand, which is 4,386 MW.

Another option is to use the discharging capacity of the system at another time frame, e.g. during the night. The extra charging could be done during the daytime peak of solar PV electricity supply. This can be an attractive option when the solar PV capacity is large, which leads to a surplus of electricity supply during the day, and potentially a deficit during the night. The vehicle to grid system could be used in this situation without changing the infrastructure or number of charging stations. The system can adapt to the situation, the only requirement is that each charging station is available for charging 8 hours a day, to provide the electricity demand for driving the EVs.

The slow development scenario does not utilize the discharging possibility, since charging power and battery capacity are limited. Therefore, the electricity demand for charging is divided from 9.00 to 17.00 and from 23.00 to 7.00.

DC charging does not incorporate a smart charging system. The electricity demand for charging in the refuelling station scenario and the parking pressure scenario both occurs from 7.00 to 23.00. The electricity demand during the day for each scenario is shown in figure 20. Even though peak demand is equal for the refuelling station scenario and the vehicle to grid scenario, the moment this peak demand occurs is not. The same applies for the parking pressure scenario and the slow development scenario. The reference scenario consists of a mix of DC and AC charging and has a lower total electricity demand, since the amount of electrically driven kilometres by PHEVs is lower. Therefore, the graph of the reference scenario is an intermediate between the other scenarios.

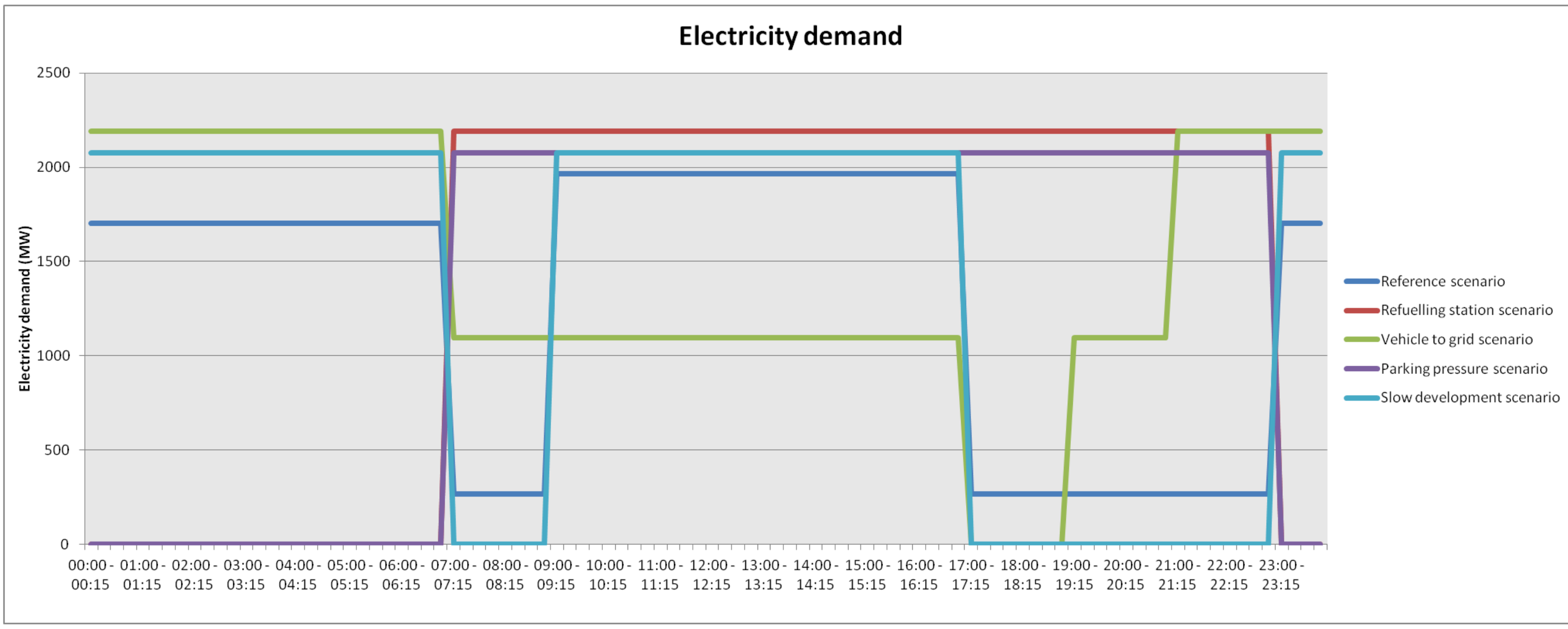


Figure 20. The electricity demand for charging in each scenario

To identify the impact on the grid of each scenario, the electricity demand during the day from figure 20 is added to the average total electricity demand in the Netherlands, obtained from averaging the electricity demand shown in figure 19. The results are shown in figure 21. What stands out in the figure is that the electricity demand peaks during the day, with the vehicle to grid scenario lowering the peak by 1,100 MW compared to the other scenarios. This is compensated by a higher demand for charging during the evening and night.

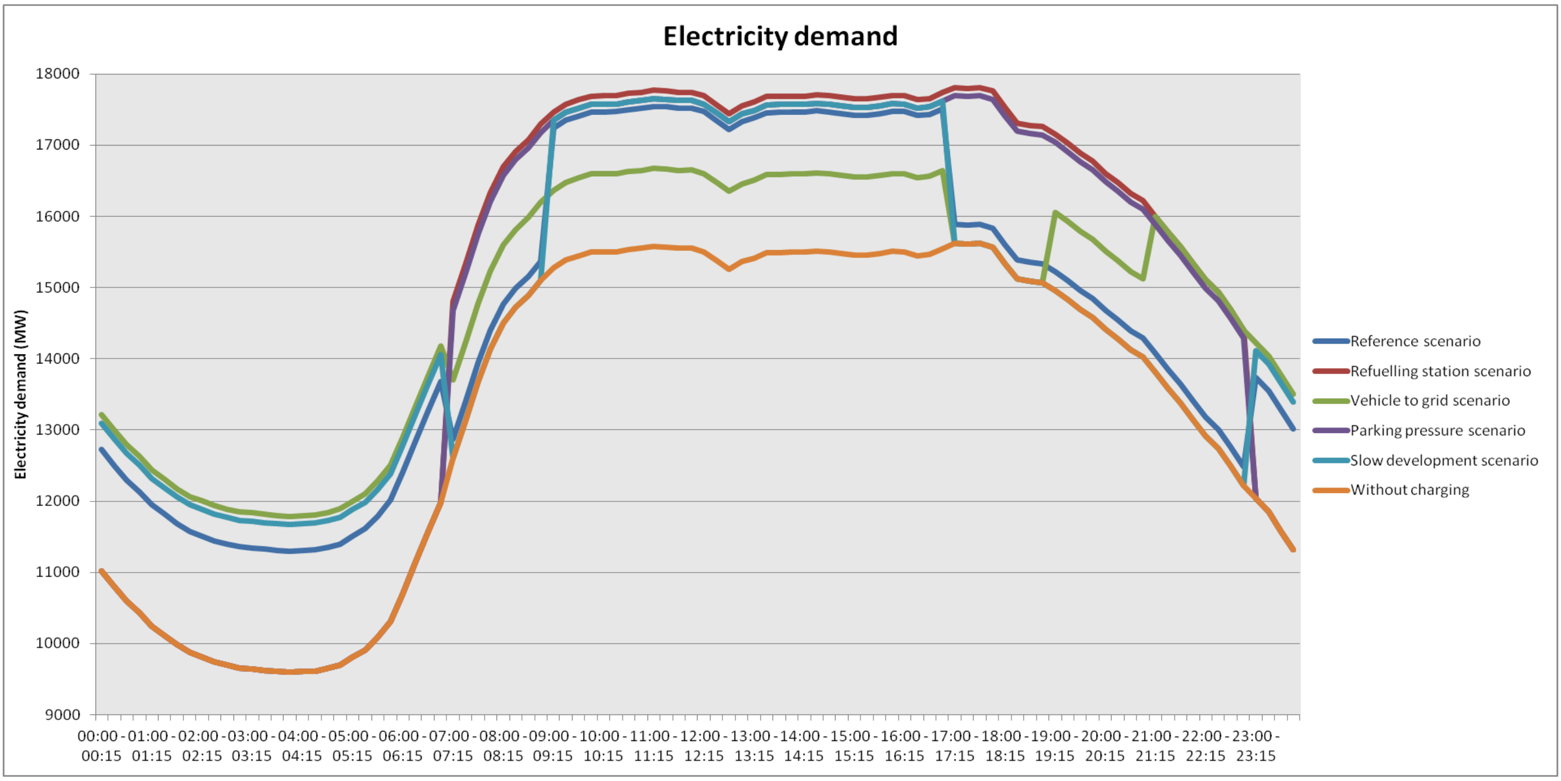


Figure 21.The impact of each scenario on the total electricity demand

Summarising, the four scenarios provide the same function: Supplying the electricity demand for charging all EVs in 2050. This demand in 2050 is approximately 11 percent of current electricity demand in the Netherlands. The scenarios with DC fast charging technology require the least number of charging stations. This is attractive when public parking spaces are limited. It is also preferred when battery capacity is high, since convenience for EV owners increases with low charging times. The DC fast charging stations can be placed at locations where currently gas stations exist. A way to stimulate DC fast charging is extending the services of fast charging stations provide, to improve profitability. Disadvantages of DC fast charging are the higher installation costs and the disruptive impact on the electricity grid.

AC charging technology requires more charging stations to provide the same electricity demand, since charging power is lower. The ability to supply electricity back to the grid is an unique property of the vehicle to grid scenario, which is useful in reducing peak demand for electricity as well as temporary storing a surplus of renewable electricity, e.g. from solar PV. In this study, the vehicle to grid scenario leads to a lower peak in electricity demand of 1,100 MW. A disadvantage of the AC charging system is the relatively low charging power. On average this is not an issue, since the average daily mileage is only 43.6 km in 2050. However, individual EV drivers may require a quick recharge on the road on long trips. The long range of EVs means that is only an issue on very long trips, and therefore this group will be relatively small.

5. Discussion

The discussion will cover the limitations of the research in section 5.1. Section 5.2 proposes directions for further research. Section 5.3 discusses policy implications.

5.1 Limitations of research

The main limitation of this research is that the model used to predict the required number of charging stations in 2050 contains several uncertainties. This is unavoidable when looking forward on a long time scale. Therefore, important uncertainties in the development of each indicator towards 2050 are described below.

The indicator car ownership corresponds with the ambition of the sustainable fuels vision that all passenger vehicles are EVs in 2050. However, there are alternatives. Hydrogen powered vehicles are currently under development and could develop to 2.5 million vehicles in 2050, in the case EV technology fails to develop sufficiently (De Tafel Wegvervoer Duurzaam Elektrisch, 2014). Another alternative are methane powered vehicles, which is called Green Gas. Methane is currently already used in passenger vehicles as an alternative for gasoline and diesel. There could be 3.5 million methane powered vehicles in 2050 (De Tafel Wegvervoer Duurzaam Elektrisch, 2014). When development of EVs fails, part of the passenger vehicle fleet in the Netherlands will consist of vehicles with other drivetrains. This would lower the electricity demand for charging, resulting in less required public charging stations. However, the aim of this research is to analyse the potential requirements on public charging infrastructure when all vehicles are EVs in 2050, so the author concludes that the chosen assumptions are justified.

The daily mileage is obtained from other studies. Assumptions on volume growth, total kilometres per year, the PBL extrapolated to 2050 from the 2030 scenario study they performed. However, these scenarios already depend on external factors such as technology, economic development and political developments. Extrapolating to 2050 increases these uncertainties. The possibility exists that the daily mileage decreases towards 2050 due to these external uncertainties.

Energy efficiency is expected to increase moderately towards 2050. The model assumes a 10 percent increase, while the potential increase in efficiency is 24 percent. However, technical potentials are an overestimation of the real potential. Therefore, the author concludes that the assumptions on energy efficiency are viable.

The indicator battery capacity is mainly determined by the specific energy of the battery cells. Current Li-ion cells have a limited specific energy, resulting in limited range for current EVs. A breakthrough in battery technology is required to increase the specific energy of Li-ion cells towards

2030 and to allow successful introduction of superior Li-air cells. The uncertainties in this development are incorporated into the scenario analysis.

Uncertainty in the indicator charging technique originates from the preference for DC fast charging or AC charging. Both systems have different consequences for designing a public charging infrastructure network, and are incorporated into the scenarios. Charging power is relatively certain, since several (market) parties stressed the ambition to increase charging power to facilitate shorter charging times. An example is the plan to increase CCS charging power to 150 kW and possibly 350 kW (CharIN e.v., 2016). For AC charging, the ambition exists to increase charging power to 44 kW to facilitate a vehicle to grid system (B. M. H. de Brey, personal communication, November 4, 2016).

Charger capacity depends on occupancy rate and charging power. The uncertainty in charging power is incorporated into the scenarios. The occupancy rate for AC charging stations increases from 14 percent in 2015 to 33 percent in 2030 and 2050 in all scenarios. This means that each AC charging station charges for 8 hours a day. For the vehicle to grid scenario, each charging station supplies electricity for 62 cars in 2050. According to the author, the occupancy rate is realistic, since only 1 of these 62 cars needs to be charging for 8 hours, or 4 cars for 2 hours. For the slow development scenario, each charging station supplies electricity for 16 cars in 2050. This means that the occupancy rate of 8 hours per day is harder to achieve. However, the author thinks it is still viable. DC charging is done from 7.00 to 23.00, with an average occupancy rate of 50 percent during those hours. This results in the same occupancy rate over the day as an AC charger: 8 hours. In the refuelling scenario, each DC fast charging station facilitates 344 cars in 2050. With a charging time, from a fully depleted to a fully charged battery, of 5 minutes for PHEVs to 1 hour and 15 minutes for the largest BEV, the typical charging time is around 30 minutes. This means that 16 out of the 344 cars need to recharge to reach the 8 hour occupancy per day. For the parking pressure scenario, each DC fast charging station supplies 156 cars with electricity in 2050. The typical charging time for these cars is shorter, due to smaller battery capacity: Approximately 20 minutes. This means that 24 cars out of the 156 must recharge to reach the 8 hour occupancy. The same observation is made as with the AC charging stations: The occupancy rate for the high range scenario seems more likely than that for the low range scenario.

The development of the indicators is unsure due the long time frame. Therefore, a sensitivity analysis is made to analyse the impact of uncertainty in the indicators on the model results. The values of the indicators in the model are increased by 20 percent separately, to see the impact on the results: The required number of charging stations. The results are shown in figure 22. The required number of charging stations increases with 20 percent with an increase of 20 percent in indicators car ownership, mileage and energy efficiency, a linear relation. The required number of charging stations does not change when the indicator battery technology is increased with 20 percent. The indicator charging power has a negative relation with the required number of charging stations: With an increase of 20 percent in charging power, the required number of charging stations decreases with 17 percent. The same observation is made for the occupancy rate of the charging stations. This highlights that the uncertainties in the assumptions for the indicators in the model are significant for the results. Therefore, the results of the scenarios are only valid for the particular set of assumptions incorporated into the model and the scenarios.

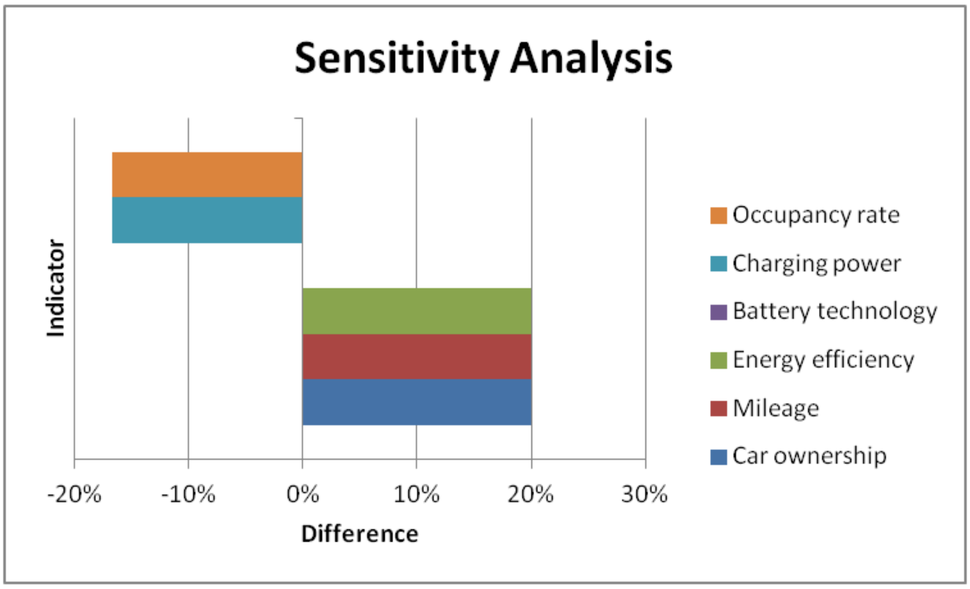


Figure 22. The sensitivity analysis

Another limitation of the study is that the scenarios are based on average values for each indicator, i.e. average daily mileage. The real daily mileage of an EV driver can be much higher or lower than the average, leading to different demands for public charging infrastructure, varying per EV driver. The model only takes into consideration one demand profile: Of the average EV driver. The use of an average occupancy rate can lead to problems during peak hours: An average occupancy rate of 50 percent means that there are, on average, sufficient free charging stations. At individual charging stations, the occupancy rate can increase to 100 percent during peak hours. This means that other EV drivers in that area which want to recharge their vehicle can’t be serviced immediately: They have to wait or drive to another charging station. This can lead to a local shortage of public charging infrastructure. To cope with peak demand, the required number of public charging stations may be higher than predicted by this study. However, since the study is on a large number of vehicles, the author believes that the use of average values is justified. The higher occupancy rate of one charging station will be compensated with a lower occupancy rate for other charging stations.

The scenario method also has limitations. The scenarios emerged from the extreme values of the critical uncertainties. The author believes that the chance that the actual development to 2050 corresponds with one of the scenarios is slim. The real development will probably be having parts of several scenarios. However, this does not render the scenario analysis useless. The scenarios are an extreme form of possible futures to highlight differences. The scenario study can be used to identify a preferred direction for the development of public charging infrastructure. This preferred pathway will depend on the judgement and priorities of the actors involved: Is net balancing more important than low charging times, associated with high charging power? Are little objects in public space and low costs more important than stimulating EV uptake by installing a network of public charging infrastructure? The answer to these questions will vary for different actors.

5.2 Further research

This study provides an overview of several ways to implement public charging infrastructure in the future, in order to provide the charging demand for 9.5 million EVs in the Netherlands in 2050, which is in compliance with the Sustainable fuels vision. The scenarios give valuable insights in the required scale of public charging infrastructure rollout. However, further research can be done to build on the results of this study.

The scenarios are based on average values for the indicators. The results from this study represent a minimum of public charging infrastructure, required to supply the charging demand. Therefore, the results do not incorporate demand during peak hours and at popular locations. Further research on the demand during peak hours can give insights in the extra charging infrastructure required to deal with these fluctuations.

The scenarios do not give any insights on optimal locations for public charging infrastructure. By taking into account actual travel patterns and other geographical data, the optimal location for public charging infrastructure can be modelled. Tactical placement of charging infrastructure will help to increase the occupancy rate, which was assumed in this study.

Another area for further research also lies in the average values incorporated in the scenarios. For each vehicle class, the daily mileage is assumed to be equal. It seems very likely to the author that this is not the case: Small vehicles will probably drive fewer kilometres per day, compared to large vehicles. The model can be improved by analysing the daily mileage of each vehicle class. This will result in a different, more realistic electricity demand for charging, since the energy efficiency of the vehicle classes differs.

As time progresses, the future development of the indicators becomes clear. The model can be updated with these developments. In this way, the model is still useful, even though the chosen developments in the indicators differ from the real future development of these indicators. The model can also be used to analyse the charging demand for new scenarios.

The analysis of the impact on the electricity grid can be improved. The scenarios use general assumptions on preferred times for charging, e.g. for fast charging. Further research can be done to establish these charging moments in more detail. This improves the impact on the grid, calculated in 4.5. The vehicle to grid impact analysis would also benefit from further research. In this study, an indication of the possibilities is presented. However, the optimal usage of the vehicle to grid network can be analysed for individual days, instead of an average daily grid load, which was used in this research.

A final area of further research is the future development of public charging infrastructure costs. Section 4.5 presents an indication of what the public charging infrastructure would cost if it would have been installed currently. Predictions on the potential decrease in production and installation costs could help in providing a more realistic view on the costs of future public charging infrastructure.

5.3 Policy implications

The policy implications that follow from this research are discussed below. As discussed in section 4.1.3, current Dutch policies focus on stimulating the uptake of EVs by providing financial support for installing public charging infrastructure. In December 2016, another 1.5 million Euros was reserved for the Green Deal publicly accessible electric charging infrastructure in order to place another 3,000 public charging stations. When the current policies end in 2020, the results of this research suggest that towards 2030, charging demand can be satisfied with installed charging infrastructure, by increasing the occupancy rate and charging power. This leads to the minimalisation of the number of new public charging stations that need to be installed in the future. Examples of suitable policies are the prohibition of parking at a charging space without charging and implementing a standardisation for charging stations that ensures high charging power. Other preferred policy interventions depend on the preferred development of public charging infrastructure by the policy maker. AC charging and DC fast charging both have advantages for EV owners with different demands, so the author advices to stimulate both charging techniques, to facilitate charging preferences for all EV drivers.

After 2030, the number of charging stations needs to increase. However, the market has matured by then, since the market share of EVs has increased to 23 percent (see table 8), which falls into the early majority category (see figure 1). Policy interventions to stimulate the installation of extra public charging stations are not required, since the business case will be positive.

Another area where policy interventions can make a difference is in the dominant charging technology. DC fast charging stations can be stimulated by allowing these stations to sell additional goods and services, similar to gas stations. This can help achieving a positive business case for these stations and provides DC fast charging stations with the same level of comfort as gas stations at service areas. Alternatively, AC charging can be stimulated by reviewing the electricity tax system. Tax rates can be adapted so that the electricity tax is only paid once per cycle of charging and discharging. In combination with a flexible electricity price, this can stimulate the development of a vehicle to grid system.

The last point to take into consideration when designing policies is that the Netherlands is not an isolated country: It is also dependent on neighbouring countries. With increasing range, trips abroad become viable for all EVs. This requires international standardisation for charging infrastructure, combined with an international public charging infrastructure network. Therefore, the author advices to tune implemented policies with neighbouring countries and make sure that an international public charging infrastructure network is developed.

6. Conclusion

This thesis has been performed to provide a view on the requirements for public charging infrastructure to supply the electricity demand for 9.5 million EVs in the Netherlands in 2050 and identify the impacts of this charging infrastructure. The results show that public charging infrastructure can be provided in several ways. 5 scenarios were analysed: The reference scenario, the refuelling station scenario, the vehicle to grid scenario, the parking pressure scenario and the slow development scenario.

The study found that the scenarios with DC fast charging technology requires the least number of charging stations, compared with AC charging technology. Sufficient locations for DC fast charging stations can be obtained by converting existing gas stations. However, installing a DC charging network is more expensive, compared to an AC charging network. The AC charging network was expanded to form a vehicle to grid network. The network can be used to decrease electricity demand during peak hours.

The preferred pathway for the development of public charging infrastructure, or the preferred scenario, will depend on the demands of policy makers: Low costs, low charging time, low grid impact or little objects in public space. However, the vehicle to grid system, with AC charging seems the most beneficial overall, since it is cheaper to install and has other benefits, e.g. improving grid stability. The results imply that focusing on improving the occupancy rate of charging stations and increasing the charging power prevent the need to install extra public charging stations up to 2030. In the period 2030 to 2050, new public charging stations are required due to the increase in number of EVs and thereby charging demand. However, this does not require additional policy interventions, since the business case for public charging infrastructure will be positive by then.

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