City of Amsterdam

Universiteit Utrecht

**Utrecht University**
**Final version internship report**

# Towards emission free traffic in Amsterdam

## *An assessment of the potential of electric vehicle charging with renewable energy*

Internship Energy Science, Utrecht University

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# Abstract

Local traffic is found to form a significant contribution to the emission of greenhouse gases and other pollutants in Amsterdam. The City of Amsterdam strives to have a clean and healthy environment and, therefore, aims to decrease local emissions. The increase usage of electric vehicles (EV) brings along the opportunity to reduce emissions from local traffic, by charging EVs with renewable power. Subsequently, the City of Amsterdam is exploring the potential of smart charging solutions as part of the SEEV4-City project to increase the amount of solar power used for charging EVs. At this moment, static smart charging is introduced at multiple charging points in Amsterdam. This research evaluates the effect of the implementation of static smart charging (which is a predefined profile of the charging power available at a charging point, where the power at a charging point is decreased between 8:00-9:00 and 17:00-20:00 and raised at other moments) on the potential uptake of solar and wind power in EVs for the period 2016-2035. Subsequently, the research estimates the impact of static smart charging on $CO_2$-emissions related to the use of EVs.

On the short term it is found that the introduction of static smart charging has the potential to increase the share of solar power for charging EVs. As a result, an additional 15 tonnes of $CO_2$ could be saved annually by 2020. This approaches the objective of 17 tonnes, which is the objective of the SEEV4-City project. After 2020, the uptake of solar power is higher when regular charging is applied in comparison to static smart charging. This is due to a decreasing charging demand between 17:00-20:00 and a higher fluctuating electricity demand during the day. Furthermore, the uptake of electricity from wind power for regular charging exceeds that for static smart charging during the full simulation period. Consequently, overall on the short and long term $CO_2$-emissions are found to increase when a static smart charging scheme is managed.

Additional research is needed to determine the impact of electricity demand by third parties on the availability of renewable energy. Nevertheless, the results indicate potential for a positive effect of static smart charging on the uptake of solar power, due to an increase in the available charging power during the day. Moreover, adjustments to the introduced static smart charging scheme are needed to utilize this potential more effectively. With regard to wind power, it is found that a constant charging power is preferred. On the basis of the research findings, it is recommended to adjust the static smart charging profile according to the charging point utilization and the capacity of renewables that are available.

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## Units

| | |
|---|---|
| A | Ampere |
| Hr | hour |
| V | Volt |
| W | Watt |
| Wh (kWh) | Watt hour (kilowatt hour) |
| Wp (kWp) | Watt peak (kilowatt peak) |

## List of abbreviations

| | |
|---|---|
| EC | Soot |
| EV | Electric vehicle |
| FEV | Full electric vehicle |
| KNMI | Royal Netherlands Meteorological Institute |
| RFID | Radio Frequency Identification card |
| PHEV | Plug-In hybrid electric vehicle |
| PM10 | Particulate matter 10 |
| SEEV4-City | Smart, clean Energy and Electric Vehicles for the City |
| V2B | Vehicle-to-business |
| V2C | Vehicle-to-city |
| V2G | Vehicle-to-grid |
| V2H | Vehicle-to-home |
| V2N | Vehicle-to-neighbourhood/street |

## Terms

| | |
|---|---|
| District | City district |
| Neighbourhood | Sub-districts (in Dutch “Buurtcombinatie”) |
| Regular charging | Standard charging power managed at charging points (see table 1) |
| Static smart charging | Charging power profile managed at charging points in the pilot (see table 1) |

# 1 Introduction

Worldwide the transport sector is found to be responsible for approximately a quarter of the emissions of greenhouse gasses (GHG) and air pollutants (Cronin et al., 2015). Respectively, these form a significant contribution to global warming and harm human health especially in urban areas (EEA, 2014; Milieudefensie, 2016). The emissions that arise from the transport sector are ascertained to originate for more than 95% from road traffic (Coenen et al., 2016). As a result, the air quality is found to be most problematic near roads in urban areas.

The city of Amsterdam is no exception to this. The air quality is classified as unhealthy and forms a threat to public health. Moreover, the concentration of some pollutants do not meet European regulations nor standards adopted by the World Health Organization (Knol, 2016). Van der Giessen & Van der Linden (2016) stated that motorised traffic causes up to half of the air pollution in certain areas in Amsterdam. Moreover, road traffic is found to be responsible for about 25% of nitrogen dioxide ($NO_2$), 25% of soot (EC) and 7% of particulate matter 10 (PM10) emissions (City of Amsterdam, 2015b). This is accompanied with an increasing amount of carbon dioxide ($CO_2$) emissions over the last few years, which was equal to 820 kilotons in 2013 (Janssens & Koelemij, 2014). In addition, road traffic forms a significant contribution to local hydrocarbon (HC) emissions (City of Amsterdam, 2015b; van der Giessen & van der Linden, 2016).

The City of Amsterdam strives to have a clean and healthy environment, which is to be achieved by decreasing emissions. In order to decrease air pollution the City has defined a pathway including multiple targets to increase the integration of sustainable energy technologies. The most important aspects of the plan include an emission free transport system in 2025 and $CO_2$-emission reductions of 40 and 75% in 2020 and 2040 respectively, with respect to 1990 levels. The wide adoption of electric vehicles (EV) forms a major opportunity to reduce the emission of local air pollutants and to increase the amount of zero emission kilometres (City of Amsterdam, 2015b). Moreover, previous research demonstrates that EVs have the potential to form a considerable contribution to decrease global $CO_2$-emissions (Cronin et al., 2015; Van Vuuren et al. 2017).

In order to achieve the desired decrease in $CO_2$-emissions EVs should be charged with renewable energy. At this moment, a total solar power capacity of 24 MWp is installed in Amsterdam (Readaar, 2017). Moreover, Amsterdam aims to increase the installed capacity to 160 MWp and 1,000 MWp in respectively 2020 and 2040. Wind power capacity currently accounts for 67 MW in Amsterdam and is planned to be expanded to 85 MW in 2020 and 405 MW in 2040 (City of Amsterdam, 2015b).

In theory, EVs in Amsterdam are charged with electricity from wind power. This means that an equal amount of electricity consumed for EV charging is bought from wind power production. However, charging points manage constant charging power outputs and the production profile of (solar and) wind power does not match the electricity demand pattern of EVs at all times (Geerts et al., 2016). As a result, in practice EVs are not merely charged with renewable energy and EVs indirectly emit $CO_2$. In order to reduce $CO_2$-emissions from road traffic, smart charging solutions are needed that match the electricity demand and supply. These solutions should allow for EVs to be charged with electricity derived from solar panels or wind turbines. To accelerate the development and introduction of smart charging solutions, the City of Amsterdam hosts a pilot that focuses on the development of these solutions. The pilot is part of the European funded SEEV4-City project, which aims to develop smart charging solutions that induce load balancing of the low voltage grid, raise local energy autonomy and increase the share of renewable energy in EVs (for more information about SEEV4-City see chapter 2).

## 1.1 Problem definition

The mismatch between the production of renewable energy and the electricity demand by EVs forms a challenge in reducing $CO_2$-emissions from road traffic in Amsterdam. The ability to overcome this lies in the adoption of smart charging solutions. A first step to develop these solutions is set in the current stage of the SEEV4-City pilot that is hosted in the city of Amsterdam, which considers the introduction of a static smart charging profile, which sets a time-dependent maximum charging rate (see chapter 3). However, at this point it is unknown to what extend this will contribute to an increase in the deployment of renewable energy for EV charging and achieve the desired $CO_2$-emission reduction. The goal of this research is to assess the potential for EV charging with renewables. Subsequently, the aim of the research is to answer the question:

*What is the potential of static smart charging to increase the utilization of solar and wind power for EV charging and decrease $CO_2$-emission by (local) traffic in Amsterdam for the period 2016-2035?*

The potential of static smart charging to decrease $CO_2$-emissions and increase the use of renewable energy in EV charging is assessed by comparison with the current charging scheme applied, referred to as regular charging. In order to answer the research question the following sub questions are addressed:

1. What is the annual solar and wind power generation in Amsterdam for the period 2016-2035, and how is the generation distributed throughout the year?
2. What is the current EV charging demand and how is this expected to develop until 2035?
3. What is the current and future maximum share of renewable energy in EV charging when respectively regular and static smart charging are applied, considering a growing capacity of solar and wind power and an increasing number of EVs?
4. What are the main obstacles to increase the share of renewable energy in EV charging and how can these be overcome?

## 1.2 Scope and boundaries

The research focuses on the city of Amsterdam. More specifically, it considers the locations that are reviewed in the SEEV4-City pilot. As a result, a first boundary of the research is described by these charging points. This implies that the charging behaviour at other charging points is not considered.

The research only considers the allocation of EVs and therewith discards other forms of transportation. Moreover, in order to estimate the future EV charging demand, focus is put on large battery full electric vehicles (battery capacity >40 kWh). This is substantiated as large battery FEVs are considered to be the standard EVs in the future (Cuijpers et al., 2016), and supported as FEVs are found to be responsible for the bulk of the electricity demand by EVs at the selected charging points (Amsterdam University of Applies Sciences, 2017).

In this research other forms of electricity demand, such as electricity demand by residents, are not considered. Consequently, all electricity flows except those caused by solar and wind power production and EV charging demand are discarded. This means that all produced solar and wind power is assumed to be available for EV charging.

Due to a lack of information regarding the electricity demand and the electricity grid, the generation and availability of renewable energy by solar and wind is proportionally divided over the charging points in Amsterdam. This implies that in this research each charging point has access to the total installed capacity of solar and wind power divided by the total number of charging points.

## 1.3 Research relevance

This research aims to identify the potential of static smart charging to increase the uptake of renewable energy and therewith decrease $CO_2$-emissions by road traffic. Consequently, it provides insights into the feasibility of the objectives as set by the City of Amsterdam and the SEEV4-City pilot. Additionally, the research provides information on how to increase the utilization of renewables in EV charging and expose possible challenges to achieve the desired results.

Although the findings relate to the city of Amsterdam, more general recommendations that apply to other cities or regions may be given. Consequently, the research forms a contribution to charging EVs with renewable electricity independent of the location. Additionally, it contributes to area of research that looks into the field of avoiding grid reinforcements, on how to increase the energy autonomy and reduce the local dependence on the transformer station by the application of static smart charging.

## 1.4 Research outline

The next chapter elaborates on the objectives of the SEEV4-City project and the project pilots. Thereafter, in chapter 3 the means of data collection and data analysis are discussed. Chapter 4 data presents the data input. Thereafter, in chapter 5 the results are discussed. This is followed by the discussion (chapter 6) and conclusion (chapter 7). References and appendices are given at the end.

## 2. SEEV4-City

"Smart, clean Energy and Electric Vehicles for the City" (SEEV4-City) is an Interreg research project funded by the North Sea Region programme 2014-2020 and the project partners[1]. The project aims to contribute to green city development by decreasing local emissions and increasing the use of renewable energy. This is to be achieved by developing smart energy solutions that effectively deploy and combine EVs and local renewable energy sources (where the main focus is put on solar power). The project exists out of seven pilots that demonstrate different applications of vehicle-to-grid (V2G) and smart charging technologies. These are vehicle-to-home (V2H), vehicle-to-business (V2B), vehicle-to-street/neighbourhood (V2N) and vehicle-to-city (V2C). The universal goal of the pilots is to develop sophisticated energy management solutions that:

- Increase the amount of ultra-low or zero emission kilometres (and avoid 150 tonnes of $CO_2$-emissions per year);
- Increase the level of energy autonomy (by 25% on average);
- Avoid (extra) investments for grid reinforcements (accounting for 100 million euros).

The pilots are situated in Belgium, Germany, Norway, the Netherlands and United Kingdom. The City of Amsterdam is one of the partners involved in SEEV4-City and hosts one of the project pilots. The other partners involved in SEEV4-City are the Amsterdam ArenA, Amsterdam University of Applied Sciences, Avere, Cenex, e8energy, KU Leuven, Leicester City Council, Northumbria University, Oslo Kommune and Polis (Amsterdam University of Applied Sciences, 2015; SEEV4-City, 2017).

The pilot in Amsterdam focuses on optimizing the interaction between prosumers and EVs. With this pilot the City of Amsterdam aims to develop a strategy in which EVs in a neighbourhood enhance the direct uptake of local renewable energy in order to (1) reduce emissions by road traffic (where $CO_2$-emissions are ought to be cut with ten to fifteen tonnes every year) (2) contribute to an increase in local energy autonomy (up to 15%) and, (3) allow for load balancing in order to prevent grid congestion or failure and the corresponding need for grid reinforcements. The final aim of the pilot hosted in Amsterdam is to evaluate the application of the V2N concept (Amsterdam University of Applied Sciences, 2015).

Nevertheless, the roll out of such an energy system is very complex. Therefore, the first phase of the pilot exists of the introduction of static charging profiles (Geerts et al., 2016). This is considered first as the charging infrastructure is currently not ready for the introduction of more advanced smart charging solutions (like dynamic charging or vehicle-to-grid). In addition, the costs to implement these are significantly higher compared to static charging. The static charging profiles are introduced at 52 public charging points that are located throughout the city. The profiles adopted at this moment are expected to form a first contribution towards achieving the intended results. Based on intermediate results the content of the second phase of the pilot will be set. Here, the implementation of more advanced smart charging solutions will be considered.

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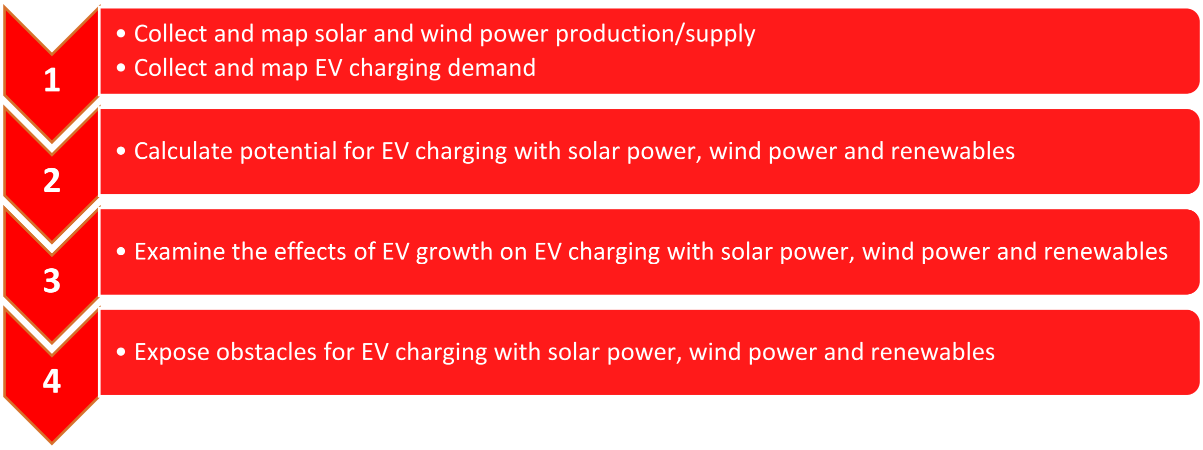
[1] For more information, see http://www.northsearegion.eu/seev4-city/

# 3. Methods

This chapter provides the set-up of the research methodology. This includes the means of data collection and the methods applied for data analysis. Figure 1 presents an overview of the steps that are conducted in this research. All simulations are run using R, considering a fifteen-minute time step.

*Figure 1 Overview of research methodology*



## 3.1 Overview of supply and demand

The first research step exists of collecting and mapping the distribution of the production of solar and wind power and the demand for EV charging. This information is mapped and allows connecting supply and demand on a local level. The data for the distribution of solar power in the city is derived from a recent research conducted by Readaar (2017). Moreover, the production of solar energy is based on general solar insolation patterns found in Amsterdam and actual electricity generation values of several PV systems (3.1.1). The electricity supply by wind power is based on national generation data and local wind speeds (3.1.2). Data for the distribution and demand of electricity for EV charging is collected at the City of Amsterdam and at the Amsterdam University of Applied Sciences (3.1.3).

### *3.1.1 Solar power supply*

To establish the solar power production profile per fifteen-minute time interval in the year 2016 two different methods have been applied. The first method determines the solar power production on the basis of solar insolation. Here, data collected by KNMI (2017) is used to establish the profile of supply. The second method reviews the actual production of eight different solar PV systems located in Amsterdam.

#### *Method I: Solar insolation*

The first method considered to determine the production profile of solar power is based on available data of solar insolation. Here, the actual electricity production of a PV system is calculated by considering the efficiencies of solar panels and PV systems, and solar insolation. The solar electricity supply profile is calculated with formula 1 (Twidell & Weir, 2015).

$$Y_S(t) = PR * I(t) * P_{PV} \qquad (1)$$

*Where:*

*$Y_s$ = Specific yield (kWh/kWp) at time (t)*
*PR = Performance Ratio of PV panel*
*I = Solar insolation (kWh/m$^2$) at time (t), average for fifteen-minute time interval*
*$P_{PV}$ = Rated power of a PV system (kWp)*

This method is applied for two different KNMI weather stations, namely the Bilt and Schiphol. Schiphol was reviewed as it is the closest weather station to Amsterdam. From Schiphol hourly solar radiation (in J/cm$^2$) is available for the year 2016. The average hourly insolation data from Schiphol is converted to a fifteen-minute time interval.

In addition, the weather station at the Bilt was reviewed as the available solar radiation data is more precise. This is explained as it includes solar radiation (in W/m$^2$) per five-minute time frame. Subsequently, the insolation data of the Bilt is aggregated and averaged per fifteen minute time interval.

### *Method II: PV system*

The second method applied to establish the solar power supply per fifteen-minute time interval is based upon monitored solar power production of eight different PV systems in Amsterdam (iCarus, 2017). At these systems the average power output (in Watt) per five minutes is collected. Subsequently, the data is aggregated and averaged per fifteen-minute time interval. Possible gaps in the dataset are supplemented with the available data from the KNMI station Schiphol. This is chosen since the actual solar insolation, and therewith the electricity production by PV systems, was found to overlap more accurately with the Schiphol weather station.

Furthermore, the capacity of the solar PV systems are unknown. As a result, it is assumed that the maximum five-minute peak production is equal to the 99th percentile of the system's converter capacity (iCarus, 2017).

## *3.1.2 Wind power supply*

To determine the wind power production profile per fifteen-minute time interval in the year 2016 two different methods have been applied. The first method considers the actual electricity production by wind turbines on a national level, and is translated by considering local electricity supply values. The second method determines the production profile on the basis of local wind speeds. In this case data collected by the KNMI (2017) is used to establish the supply of electricity.

### *Netherlands*

The first method estimates the wind power supply profile by converting national values to numbers that are deemed representative for Amsterdam. In this method the electricity production of onshore wind turbines per fifteen-minute time interval is reviewed and converted to regional production estimates (ENTSO-E, 2017; Windstats, 2017). For this conversion the efficiency of wind turbines, in terms of annual electricity production per unit of power, are considered on a national and regional level. Subsequently, the supply profile is calculated by considering formula 2 and 3.

$$P_r(t) = \frac{E_{wind}(t)}{P_{cap}} * \alpha \qquad (2)$$

$$\alpha = \frac{\beta_{AMS}}{\beta_{NL}} \qquad (3)$$

*Where:*
*$P_r$ = Reference wind power production (kWh/MW) at time (t)*

*$E_{wind}$ = Electricity production by onshore wind (kWh) at time (t)*
*$P_{cap}$ = Wind power capacity in the Netherlands (MW)*
*$\alpha$ = Correction factor for national average to Amsterdam*
*$\beta_{AMS}$ = Wind power electricity production in Amsterdam (kWh/MW)*
*$\beta_{NL}$ = Wind power electricity production in the Netherlands (kWh/MW)*

### *KNMI*

The second method applied in order to establish the electricity supply profile of wind power in Amsterdam considers the average hourly wind speed at Schiphol (KNMI, 2017). In this method the power generation of a wind turbine is calculated by considering wind turbine characteristics and local conditions, see formula 4 and 5 (Twidell & Weir, 2015). Moreover, the power coefficient of each wind turbine is estimated by matching the annual generation according to formula 4 to the annual generation per wind turbine in Amsterdam as documented by Windstats (2017). In order to create a fifteen-minute wind supply profile the average wind speed of the first quarter of each hour is equal to the average wind speed of that hour and the hour before. Similarly, the average wind speed during the last quarter is equal to the average wind speed of that hour and the hour after.

$$P_t = 0.5 * \rho * C_p * A * v^3 * C_b \tag{4}$$

$$for\ cut\ in\ speed \leq v\ \geq cut\ out\ speed\ \&\ P_t \leq\ P_{max}$$

*Where:*
*$P_{max}$ = Power capacity of the wind turbine*
*$P_t$ = Power generation of the wind turbine (kW)*
*$\rho$ = Air density*
*$C_p$ = Power coefficient (%), which is based on the annual electricity production from Windstats (2017)*
*A = Swept area ($m^2$)*
*v = Wind speed at hub height (m/s), formula 5*
*$C_b$ = Betz limit (16/27)*

$$v = v_0 * \frac{\log\left(\frac{HH}{RF}\right)}{\log\left(\frac{RH}{RF}\right)} \tag{5}$$

*Where:*
*$V_0$ = wind speed at reference height, RH of 10 meter (m/s)*
*HH = Hub height of the wind turbine (m)*
*RF = Roughness factor (0.05 (KNMI, 2017))*
*RH = Reference height (10 meter)*

### *3.1.3 Energy demand by EVs*

To estimate current and future charging demand profiles of EVs a dataset of previous EV charging sessions was analysed. This dataset holds over 83,000 charging sessions that have taken place at the 52 charging points selected in the SEEV4-City pilot for the period January 2014 until July 2017. These only consist of EV charging session by regular users. Moreover, sessions by Car2Go, connexion and taxi drivers are discarded in this research since charging behaviour is unpredictable and growth rates are unknown. When required, the analysis is supplemented with additional information obtained from literature.

## 3.2 Potential for static smart charging

### *3.2.1 Static smart charging in 2016*

On the basis of the supply and demand profiles found in the selected areas, the potential for static smart charging to increase the share of solar and wind power in EV charging is examined. This is done by calculating and comparing the potential or maximum uptake of solar and wind power by EVs for both charging schemes (see table 1). Subsequently, by considering the obtained difference and an average emission from electricity production in the Netherlands of 0.57 kg per kWh (City of Amsterdam, 2017a), the impact of the charging schemes on $CO_2$-emissions is evaluated. Next, the findings are compared to the desired $CO_2$-emission reduction as set in the SEEV4-City project.

*Table 1 Time dependent charging power at charging point (kW)*

| Time span | | | **Regular charging** | **Static smart charging** |
|---|---|---|---|---|
| 00:00 | - | 07:00 | 11 | 22 |
| 08:00 | - | 09:00 | 11 | 11 |
| 09:00 | - | 17:00 | 11 | 22 |
| 17:00 | - | 20:00 | 11 | 8.28 |
| 20:00 | - | 00:00 | 11 | 22 |

### *3.2.2 EV, and solar and wind power growth*

Thereafter, the growth of electricity supply by solar and wind power and the increase in electricity demand by EVs is reviewed in order to determine how the charging schemes affect the utilization of solar and wind power in the future. In addition, here the effectiveness of the applied charging strategy to increase the uptake of renewable energy and achieve the objective decrease in $CO_2$-emissions are examined. The growth of EVs is based on national growth rate predictions achieved from Steinbuch (2017). Moreover, the growth for solar and wind power is according to targets set by the City of Amsterdam.

## 3.4 Obstacles for EV charging with solar and wind power

Next, the findings are discussed, which provide insight into the major obstacles for EV charging with solar and wind power. Moreover, this section will provide insights into the advantages and disadvantages of the static smart charging profile in comparison to regular charging.

## 3.5 Key performance indicators

The potential of static smart charging to increase the share of solar and wind power in EV charging is assessed on two key performance indicators (KPI).

### *KPI I: Renewable charge*

The first performance indicator evaluates the amount of electricity for EV charging that originates from solar and wind power. The KPI is expressed in volume (kWh).

### *KPI II: $CO_2$-emissions avoided*

The second performance indicator considers the $CO_2$-emission that could be avoided due to EV charging with renewable power. This KPI is expressed in terms of mass of $CO_2$-emissions polluted by EVs (in kg and tonnes). The share of the EV charging demand that cannot be supplied by solar power is assumed to be supplied by the Dutch energy mix found at that time.

# 4. Data input

## 4.1 Solar power

### 4.1.1 Solar Power in Amsterdam

In this research several assumptions are made regarding the characteristics of PV panels, to estimate the solar power supply profile. These assumptions are based on average PV panel values and presented in table 2.

*Table 2 PV panel characteristics*

| ***Assumption*** | ***Value*** | ***Source*** |
|---|---|---|
| *PR* | *0.85* | *Twidell & Weir, 2015* |
| *PV panel* | *270 Wp*<br>*1.65 $m^2$* | *Twidell & Weir, 2015*<br>*Readaar, 2017* |
| *Ppv* | *6.1 $m^2$/kWp* | *= 1000Wp*1.65$m^2$/270Wp* |
| *n* | *0.195* | *Twidell & Weir, 2015* |
| *I* | *Time dependent (kWh/$m^2$)* | *KNMI, 2017* |

### 4.1.2 Solar Power growth

The City of Amsterdam has described their objectives for the growth of solar power in *Schaalsprong Zon* and *Duurzaam Amsterdam* (City of Amsterdam 2015a; City of Amsterdam 2015b). Research by Readaar (2017) indicated that the cumulative capacity of solar power installed was almost 24 MWp in April 2016. The target as set by the City of Amsterdam was to reach 25 MWp by the end of that year. Considering the recent growth of PV systems in Amsterdam, it is very likely that this target was met in 2016, and is therefore on schedule. In this research the growth rate of the cumulative solar power capacity installed is based on the targets set by the City of Amsterdam, whereas a linear growth rate is assumed (figure 2).

## 4.2 Wind Power

### 4.2.1 Wind power in Amsterdam

At this moment there are 39 wind turbines installed in Amsterdam, which characteristics are presented in table 3. To establish the wind power supply profiles in Amsterdam on the basis of KNMI wind speeds, several assumptions are considered which can be found in table 4.

*Table 3 Wind turbines in Amsterdam (ENTSO-E, 2017; Windstats, 2017)*

| **Type** | **Vestas 3MW** | **Vestas 2MW** | **Vestas 0.66MW** | **Bouma 0.16MW** |
|---|---|---|---|---|
| Pt (MW) | 3 | 2 | 0.66 | 0.16 |
| Cp | 0.62 | 0.65 | 0.55 | 0.2 |
| A ($m^2$) | 6362 | 4072 | 1735 | 314 |
| HH (m) | 80 | 68 | 65 | 24 |
| Cut in speed (m/s) | 3.5 | 4 | 4.5 | 5 |
| Cut out speed (m/s) | 25 | 25 | 25 | 20 |
| Number of turbines installed | 17 | 1 | 20 | 1 |

*Table 4 Wind power characteristics*

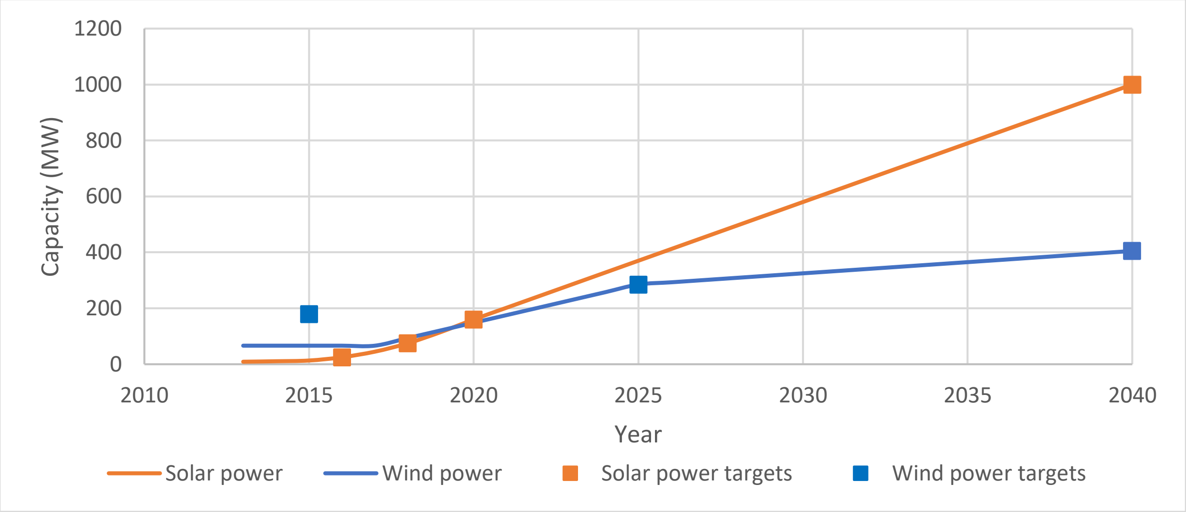
| **Assumption** | **Value** | **Source** |
|---|---|---|
| $\rho$ | 1.23 kg/m$^3$ | Twidell & Weir, 2015 |
| $C_b$ | 16/27 | Twidell & Weir, 2015 |
| RF | 0.05 | Twidell & Weir, 2015 |
| RH | 10 m | KNMI, 2017 |
| $V_0$ | Time dependent (m/s) | KNMI, 2017 |
| $E_{wind}(t)$ | Time dependent (kWh/15-min) | ENTSO-E, 2017 |
| $P_{cap}$ | 3,034 MW | ENTSO-E, 2017 |
| $\beta_{NL}$ | 6,179 mln kWh in 2016 | ENTSO-E, 2017 |
| $\beta_{AMS}$ | 155 mln kWh in 2016 | Windstats, 2017 |
| $\alpha$ | 0.025 | Formula 3 |

### 4.2.2 Wind Power growth

Similar to solar power, the ambitions of the City of Amsterdam for the growth of wind power have been set in *Windvisie* (City of Amsterdam, 2012). However, the wind power capacity has not increased in Amsterdam over the past few years due to refusal of permits by the province of North Holland (Raad van State, 2017). As a result, the cumulative installed capacity of wind power is currently 66 MW, which is far below the target of 180 MW set for the year 2015. At this moment there are no planned constructions for wind turbines within the city. Therefore, it is expected that the cumulative installed wind power capacity will remain 66 MW until 2018. From 2019 onwards a linear growth rate is considered based on the targets set for 2025 and 2040.

As the City of Amsterdam characterised the Westelijk Havengebied and Bedrijventerrein Sloterdijk as the districts with the most potential for wind power, these districts are most likely to encounter the growth in wind power capacity installed (City of Amsterdam, 2012).

*Figure 2 Expected growth of solar and wind power (City of Amsterdam, 2012; City of Amsterdam, 2015a)*



## 4.2 Electric Vehicles

### *4.2.1 EV characteristics*

As described in the introduction, a distinction is made between PHEVs and FEVs in this research to simulate future EV charging behaviour. FEVs are filtered from the database by considering the battery volume and charging power. Both values are determined on the basis of all historical charging sessions of the vehicle (which are collected on the basis of the RFID number). Here, the battery volume is set equal to the maximum volume charged by the vehicle. In addition, the charging power is considered to be the maximum average charging power of an EV. As the largest battery of a PHEV was 12 kWh until June 2016, and 17.5 kWh after that, EVs are labelled as a FEV when the volume of a session has exceeded this (table 5).

Subsequently, a distinction is made between FEVs with a large and small battery. This distinction is made in order to review varying charging patterns per EV type. FEVs are labelled to have a large battery when the battery exceeds 40 kWh (IDO-Laad, 2017).

Next, the charging power is determined on the basis of the maximum charging power experienced during a session and the battery volume as indicated in the table. Moreover, FEVs in the future are assumed to allow for a charging power of 22 kW.

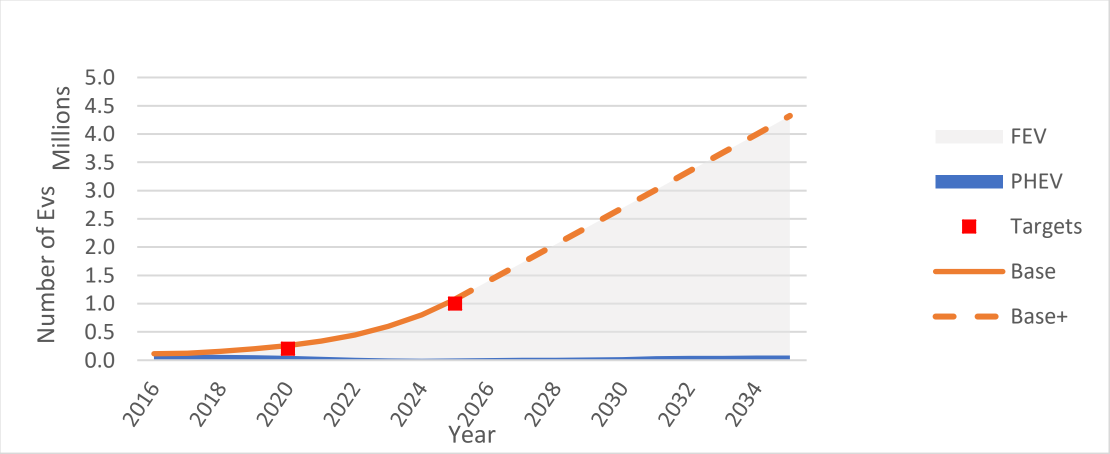
*Table 5 Conditions for EV labelling (EV Database, 2017)*

| EV | Battery capacity (kWh) | Max. charging Power (kW) |
|---|---|---|
| *FEV (Large battery)* | > 40 | 11 / 22 |
| *FEV (Small battery* | < 40 | 3.7 / 11 / 22 |
| *PHEV* | < 17.5 (< 12*) | 3.7 |
| *Until June 2016 | | |

### *4.2.2 EV growth*

Due to a lack of information regarding the amount of EVs in Amsterdam and the associated growth rate, national EV growth numbers and scenarios are reviewed. In this research EV growth is based on predictions by Steinbuch (2017, see figure 3). The scenario is considered as it aligns with targets set by the Dutch government (ECN, 2016) and was found to meet previous growth rates.

*Figure 3 EV growth in the Netherlands*



# 5. Results

This chapter presents the results of this research and is structured according to the sub questions. In section 5.1 the supply of solar and wind power is discussed. Then, the electricity demand by EVs is analysed in section 5.2. In section 5.3 the potential of EV charging with solar and wind power and the corresponding $CO_2$-emissions for regular and static smart charging is discussed. Finally, in section 5.4 alterations to current charging schemes are reviewed in order to increase the share of solar and wind power in EV charging.

## 5.1 Energy supply

The first section of the chapter reviews the annual solar and wind power supply in Amsterdam. As a result, this section provides an answer to the sub question "What is the annual solar and wind power generation in Amsterdam for the period 2016-2035, and how is the generation distributed throughout the year?" In order to answer the sub question, first the solar power supply in Amsterdam is examined. This is followed by a discussion of the wind power supply. Finally, as electricity production of solar and wind power overlap occasionally, their combined supply in Amsterdam is reviewed as the renewable power supply.

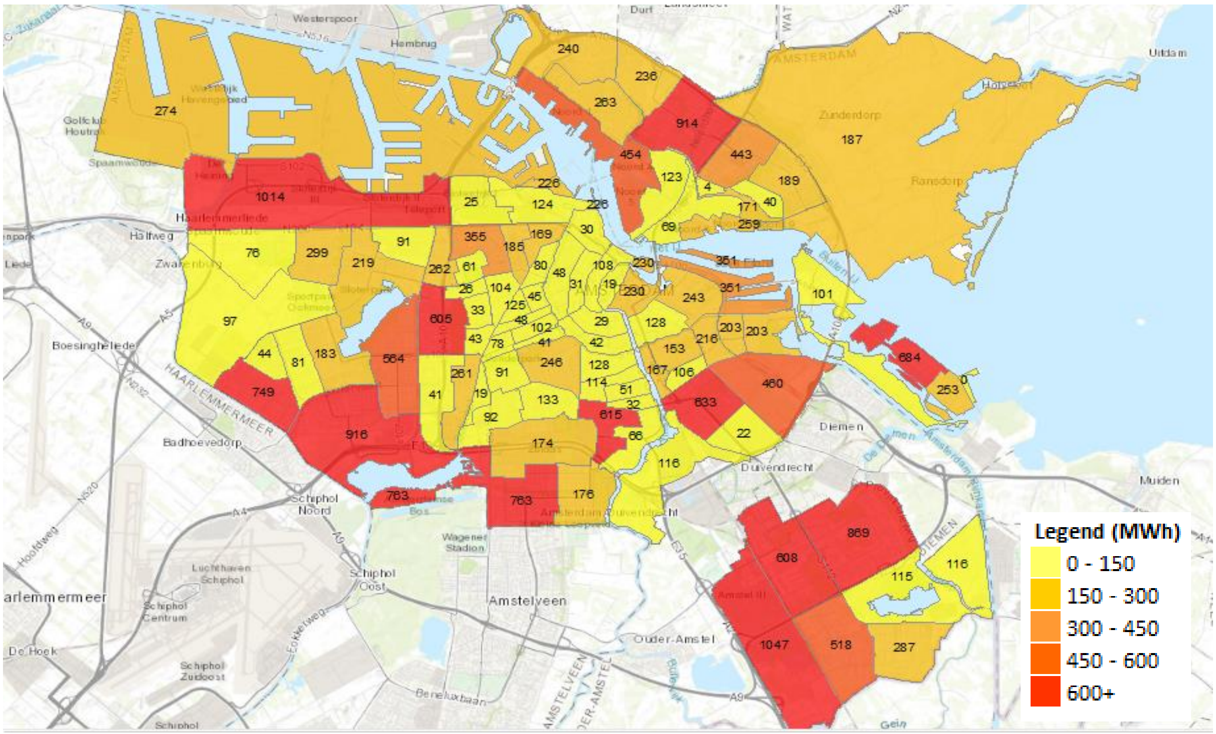
### *5.1.1 Solar power supply*

#### *Solar power distribution and yield*

The average specific yield of a PV system in the Netherlands is set at 875 kWh per kWp (van Sark, 2014). However, the yield of a solar PV system within the Netherlands varies per region. Since the annual solar insolation in Amsterdam is slightly above the national average (KNMI, 2017), the specific yield of PV systems in Amsterdam is expected to be higher. This is confirmed as the average annual production of 84 PV systems in the city of Amsterdam was found to be 925 kWh per kWp (PVOutput, 2017 & iCarus, 2017). Consequently, in this research an average production of 925 kWh per kWp is considered.

The installed capacity of solar PV systems in Amsterdam is 23.9 MWp (Readaar, 2017). Consequently, the total electricity production by solar power is expected to be approximately 22 million kWh per year. The distribution of the annual electricity production per neighbourhood in Amsterdam is shown in figure 4, based on the distribution of PV systems (Readaar, 2017). From the map it can be found that the supply of solar power varies significantly per neighbourhood. Detailed data can be found in Appendix A.1.

*Figure 4 Solar power production per city district for 2016 (in MWh)*



## *Annual solar power supply profile*

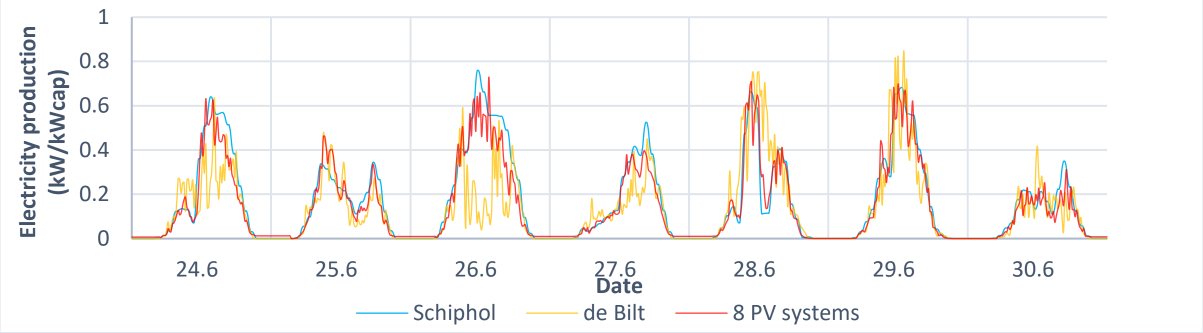
As discussed in the section 3.1.1, three different methods are used to generate the annual supply profile of solar power. The first solar power profile is based on insolation data at *Schiphol* (KNMI, 2017). Here, the annual solar production in 2016 was found to be 936 kWh, which is slightly above the average annual solar PV production of 925 kWh per kWp. At de Bilt an average PV systems was found to have an output of 898 kWh per kWp in 2016, which is below the average annual solar PV production found in Amsterdam. The third solar power supply profile was based on the electricity production of 8 PV systems in 2016, from which five-minute power production data is available. The average annual output of these systems was found to be 898 kWh per kWp.

The three estimated electricity supply profiles for solar power are depicted for one week in 2016 in figure 5. From the figure it can be obtained that the Schiphol profile is relatively constant, when compared to the two other supply profiles. This is explained as the Schiphol profile considers hourly insolation data. However, in this research emphasizes is put on the variations of supply and demand on a fifteen-minute basis. Therefore, the information from the Schiphol weather station does not comply with the needs for this research.

In addition, the data indicates that the profiles for Schiphol and the eight monitored PV systems vary significantly with de Bilt data (also see figure 5). This is a direct result of the geographical location where data was retrieved, as solar power generation varies significantly per region. Since this research considers the supply of solar power for the City of Amsterdam, the available information from de Bilt is considered to be less accurate than the third considered profile.

As a consequence, the electricity power production profiles of the eight PV systems in Amsterdam are employed in the continuation of this research. Moreover, for the solar power supply in the city the average supply of eight PV systems is considered. To match the city's average production, the eight system profile is normalized to match a total annual production of 925 kWh per kWp.

Figure 5 Solar power production

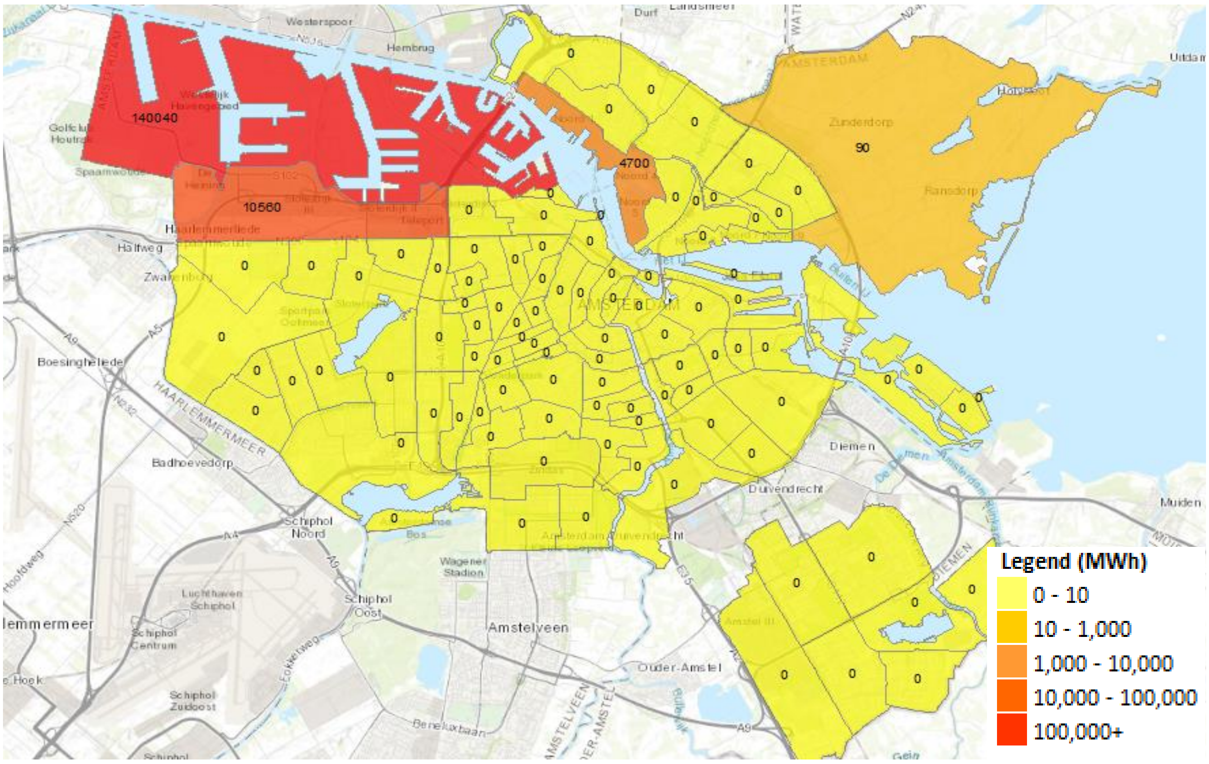


### *5.1.2 Wind power supply*

#### *Wind power distribution and yield*

Wind turbines in Amsterdam are commonly found to have about 2,500 full-load hours per year (City of Amsterdam, 2012). At the moment, Amsterdam holds a total of 39 wind turbines with a combined capacity of 66.36 MW (Windstats, 2017). Subsequently, the expected annual supply is approximately 166 million kWh. However, the actual electricity production from wind power was slightly lower in 2016, 155 million kWh (Windstats, 2017). Figure 6 shows the distribution of electricity production from wind power in Amsterdam (City of Amsterdam, 2017b). As can be observed in the figure, wind power is generated in four city districts, where the share is highest for respectively Westelijk Havengebied and Bedrijventerrein Sloterdijk. Clearly, in the city itself no wind turbines are installed.

*Figure 6 Wind power production per city district for 2016 (in MWh)*



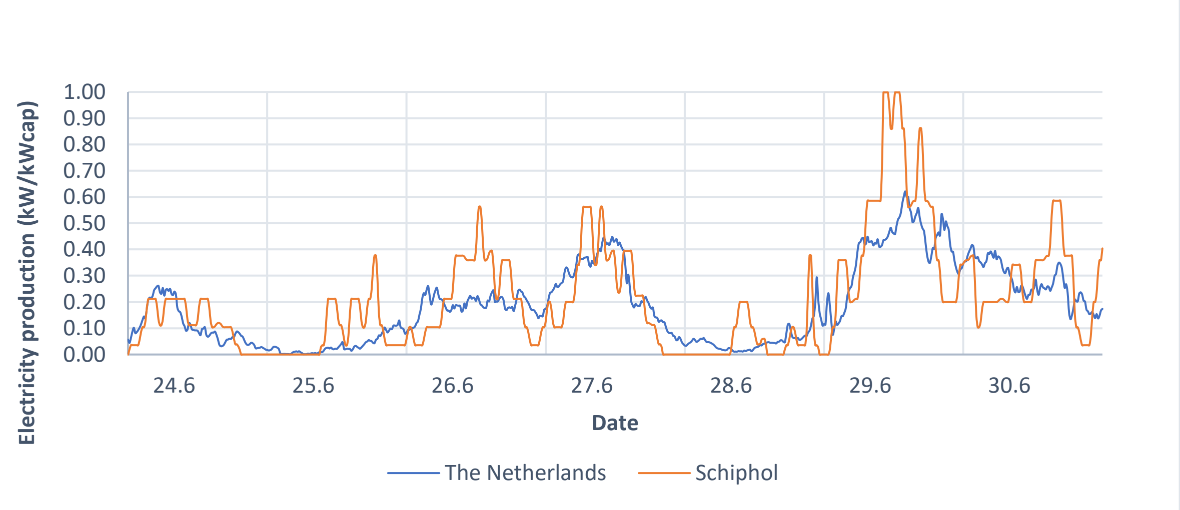
*Annual wind power supply profile*

To establish the annual profile of electricity supply by wind power in Amsterdam two different methods have been applied. As discussed in section 3.1.2, the first method is based on hourly average wind speed values of KNMI. The second method considers the national average production of all wind turbines. Both methods result in a total annual electricity production of 156 million kWh, which is equal to the reported wind production (Windstats, 2017). This is explained as the power coefficient ($C_p$) and the correction factor ($\alpha$) were both normalized to match the actual electricity production in 2016 (see 3.1.2).

Figure 7 holds the electricity supply profiles by wind power according to both methods for a week in 2016. Although the figure shows some overlap between the two profiles of, at several moments in time the difference between both profiles is significant. Moreover, from the figure it can be obtained that the supply profile for the Netherlands varies more gradually compared to the Schiphol profile. This is explained as wind speeds can vary significantly in time when considered locally. However, on a national level these variations are less visible (KNMI, 2017).

Because this research considers the supply of wind power for Amsterdam, the average national onshore wind power production profile is considered to be insufficient. This is supported as the profile does not allow for insights in local variations of supply. Consequently, in the continuance of this research the KNMI supply profile for wind is considered. Nevertheless, a disadvantage that should be taken into account is that the KNMI supply profile is not optimal as it considers hourly average wind speeds, which does not match with the fifteen-minute time step considered in this research.

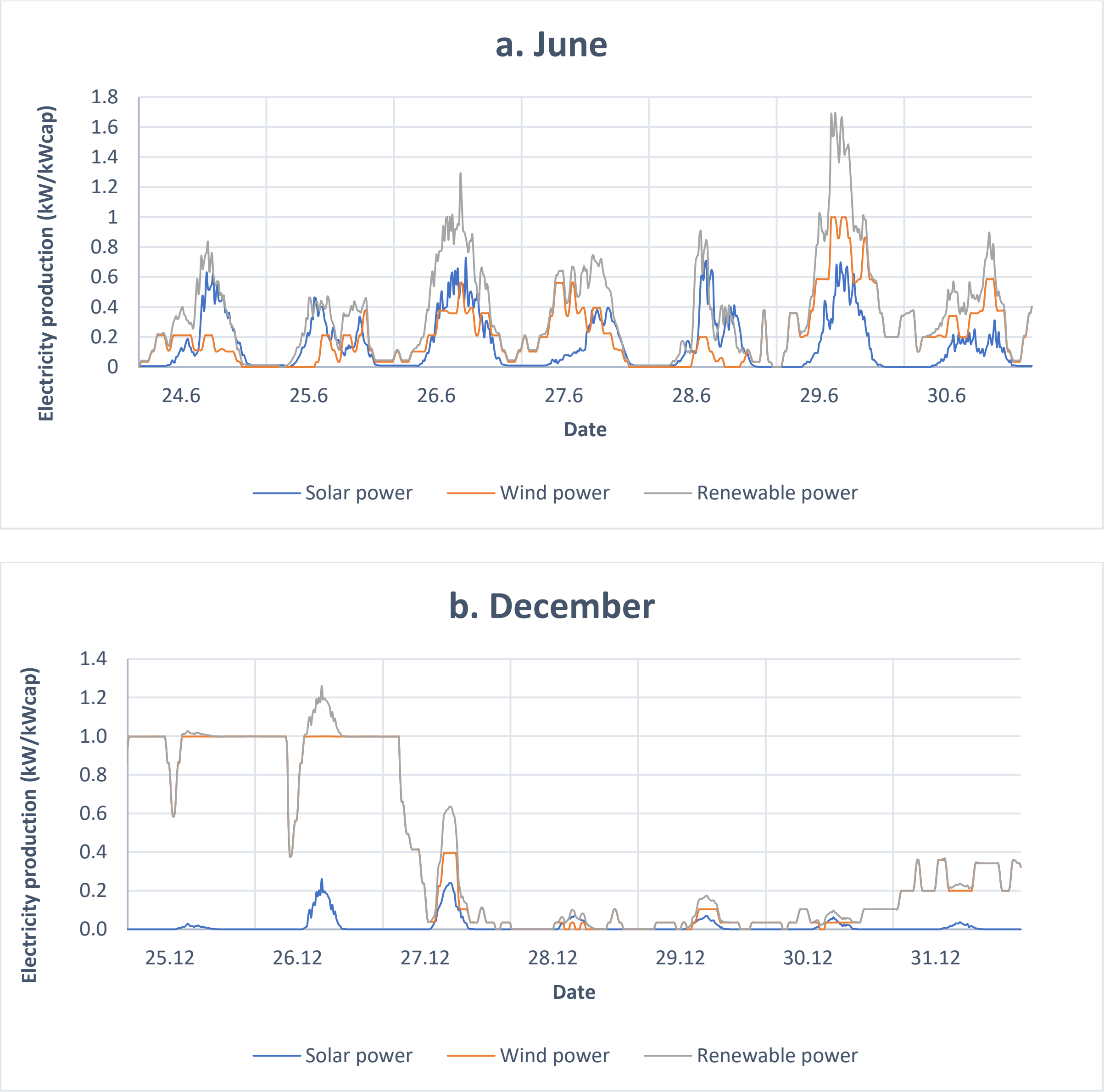
*Figure 7 Wind power production*



## 5.1.3 Renewable power supply

Figure 8 displays two weeks of electricity production by solar and wind power. From the figure it can be obtained that electricity production of solar and wind power frequently overlaps, and can differ substantially for different seasons (summer, winter). Moreover, on an annual basis it is found that the production of electricity by solar panels and wind turbines in Amsterdam coincides 43.5% of the time in 2016 when there is an EV charging demand. At these times supply often exceeds demand, such that either electricity from solar or wind power is utilized. In order to calculate the maximum renewable charge potential, a renewable supply profile is established. This profile combines the electricity production from solar and wind power.

*Figure 8 Electricity supply by solar, wind and renewable power*



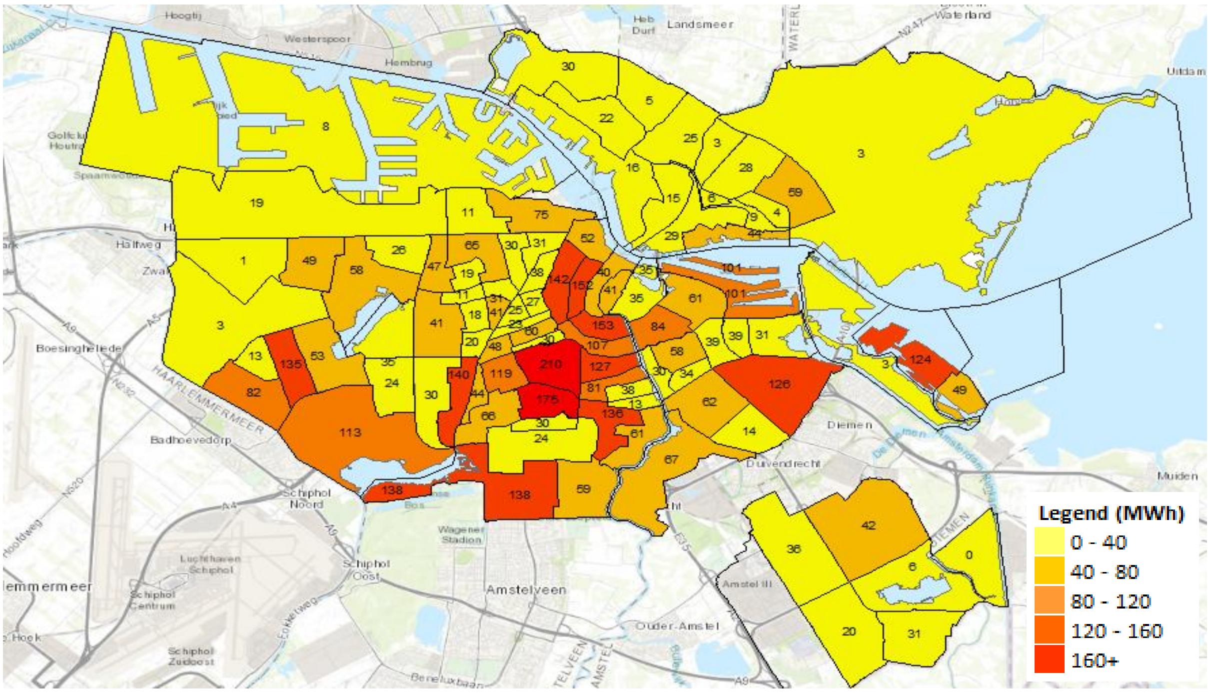
## 5.2 Energy demand

This section addresses the EV charging demand in Amsterdam. Consequently, it provides an answer to the second sub question "What is the current EV charging demand in Amsterdam and how is this expected to develop until 2035?" Subsequently, the distribution of the EV charging demand in Amsterdam is reviewed first. This is followed by an analysis of the EV charging behaviour including the demand profile per public charging points enclosed in the pilot. Finally, the effect of a growing number of FEVs on the EV charging demand is discussed.

### 5.2.1 Distribution of EV charging demand

The charging demand of EVs at public charging points in Amsterdam has significantly grown over the past few years, to 5.35 million kWh in 2016. This demand varies significantly per neighbourhood. Figure 9 depicts the total EV charging demand per district for the year 2016.

*Figure 9 EV charging demand per city district in Amsterdam for 2016 (in MWh)*



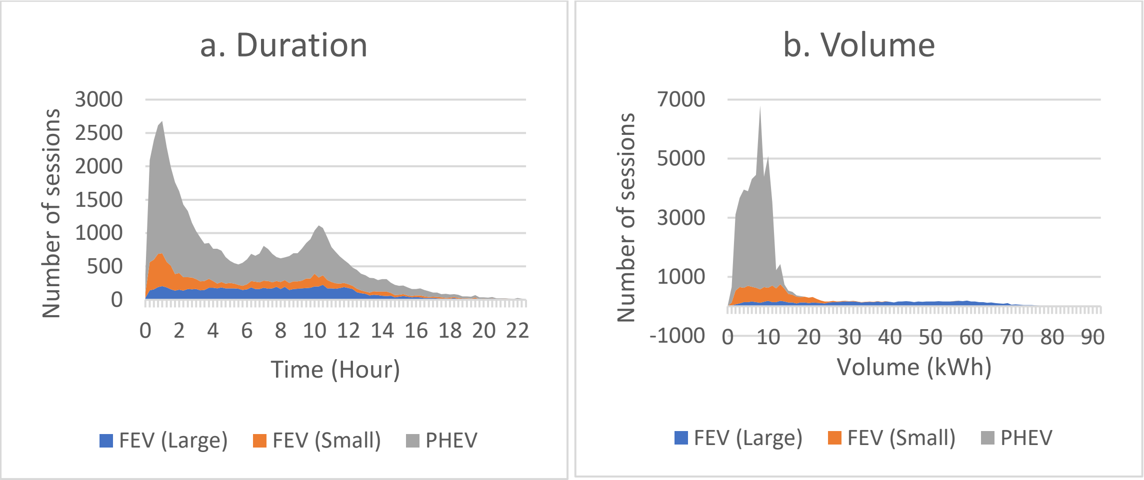
### 5.2.2 EV charging behaviour

#### *FEV and PHEV charging characteristics*

Typical EV charging characteristics, like charging duration and volume, are depicted in figure 10. Both figures are based on all charging sessions that have taken place at the 52 selected charging points in the pilot in 2016. In general, it can be found that most charging sessions are relatively short, take between zero and three hours, and consider a charged volume of below twelve kWh. However, the figures also displays that these charging characteristics deviate significantly for different types of EVs. From the figures two trends can be identified. Firstly, as the size of the battery of the EV increases the relative amount of short sessions decreases. Subsequently, the amount of short sessions is significantly greater for PHEVs than for FEVs with a small battery. The same can be said for small battery FEVs compared to FEVs with a large battery pack. The second trend is similar, and indicates a strong decrease in session where a small amount of electricity is charged (<12 kWh) when the EV battery increases (appendix A.2). Moreover, the volume charged per session is more evenly distributed for FEVs with a large battery compared to the alternatives.

Research by IDO-Laad (2017) considering charging points in Amsterdam, The Hague, Rotterdam and Utrecht confirm these trends. Moreover, this research also stated that as the range of EVs increases the frequency of charging is expected to decrease accordingly. Subsequently, FEVs with a large battery are found to charge 2.4 times per week, compared to a frequency of respectively 3.6 and 3.7 for PHEVs and small battery FEVs. This difference is mostly likely to be explained by a decrease in the number of short charging sessions (< 3 hours).

*Figure 10 EV charging behaviour on the SEEV4-City charging points in 2016*



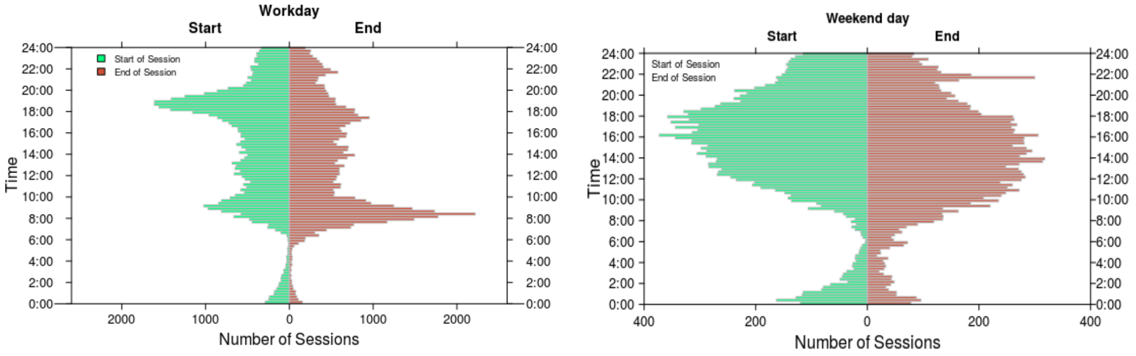
*EV connection time*

The EV charging behaviour in terms of connection times are depicted in figure 11. From the figures it can be obtained that on workdays most sessions start between 18:00 and 20:00, followed by a second peak around 08:30. In addition most sessions end in the morning around 08:00. During weekend days most sessions start and end during the day, between 09:00 and 19:00.

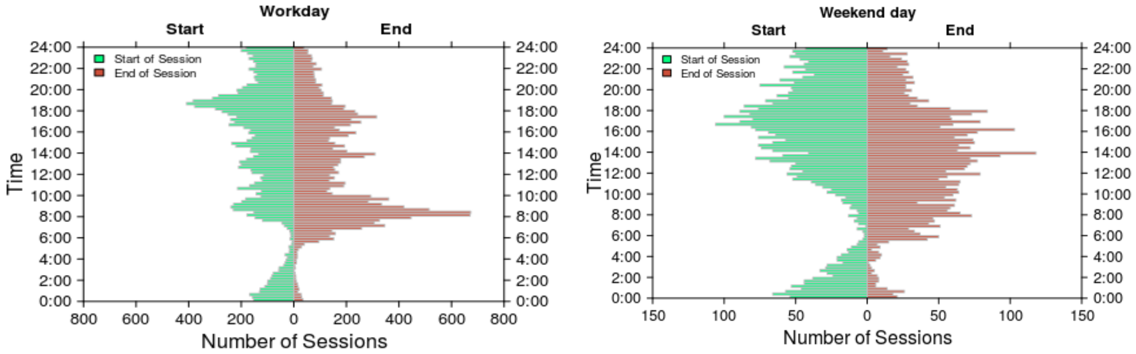
Noticeable from the figure is that there does not exist a distinctive difference for the charging behaviour of PHEV and FEV drivers. This holds for both week- and weekend days. Similarly, analysis shows that there is no apparent difference in charging behaviour for FEVs with small or large batteries.

*Figure 11 EV charging start and end times of the SEEV4-Cit charging points in 2016*

a. PHEV



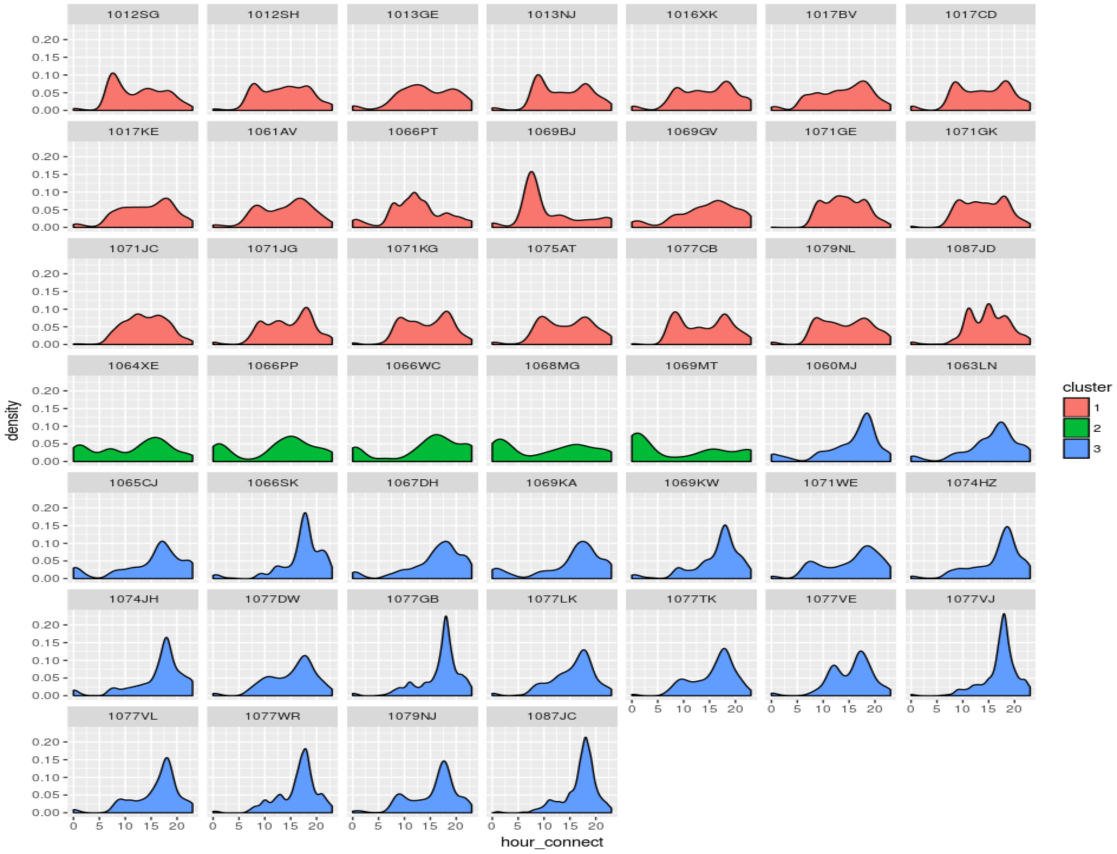
b. FEV



### *EV charging profile per charging point*

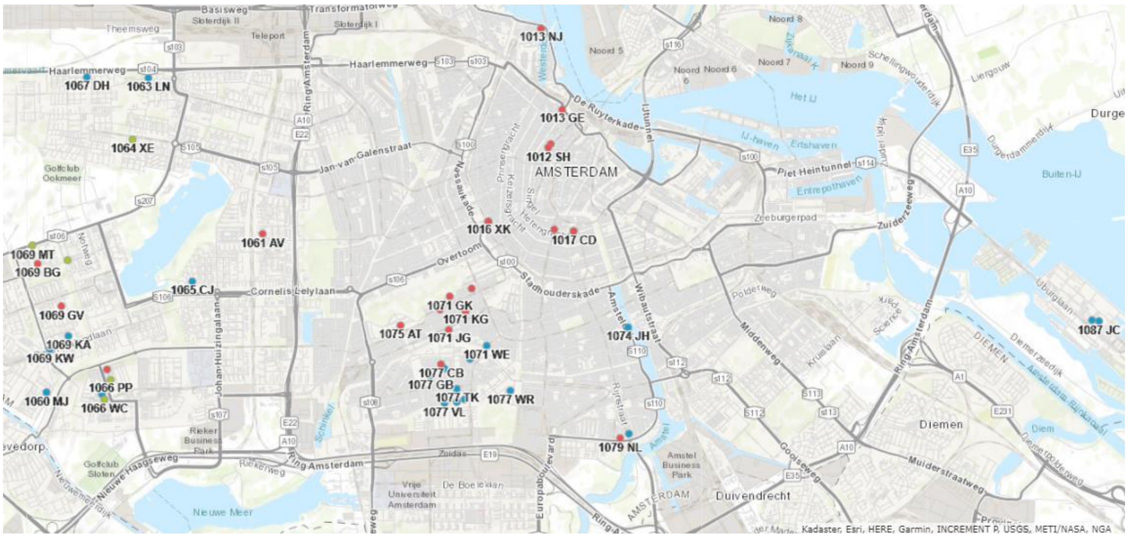
The EV charging behaviour and therewith the EV charging demand profile differs per charging point. Figure 12 shows insight into these deviating charging profiles. Moreover, the figure presents the charging profile as a function of the start of the session. Subsequently, a sub figure peaks when relatively seen most EVs start their charging session. A model analysis has categorised all the charging points into three clusters. The first cluster represents the charging points that experience most EV sessions during the day. These charging points are mainly used by visitors and commuters and are mostly found in the centre and south of Amsterdam (figure 13). The second cluster holds the charging points with a considerable amount of sessions that start in the late evening and during the night. All these charging points are located in Nieuw-West. Finally, the third cluster show similarity as most sessions start between 17:00 and 20:00, which are most likely to be caused by residents. These charging points are found in residential areas in the east, south and west of Amsterdam.

*Figure 12 EV charging profile per SEEV4-City charging point in 2016*



*The pilot consists of 52 charging points, however the figure only holds 46 graphs. This is explained as charging points that are located on the same address are reviewed as one. This is supported as EV drivers are assumed to be indifferent on connecting to either one of them.*

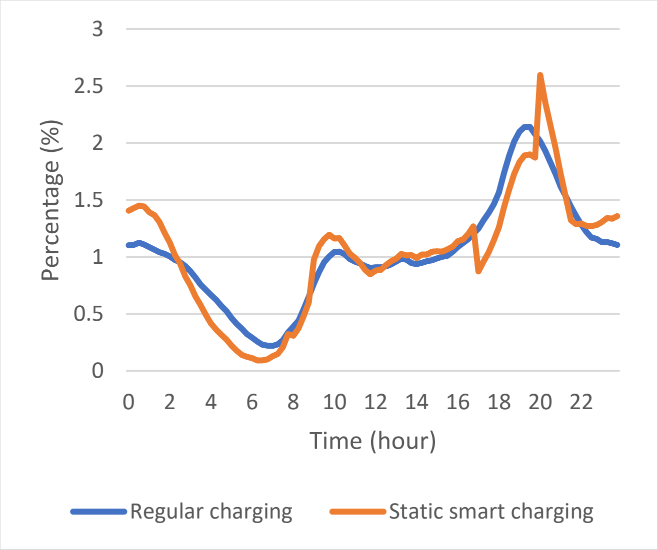
*Figure 13 Distribution of the charging point clusters*



### 5.2.3 Regular and static smart charging

Figure 14 displays the average daily distribution of the charging demand density for regular and static smart charging. Moreover, the figure shows the effect of the applied charging profile on the electricity demand for EV charging. The implementation of the static smart charging profile induces a shift in the charging demand. First of all, the electricity charged in the morning increases due to an increase charging power availability. Secondly, a decrease in the EV charging demand occurs between 17:00 and 20:00 due to a decreasing charging power availability at the charging point. This in combination with an increase in the charging power induces a peak in the EV charging demand after 20:00. At last, the electricity charged during the evening and around midnight increases due to an increase in the charging power. This also causes the EV charging demand to decrease in the early-morning (2:00-7:00).

*Figure 14 Daily distribution of EV charging demand on the SEEV4-City charging points in 2016 (fifteen-minute time resolution)*



### 5.2.4 Future EV charging

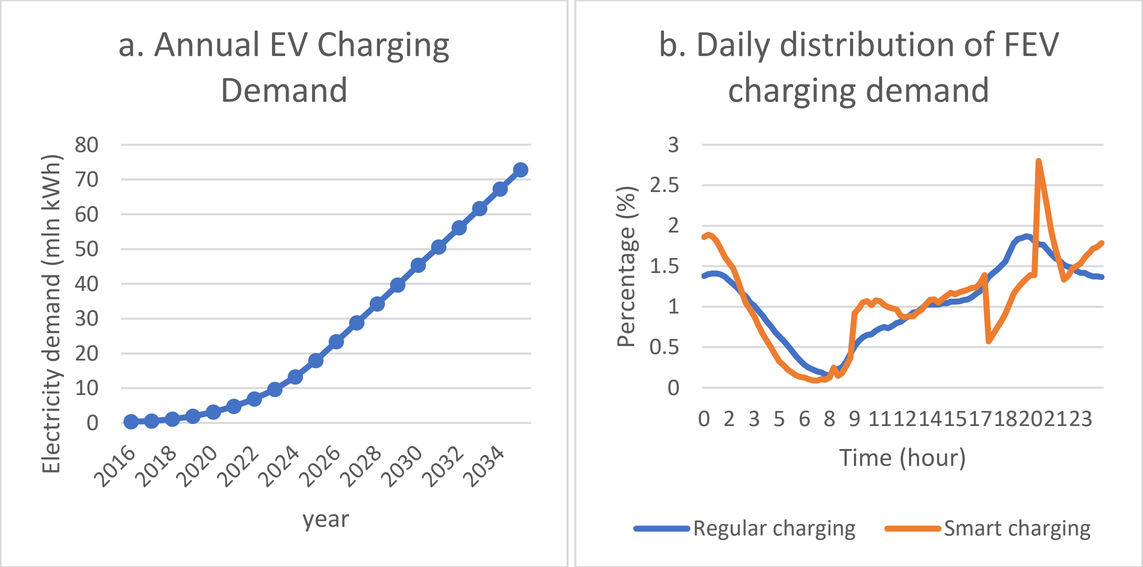
As stated in 4.2.2, the number of FEVs with battery capacities that exceed 40 kWh is expected to increase significantly in the next few years, whereas the amount of PHEVs is expected to decrease. As a result, to predict the EV charging demand of the future, it is assumed that all EVs are large FEVs. Since the size of the battery is found to influence the charging behaviour of the driver in terms of duration per session, volume per session and charging frequency, the charging behaviour of EVs is likely to change following the increase in number of large FEVs. Moreover, this is likely to result into less short sessions in which a small volume is charged. Therefore, to predict future EV charging only the current charging behaviour of FEVs with a large battery are considered (see table 6 and appendix A.2). In addition, this also implies that this research merely considers the session start and end time of these FEVs since this affects the duration of the charging session. As a consequence, the annual demand for electricity is expected to increase as depicted in figure 15a.

On the basis of the current charging behaviour of large FEVs, also an estimation is made of the average daily distribution of electricity demand by EV charging in the future. Figure 15b shows the expected distribution of EV charging demand throughout the day when regular charging is applied, and how this is affected by applying the static smart charging profile. The figure shows an increasing charging demand in the morning as a result of the higher charging power available. In addition, due to the decreasing power between 17:00 and 20:00 the charging demand decreases, followed by a peak in the EV charging demand from 20:00. Finally, the EV charging demand increases around midnight and decreases in the early morning when static smart charging is applied compared to regular charging. This is also explained by an increasing available power output of charging points, resulting in faster charging EVs.

*Table 6 Charging behaviour per vehicle*

| | **Charging sessions per week** | **Mean volume per session (kWh)** |
|---|---|---|
| FEV large (>40kWh) | 2.4 | 35.7 |
| FEV small (<40kWh) | 3.7 | 10.9 |

*Figure 15 Future EV charging demand at the SEEV4-City charging points*



## 5.3 Matching demand and supply per neighbourhood

This section aims to estimate the amount of solar and wind power that can be used to charge EVs. In order to do so, it combines the electricity supply and EV demand profiles defined in 5.1 and 5.2. As a result an answer is given to the third sub question "What is the current and future maximum share of renewable energy in EV charging when respectively regular and static smart charging are applied, considering a growing capacity of solar and wind power and an increasing number of EVs?" In this section, first the annual supply and demand per neighbourhood is presented. Thereafter, the current and future share of solar and wind power is discussed in respectively 5.3.2 and 5.3.3. At last, the results are interpreted for all charging points located in the city of Amsterdam.

### *5.3.1 Annual supply and demand*

The annual supply of electricity by solar power exceeds the EV charging in all districts except Centrum (see table 7). Moreover, when evaluated on a neighbourhood level it is found that on an annual basis enough solar power is produced for EV charging in all neighbourhoods except Appollobuurt, Grachtengordel-West, Grachtengordel-Zuid, Haarlemmerbuurt, Jordaan, Osdorp-Midden, Schinkelbuurt, Tuindorp Buiksloot, Weteringschand and Willemspark (see appendix A.1).

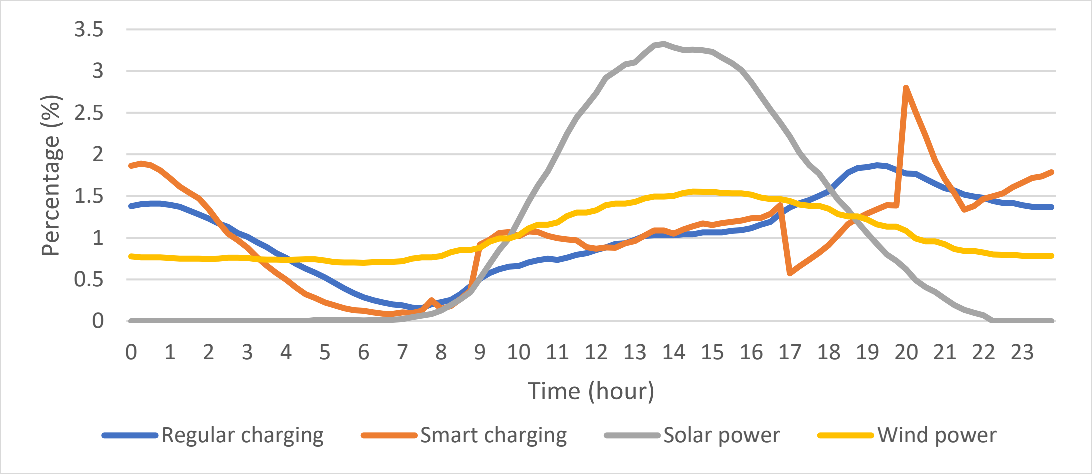
The wind turbines are located in two districts only which are Noord and Westpoort. The total power supply of these turbines exceeds the total charging demand significantly in 2016. Nevertheless, the production of wind power is limited to the neighbourhoods Bedrijventerrein Sloterdijk, Buiksloterham, Waterland and Westelijk Havengebied (see appendix A.1).

*Table 7 Electricity demand and supply per city district in Amsterdam for 2016*

| District | Solar power (MWp) | Solar energy (mln kWh) | Wind power (MW) | Wind energy (mln kWh) | EV charging demand (mln kWh) |
|---|---|---|---|---|---|
| Centrum | 0.98 | 0.88 | | | 0.98 |
| Nieuw West | 4.29 | 3.86 | | | 0.75 |
| Noord | 3.88 | 3.49 | 2.16 | 5.6 | 0.31 |
| Oost | 3.97 | 3.57 | | | 0.84 |
| West | 2.31 | 2.08 | | | 0.69 |
| Westpoort | 1.39 | 1.25 | 65.52 | 150.6 | 0.01 |
| Zuid | 3.21 | 2.89 | | | 1.64 |
| Zuidoost | 3.85 | 3.46 | | | 0.14 |
| **Total** | **23.88** | **21.49** | **67.68** | **156.2** | **5.35** |

Figure 16 shows a density plot of the average daily distribution of the supply and demand at the SEEV4-City charging points in 2016. Consequently, the figure gives an impression of at what moments in time the electricity supply and demand peak. In the figure it can be observed that the electricity production from solar power peaks around midday, whereas supply by wind power is more evenly distributed throughout the day. Furthermore, the figure shows the shift in EV charging demand as a result of the applied charging profile. Subsequently, the figure indicates the increase and decrease of electricity demand due to a change in the charging profile applied, at moments of renewable production. From the figure, it becomes clear that the reduced charging power between 17:00 and 20:00 with static smart charging affects the potential uptake of solar power. The same can be said for wind power in the early morning (02:30-07:00).

*Figure 16 Density plot of average daily distribution of electricity supply and demand by the SEEV4-City charging points in 2016*



## 5.3.2 Actual sustainable charge in 2016

By comparing the electricity supply of solar and wind power with the demand for EV charging on a fifteen-minute basis throughout the year, the potential share of solar and wind power in EV charging can be calculated. Table 8 shows the potential amount and share of these renewables in the electricity mix with which EVs are charged in the year 2016. Moreover, the table indicates the effect that the considered charging profile, either regular or smart, has on the mix. Here, the amount of renewable energy in charged into the EV is lower than the sum of solar and wind power combined. This is explained by the overlap between solar and wind power. This occurs when at a certain moment in time electricity is supplied by solar and wind power, but the combined electricity supply exceeds the electricity demand by EVs (see section 5.1).

### *Solar power*

From the table it is apparent that the implementation of the static smart charging scheme results into a small decrease in the electricity charged from solar and wind power, thus a decreasing share of renewables in EVs. For solar power this loss is explained by the shift in electricity demand. Moreover, this is caused by a decreasing electricity demand between 17:00 and 20:00, due to the limited available charging power. In addition, the reduction in the amount of solar electricity charged is caused by a decreasing amount of electricity charged in the early morning (4:00-8:00) (see appendix A.3). Furthermore, the consumption of solar power for EV charging is similar during the day. This is explained by the great surplus of solar power during the day and a limited charging demand.

### *Wind power*

The decrease in wind power charged is best explained by the reduction of electricity charged between 17:00-20:00. Moreover, as can be seen in figure 17, on an annual basis wind power production is above average around this time in Amsterdam. On the other hand, appendix A.3 indicates an increasing amount of electricity charged by wind power between 21:00 and 02:00. This is explained by the increasing electricity demand and compensated by a decreasing amount of electricity demand and therefore a decreasing amount of electricity charged from wind power in the early morning (03:00-08:00). During the day, the electricity charged by wind power is more or less similar in both charging schemes.

*Table 8 Potential solar and wind power contribution to EV charging at the SEEV4-City charging points for 2016*

| | **Volume (MWh)** | | **Share of source (%)** | |
|---|---|---|---|---|
| *Charging scheme* | *Regular* | *Smart* | *Regular* | *Smart* |
| **Total** | 331.9 | 331.9 | 100 | 100 |
| **Solar power** | 110.3 | 108.6 | 33.2 | 32.7 |
| **Wind power** | 256.3 | 253.3 | 77.2 | 76.3 |
| **Renewable power** | 270.7 | 267.1 | 81.6 | 80.5 |
| **CO2 emissions saved (kg)** | 154.3 | 152.2 | - | - |
| **CO2 emissions (tonne)** | 34.9 | 36.9 | - | - |

### *$CO_2$-emissions*

As a result of a decrease in the share of solar and wind power that can be charged into the EVs, also the overall share of renewables in EVs decreases. Moreover, as a direct consequence the $CO_2$-emissions from EV charging increase due to implementation of the static smart charging profile. Subsequently, annual $CO_2$-emissions from EV charging would increase by over a tonne in 2016 (see table 9). Considering the objective of the municipality to save about 17 tonnes of $CO_2$-emissions annually by implementing a static smart charging scheme, it can be concluded that at this moment the implementation of static smart charging would be counter effective.

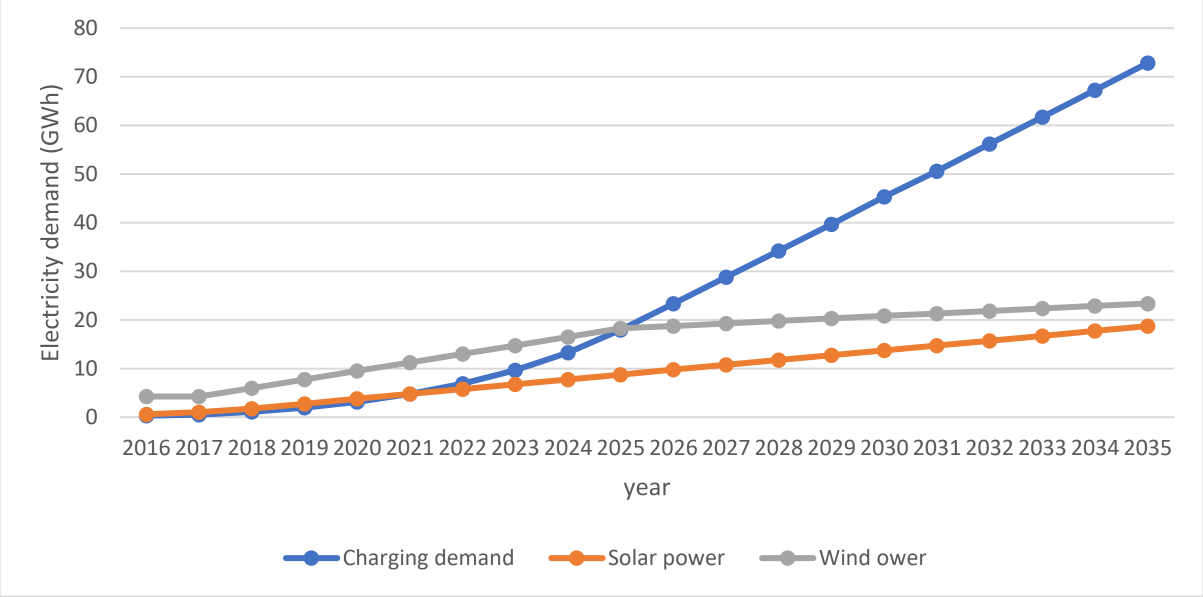
*Table 9 Difference in $CO_2$-emissions between regular and static smart charging (kg)*

| | **2016** |
|---|---|
| **Solar power** | 548 |
| **Wind power** | 956 |
| **Renewable power** | 1,159 |

### 5.3.3 Future potential of sustainable charge

Similar to the previous section, this section establishes the potential share of solar and wind power in EV charging by comparing the electricity supply and demand profiles. The future potential of the renewables charged into EVs is estimated on the demand and supply profiles established for 2016. Moreover, here an increasing installed capacity of solar and wind power, and an increasing amount of EVs in Amsterdam are considered (as explained in chapter 4). In table 10 the potential amount and share of the renewables in EV charging can be reviewed for the period 2020 to 2035. The table quickly shows a strong decrease of the share of both solar and wind power, and therefore renewables, in the electricity mix of EV charging. This is explained by the fact that the number of EVs increases relatively significantly stronger than the capacity of solar and wind power, and electricity demand increases stronger than the supply, such that the surplus of renewables decreases. Nevertheless, this is the result of a great oversupply of renewables at this moment rather than a shortage of renewables in the future. Consequently, it becomes more important to better match renewable supply to the EV charging demand in the future.

*Figure 17 Annual electricity supply and demand at the SEEV4-City charging points*



### *Solar power*

In table 10 the effect of the implementation of static smart charging on the share of solar and wind power in EV charging can be observed by comparing with regular charging. Initially it is found that the share of solar power in the electricity mix increases. Nevertheless, from 2025 the share of solar power in the electricity mix is greater for regular EV charging than for static smart charging.

The gain of solar power charged when static smart charging is applied is explained due to a higher charging power availability during the day. Due to the increased power, EVs that are charging are able to increase the uptake of solar power. Consequently, in 2020 more solar power is used for static smart charging compared to regular charging between 09:00 and 17:00. However, this positive effect decreases as the relative availability of solar supply per EV decreases, due to a stronger increase in demand than supply. As a result less often there is a surplus of solar power, and an increasing power availability causes a negative effect on the amount of solar power charged. Moreover, this is explained as a higher power availability results into a less well-distributed electricity demand. Consequently, only more solar power is charged between 11:00 and 15:00 in 2025, and between 11:00 and 13:00 for both 2030 and 2035. Although between 11:00 and 13:00 the additional amount of solar power in EVs increases in the period until 2035 when static smart charging is applied, the additional amount of solar energy consumed in regular charging during the rest of the day increases more significantly.

The decrease of solar power charged during the day is explained by a number of reasons. For the period 2020 until 2035 a significant greater amount of solar power is used for charging in the early morning. This is explained as an increased power availability with static smart charging results into a shift of electricity demand in time. Moreover, this induces a shift in the electricity demand from the early morning to the night, such that less electricity is demanded in the morning when solar power is available (see figure 14 and 15b). The same argument holds for the morning and the afternoon. Since in static smart charging more power is available in the morning, less electricity is demanded around midday when the solar power production peaks. The third reason is explained by the limited power availability when static smart charging is applied between 17:00 and 20:00, which causes a lower uptake of solar electricity. The relative effect of this diminishes over time since the surplus of solar power diminishes. Similarly, the surplus of solar power during the day decreases over time. As a consequence it appears that the uptake of solar power benefits from a more evenly distributed charging demand, which is the case with regular charging. Furthermore, the increased charging demand after 20:00 does not cause an increase in the solar electricity charged, since the supply of solar power is limited after 20:00 (see appendix A.3). At last, an increased charging power availability causes an increased fluctuating demand, which negatively effects the solar power uptake by EVs. This is explained as at these moments the electricity demand exceeds availability of solar supply more often.

### *Wind power*

The implementation of the static smart charging scheme leads to a continuous decrease in the share of electricity of wind power in EV charging. Nevertheless, the introduction of the static smart charging profile does not lead to a decrease into a decreasing share of wind power at all moments during the day. For the period until 2025 an increasing amount of electricity from wind power is charged during the day (09:00-16:00) and during the evening (20:00-02:00). On the other hand less electricity from wind power is charged between 16:00-20:00 and 02:00-08:00. The differences are simply explained by shifts in electricity demand for EV charging, which is a direct result of the power availability of the charging point. However, the extra charged electricity from wind power during the day and night does not outweigh the shortage in the early morning and evening.

After 2025, the additional amount of electricity charged from wind power decreases. This is due to a relative stronger increase in the demand compared to supply. As a result, the surplus of electricity by wind power decreases. Similar to the case of solar power, this is in favour of the regular charging, as this scheme results in a more well-distributed EV charging demand. Similarly as with solar power, this more constant demand optimizes the utilization of wind power.

*Table 10 Potential solar and wind power contribution in EV charging for the SEEV4-City charging points*

| **Year** | **2020** | | | | **2025** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Volume (MWh)** | | **Share (%)** | | **Volume (MWh)** | | **Share (%)** | |
| *Charging Scheme* | *Regular* | *Smart* | *Regular* | *Smart* | *Regular* | *Smart* | *Regular* | *Smart* |
| **Total** | 3208 | 3208 | 100 | 100 | 18339 | 18339 | 100 | 100 |
| **Solar power** | 880 | 907 | 27.4 | 28.3 | 3458 | 3339 | 18.9 | 18.2 |
| **Wind power** | 1971 | 1885 | 61.4 | 58.8 | 7654 | 7130 | 41.7 | 38.9 |
| **Renewable power** | 2171 | 2119 | 67.7 | 66.0 | 9115 | 8757 | 49.7 | 47.7 |
| **Potential $CO_2$-emissions saved (tonne)** | 1238 | 1208 | | | 5196 | 4991 | | |
| **Total $CO_2$-emissions (tonne)** | 591 | 621 | | | 5258 | 5462 | | |
| | | | | | | | | |
| **Year** | **2030** | | | | **2035** | | | |
| | **Volume (MWh)** | | **Share (%)** | | **Volume (MWh)** | | **Share (%)** | |
| *Charging Scheme* | *Regular* | *Smart* | *Regular* | *Smart* | *Regular* | *Smart* | *Regular* | *Smart* |
| **Total** | 46308 | 46308 | 100 | 100 | 74390 | 74390 | 100 | 100 |
| **Solar power** | 6812 | 6280 | 14.7 | 13.6 | 10239 | 9339 | 13.8 | 12.6 |
| **Wind power** | 12406 | 11114 | 26.8 | 24.0 | 15402 | 13494 | 20.7 | 18.1 |
| **Renewable power** | 16651 | 15521 | 36.0 | 33.5 | 22695 | 20928 | 30.5 | 28.1 |
| **Potential CO2 emissions saved (kg)** | 9491 | 8847 | | | 12936 | 11929 | | |
| **Total CO2 emissions (kg)** | 16905 | 17549 | | | 29466 | 30474 | | |

### $CO_2$-emissions

Despite the additional electricity charged from solar power in 2020 the share of renewables in the electricity mix is lower for static smart charging than for regular charging during the full simulation period. Consequently, the $CO_2$-emissions increase significantly over time when static smart charging is applied instead of regular charging. Therefore, overall it can be concluded that on the long term the implementation of static smart charging would be undesirable.

On the other hand, the municipality has set the target to save approximately 17 tonnes of $CO_2$-emissions per year. This is initially to be achieved by an increasing share of solar power. The simulation results show that static smart charging almost has the potential to achieve this in 2020, as the charging scheme saves up to 15 tonnes of $CO_2$-emissions on an annual basis. Nevertheless, the negative effect that static smart charging has on the share of wind power in the electricity mix outweighs this.

*Table 11 Difference in $CO_2$-emissions between regular and static smart charging (tonne)*

| | **2020** | **2025** | **2030** | **2035** |
|---|---|---|---|---|
| **Solar power** | -15.0 | 68.1 | 303.0 | 512.8 |
| **Wind power** | 48.8 | 298.6 | 736.5 | 1,088 |
| **Renewable power** | 29.8 | 204.3 | 644.0 | 1,008 |

### 5.3.4 Static smart charging in Amsterdam

On the basis of the results presented in the previous sections an estimation is made of the effect that static smart charging would have when rolled out at all the city's charging points. Here, it is assumed that the average charging point in Amsterdam behaves like the average charging point included in the pilot. Moreover, among others this considers an average charging point usage equal to 530 kWh per month. For similar reasons as discussed in section 5.3.2 and 5.3.3, will the implementation of the static smart charging scheme result in an increase in $CO_2$-emissions (see table 12).

*Table 12 Difference in $CO_2$-emissions between regular and static smart charging (tonne)*

| | **2016** | **2020** | **2025** | **2030** | **2035** |
|---|---|---|---|---|---|
| **Solar power** | 21 | -586 | 2,659 | 11,829 | 20,019 |
| **Wind power** | 37 | 1,905 | 11,657 | 28,752 | 42,466 |
| **Renewable power** | 45 | 1,163 | 7,976 | 25,141 | 39,331 |

## 5.4 Optimization for static smart charging

This section discusses the main obstacles that prevent a higher electricity uptake from solar and wind power. It analyses the effects that both charging schemes have on the electricity uptake from renewables. Subsequently, the section aims to provide policy recommendations on how to increase the share of solar, wind and renewables in electricity demanded for EV charging. This answers the fourth sub question "What are the main obstacles to increase the share of renewable energy in EV charging and how can these be overcome?" First, the uptake of electricity from solar power is discussed. Followed by the charge from wind power and renewables (solar and wind power combined). At last, the renewable uptake per type of neighbourhood is discussed.

### 5.4.1 Solar power charging

#### Obstacles

The obtained results for solar power show that the extra charging power available during the day, from 9:00 until 17:00, increases the amount of electricity charged from solar power significantly in the period until 2025. This is explained, as with this increased charging power EVs are able to employ the great surplus of solar power which is apparent during most of the days (see appendix A.3). This is especially the case until 2020, when there is a surplus of solar power for over 90% of the time. After 2025 the solar power surplus diminishes due to a relative strong increase in EV charging demand. Moreover, this is when the additional power availability at the charging points affects the potential electricity charged from solar power. This is supported as a lower charging power results into a more well-distributed electricity demand. Consequently, electricity demand will be less fluctuating and therefore less often exceed supply compared to the case where a higher charging power is handled. The potential uptake from solar power during the day would become more positive when the installed capacity increases. In addition, the relative high supply of solar power in 2020 results in a higher uptake of electricity from solar power for static smart charging compared to regular charging. However, this is not apparent after 2020 since the relative installed capacity of solar power per EV decreases.

Another result of the introduction of static smart charging is a higher charging power during the night. Due to a lack of solar power availability, this does not directly influence the uptake of solar power. Nevertheless, the shift in electricity demand caused by this does affect the solar power uptake, due to a decreasing charging demand in the (early-)morning.

Finally, the reduced power between 17:00 and 20:00 affects the electricity demand. Moreover, a lower demand results into a lower electricity uptake from solar power. This effect is more apparent during the period until 2025. After 2025, the charging demand for both charging schemes exceeds the solar power supply more often and, therefore, the influence of a limited charging power on the solar power uptake decreases. The effect will remain comparable if the installed capacity of solar power increases.

#### Policy recommendations

To increase the uptake of solar power the electricity demand should be shifted to the moment where the surplus of solar power is the greatest. Since there is a great surplus of solar power during the day it is recommended to increase power during the day (07:00-17:00). The positive effect that this has on the amount of solar power charged is visible by the difference in solar power charged between regular and static smart charging scheme, where static smart charging is found to be able to employ this surplus effectively (appendix A.3).

Furthermore, since there is a lack of solar power available during the night (20:00-07:00), it is advised to decrease the power output at night.

Based on the results of this research, it is recommended to not decrease the charging power between 17:00 and 20:00 as is done in the static smart charging profile, or decrease the output less significantly. Until 2025 this greatly affects the uptake of solar power between 17:00 and 19:00. On the long term this holds especially for the first hour only.

A first analysis shows that the EV uptake of electricity from solar power can be increased by at least 5% throughout the simulated period compared to the case of regular charging when the charging power is increased during the day. This profile considers a charging power of 22kW during the day (07:00-20:00), whereas a charging power of 11kW is maintained during the night (20:00-8:00). This result is mostly limited due to a limited charging demand by EVs during the day compared to solar supply.

### *5.4.2 Wind power charging*

#### *Obstacles*

The increase in charging power availability when static smart charging is applied, leads to an increase in electricity from wind power charged during the day and evening. On the other hand, it causes a decrease in wind power charged between 17:00 and 20:00 and in the early morning. Both effects of the introduction of static smart charging are explained by a shift in the electricity demand. Moreover, since more electricity is demanded during the day and evening, the uptake of electricity from wind power increases and vice versa. Nevertheless, the additional electricity charged from wind power does not outweigh the decrease. As a result, the introduction of static smart charging has a negative influence on the share of wind power in the electricity mix employed by EVs.

#### *Recommendations*

In order to increase the share of wind power in EV charging, it is recommended to try to shift the electricity demand of EV charging to the time of the day when the surplus of wind power is the highest. Most surplus of wind power is found during the day. Nevertheless, the additional amount of wind power charged into EVs during the day when static smart charging is applied is ample outweighed by the times that less wind power is utilized for EV charging. Consequently, it appears that the share of electricity charged derived from wind power benefits from a more well-distributed electricity demand. On the long term this is strengthened as the relative positive effect of a higher charging power decreases significantly. Which is explained as the charging demand exceeds the supply more often in both charging schemes. Therefore, the regular charging scheme is preferred over static smart charging.

### *5.4.3 Renewable charging*

#### *Recommendations*

For the simulated period, during most days a surplus of renewables is found during the morning. Therefore, it is recommended to shift the electricity demand to the morning (7:00-14:00). This surplus is due to the limited electricity demand for EV charging compared to the supply by solar and wind power. In addition, on the short term a surplus of renewables is also often found during the day. Therefore, an increase in the charging power during the day is likely to increase the share of renewables in EV charging.

### *5.4.4 Renewable charging per neighbourhood*

In section 5.2.2, the selected charging points were, according to the charging behaviour, divided into three different clusters. Cluster one is characterised by a high electricity demand during the day (7:00-23:00). Moreover, these charging points have a great potential to utilize solar power. Therefore, it is recommended, especially on the short term, to increase the charging power at these charging points during the day in order to shift the electricity demand. Moreover, it is advised to limit the charging power during the night, such that the electricity demand is better distributed overnight, which optimizes the utilization of wind power.

Cluster two represents the charging points where most sessions take place during the night. Consequently, the share of solar power in EV charging is significantly low. Moreover, based on the current overnight charging behaviour at these charging points, it would be hard to increase the share of solar power, as there is no demand for electricity during the day. At these charging points it is recommended to maintain a limited charging power in order to distribute the electricity demand more evenly over night. This will allow for optimization of the uptake of wind power. Moreover, by postponing the electricity demand to the early morning, one may be able to increase the uptake of solar power as well.

Cluster three exists of the charging points that have a clear demand for EV charging during the evening. Moreover, at these charging points the decreased power availability during the evening results in a limited ability to utilize solar power. Similar as for the previous cluster it is advised to maintain a limited charging power in order to distribute the electricity demand more evenly and optimize the uptake of wind power.

# 6. Discussion

The results obtained in this research provide insights into the effects of the utilization of regular and static smart charging on the share of solar and wind power in EV charging. Nevertheless, due to the simplifications and assumptions made in the research these results also come with certain limitations. This chapter aims to review the limitations by discussing the data quality (section 6.1) and the research limitations (section 6.2). Thereafter, in section 6.3 the implications of the research are set forth.

## 6.1 Data quality

### *6.1.1 Solar power production*

A first note to the research results obtained considers the solar power production. Moreover, the production profile of solar power is in this research based on the data of eight PV systems located in Amsterdam. Only eight systems were reviewed as solar power production data per fifteen minute time frame was only available at these systems. The total revenue of these systems was already corrected from 880 kWh per kWp to the average found in Amsterdam of 925 kWh per kWp. However, since only eight systems are evaluated, the impact of a single station on the estimated production is significant. Therefore, the supply profile is sensitive to errors in the data collection of these systems.

### *6.1.2 Wind power production*

Another consideration concerns the wind power production profile. In this research a fifteen-minute time frame is considered. However, due to the limited data availability of wind power production in Amsterdam, the wind power supply profile is based on hourly average windspeeds. Moreover, the hourly averages flatten out the fluctuating nature of wind power production. Consequently, the established wind power supply does not accurately describe the actual wind power production. As a result, the estimation of the uptake of electricity produced by wind power could be under- or overestimated, depending on the timely coincidence of supply and demand.

### *6.1.3 Charging demand*

The time dependent EV charging demand is estimated on the data available in the EV Dataset. Since the EV Dataset is incomplete, as it does not hold information regarding the EV, the charging power during the session nor the duration of the charging session, a number of assumptions were made to establish the charging demand and determine the EV characteristics (section 4.2). As a direct result, EVs may be incorrectly categorized such that PHEVs are tagged as a FEV or vice versa. This would affect the course of extracted power during a charging session, and therewith may influence the charging demand profile established in this research. Nevertheless, the impact of this is expected to be limited since this will consider a relative low amount of sessions compared to the 28,783 sessions considered.

## 6.2 Research limitations

### *6.2.1 Solar power*

In addition, the annual solar power supply profile for the period 2016-2035 is based on the profile established for the year 2016. However, it is likely that this profile differs somewhat per year, which is likely to affect the uptake of solar power at certain moments during the day. However, on an annual basis the subsequent effect of this on the difference between the uptake of solar power by EVs for regular and static smart charging is expected to be limited.

The growth of the installed capacity of solar power is based on targets set by the City of Amsterdam. Consequently, an accelerated or delayed growth of the installed capacity will affect the annual solar power generation and the share of solar power in EV charging.

Furthermore, a potential increase in the efficiency of a PV system is not considered in the established future production profile. Therefore, the amount of solar power generated and therewith the potential share of solar power in EV charging is likely underestimated. On the other hand, as more PV systems are placed less favourable orientation for these systems will have to be employed. Consequently, less solar power will be produced. These effects may even each other out.

### *6.2.2 Wind power*

The production profile of wind power for the period 2016-2035 is based on the 2016 profile. However, similarly as with solar power, the wind power supply profile will vary per year and influence daily uptake values of electricity from wind power. Nevertheless, as the amount of full load hours is expected to be similar per year, the net annual effect of this is expected to be limited.

Furthermore, the growth of wind power was estimated according to the targets set by Amsterdam. However, it remains questionable whether these targets will be met as the City is behind schedule (City of Amsterdam, 2012). Besides that, in this research a linear growth of wind power is considered, which is unlikely as wind turbines are often installed in the form of wind parks and therefore a sudden increase in the installed capacity may be more likely. Since the date and the form of construction of new wind turbines in the city is unknown, a gradual growth rate is considered.

In this research a constant power coefficient and efficiency of wind turbines in Amsterdam is assumed, which is set equal to current values. However, due to the development of wind turbines and increasing sizes in terms of power, wind turbines have become more efficient over the past years. Moreover, it is likely that newly installed wind turbines have improved efficiencies, such that the power output of wind power per installed power unit increases (Twidell & Weir, 2015). Consequently, the production of electricity of wind power, and also the potential share of wind power in EV charging, is underestimated with regard to the future.

### *6.2.3 Charging demand*

Another limitation of this research considers the estimated future charging demand of EVs. In this research the future electricity demand is based on the current charging behaviour of FEVs with a large battery. This charging behaviour is described using the charging frequency, volume per session, session start time and session end time. Nevertheless, the charging behaviour may change significantly in time as a result of the adoption of EVs in different kind of user groups. This is explained as FEVs are at this moment most profitable for commuters, such that it is likely that most FEVs are driven by commuters. Since commuters have a different charging behaviour than e.g. private car owners, on the long term the average charging behaviour may differ from current behaviour. Research by Cuijpers et al. (2016) indicates that commuters have a relative high annual mileage. Consequently, the EV charging demand may likely be overestimated for the long term.

Furthermore, the growth of EVs is based on national predictions and targets, and applied to the City of Amsterdam. Nevertheless, it is uncertain whether the EV growth rate in Amsterdam will be similar to the national average. Moreover, in the growth of EVs limited consideration is given to (the effect of) car sharing initiatives, which is already apparent in Amsterdam. For these reasons the EV charging demand may be over- or underestimated in this research.

### 6.2.4 Electricity demand

Another side note to this research considers the possible effects of the absence of electricity demand by others, e.g. residential and commercial users, on the amount renewable electricity charged. In section 3.2 it is stated that this research would provide insights into the differences between both charging schemes by studying the potential or theoretical share of renewables in EV charging rather than the actual share. In addition, the section describes that research into the displacement of renewable electricity consumption is excluded from this research.

Although this provides insights into the differences of regular and static smart charging, this also comes with certain limitations. Moreover, the surplus of renewable power at certain time of the day may be affected by the electricity demand from third parties. The consideration of the actual electricity demand from others may affect the effectiveness of both charging schemes, which would lead to a faulty estimation of the renewable uptake by EVs. For example, a standard electricity demand profile for residential neighbourhoods has a peak in the evening, while electricity demand is limited during the day. When this electricity demand would have been included in the study the surplus of solar power would decrease stronger during the evening than during the day. As a result, the additional solar power consumed in regular charging compared to static smart charging between 17:00 and 20:00 would decrease more than the additional uptake of solar power by static smart charging during the day. This case would favour the case of static smart charging. Therefore, it is highly recommended to research the effect of energy demand by others on the surplus of solar and wind power and how this affects the potential of regular and static smart charging.

## 6.3 Research implications

### 6.3.1 Solar and wind power in EV charging

The research points out the differences in the EV charging demand when regular and static smart charging are applied. Moreover, it estimates the potential uptake of solar and wind power for both charging schemes at this moment and in the future. The results indicate that for 2016 regular charging is slightly preferred over static smart charging, as the uptake of renewables in regular charging exceeds the uptake in static smart charging. The effect is among others limited due to the relative large amount of PHEVs and FEVs that are not influenced by the introduced charging profiles as their maximum charging power (3.7 kW) is at all times below the charging powers available.

When the number of FEVs increase, a greater amount of EVs is able to employ the extra charging power available during the day. As a consequence, for the period until 2020 the static smart charging profile is preferred over the regular charging profile, as this has the potential to save an additional of 15 tonnes $CO_2$ annually in 2020. Nevertheless, this amount is compensated by the deficit amount of wind power charged in EVs when static smart charging is applied. Therefore, from an overall renewable perspective regular charging is preferred.

After 2020, again regular charging is favoured over static smart charging from both a solar and wind power perspective as the results indicate that the uptake of renewable by EVs is higher for regular than for static smart charging. This is explained as the charging demand at a time more often exceeds the supply of electricity by renewables in both charging schemes. This favours a more evenly distributed charging demand, as is the case with regular charging

### 6.3.2 SEEV4-City objective

The SEEV4-City project runs from 2016 until 2020 and is focused on increasing the uptake of solar power. The results indicate that the uptake of solar power by EVs is higher for static smart charging than for regular charging in this period. As a result with static smart charging an additional of 15 tonnes $CO_2$ per year can be saved in 2020, which approaches the project's objective to save 17 tonnes of $CO_2$ per year by static smart charging. Therefore, from the project's perspective the implementation of static smart charging is recommended. Nevertheless, this does not hold for the period 2020 onwards unless essential adaptations are made to the static smart charging profile.

### 6.3.3 Energy autonomy

Another goal of the SEEV4-City is increasing energy autonomy due to the introduction of smart charging solutions. Here, energy autonomy means to decrease the amount of electricity flows, into and out of the local grid, which go through the transformer substation. In addition, SEEV-City aims to reduce the amount of grid investments needed, by decreasing increasing local electricity flows. In Amsterdam energy autonomy can only be raised by effective utilization of solar power, since solar power is the only form of local energy production that is found in the city.

Since it is found that static smart charging increases the uptake of solar power in 2020, this research indicates that static smart charging could increase the energy autonomy on the short term. However, the uptake of solar power by EV charging would only actually contribute to local energy autonomy when there is a local surplus. Therefore, in order to determine changes in energy autonomy due to static smart charging all electricity flows in a neighbourhood should be mapped. In addition, since electricity production and demand differs significantly per neighbourhood (figure 12 and 13), some neighbourhoods will have a greater potential for increasing energy autonomy by static smart charging than others. Moreover, a selection of neighbourhoods with most potential to increase energy autonomy can be made on the basis of figure 12 and appendix A.1, whereas neighbourhood with high flows of electricity are expected to benefit most from static smart charging measures to raise energy autonomy. Nevertheless, information regarding the electricity grid and the local electricity generation is needed in order to evaluate the potential impact of static smart charging on the energy autonomy of a neighbourhood.

### 6.3.4 Policy development

This research indicates that the charging behaviour of EVs differs per charging point (see figure 12). However, the similarities encountered between multiple charging points in terms of behaviour allow for categorization of the studied charging points. Subsequently, this research identified three main clusters of charging points, which are characterised by day, evening and night charging. Unfortunately, this study did not identify the effectiveness of static smart charging on the uptake of renewables per charging point nor cluster of charging points. Nevertheless, on the basis of the daily solar power production profile and the daily EV charging behaviour at the studied charging points, it is very likely that the effectiveness of static smart charging varies significantly per charging point. Consequently, the adoption of a different static smart charging profile per cluster may increase the uptake of renewables. To estimate the differences in effectiveness of deviating static smart charging schemes, additional research is needed that focuses on individual charging points.

Another adjustment to static smart charging that deserves additional attention in future research is the introduction of seasonal charging schemes. Moreover, this is explained as the production of solar power is concentrated in the months April until September (iCarus, 2017; KNMI, 2017). Subsequently, it may be more successful to focus on EV charging with solar power in these months and to focus on wind power during the remaining months.

Besides that, it is recommended to research the effectiveness of other measures which could be employed that shift either electricity demand or supply in order to increase the uptake of solar and wind power by EV charging. First of all, a shift in the electricity demand may be achieved by inducing behavioural changes of EV drivers. For example, an increase in the uptake of solar power could be achieved by stimulating EV drivers to charge during the day instead of evening or night. The renewable electricity supply may be shifted by the introduction of local storage. Subsequently, these storages could e.g. be charged with an excess of solar power during the day, which could be used to charge EVs in the evening.

# 7. Conclusion & Recommendations

The aim of this research was to assess the effect of the implementation of static smart charging on the amount of solar and wind power that could be charged in EVs, and how this effect changes over time. In order to establish this impact, the electricity supply from renewables, solar and wind power, and the electricity demand from EVs haves been estimated for the period 2016 until 2035. Next, the potential uptake of electricity from solar and wind power by EV charging was calculated. Finally, the main obstacles to increase the share of renewables in EV charging are discussed, in order to provide an answer to the research question:

*What is the potential of static smart charging to increase the utilization of solar and wind power for EV charging and decrease $CO_2$-emission by (local) traffic in Amsterdam for the period 2016-2035?*

First of all, the increased charging power availability present in static smart charging is found to increase the net uptake of solar power during the day until 2020. However, the reduced power availability between 17:00 and 20:00 and a shift of the electricity demand compensates (partly) for the additional solar power uptake. After 2020 this leads to a net negative effect of the static smart charging profile on the uptake of solar power, when compared to regular charging. Consequently, from a perspective of solar power it is advised to implement the static smart charging profile on the short term. After 2020, adjustments to the static charging profile are needed to increase solar power uptake in order to cause a net positive impact with regard to regular charging.

With regard to wind power it is found that an increased amount of electricity is used for charging EVs at varying moments during the day and evening due to static smart charging. Nevertheless, for every year in the simulated period this positive effect is outweighed by the decrease of electricity uptake from wind power during the rest of the day. Therefore, from a wind power perspective the regular charging profile is preferred over static smart charging.

The overall impact of the implementation of static smart charging on the uptake of renewables by EVs is found to be negative for the entire simulation period. Subsequently, on the grounds of the assumptions made, the introduction of static smart charging will lead to an increase in $CO_2$ emitted by EVs. However, it needs to be pointed out that this research does not include potential effects of energy demand by others on the surplus of renewables, which may favour the case of static smart charging over regular charging. To map this effect more accurately it is essential to research the influence of electricity demand by third parties on the solar and wind power surplus.

Furthermore, on the basis of the research findings and the objectives set in the SEEV4-City project, it is recommended to implement static smart charging on the short term as it has the potential to save 15 tonnes of $CO_2$-emissions by 2020. Nevertheless, since the project aims to save 17 tonnes per year additional measures or adjustments to the static charging profile are needed.

Finally, to optimize the uptake of renewables by EVs it is recommended to adjust the static charging profile according to the local charging behaviour, and local electricity supply and demand third parties. Moreover, the development of different static smart charging profiles for different types of neighbourhoods may has the potential to increase the effectiveness static smart charging. To establish this, additional research is required into the electricity supply and demand per neighbourhood.

# References

Amsterdam Univerisity of Applied Sciences (2015). Smart, clean Energy and Electric Vehicles for the City. Full Application. April 2015.

Amsterdam Unversity of Applied Sciences (2017). Dataset for EV charging sessions in Amsterdam. June, 2017.

City of Amsterdam (2012). De Windvisie. Ruimte voor windmolens in Amsterdam. July, 2012.

City of Amsterdam (2015a). Schaalsprong Zon. Uitvoeringsprogramma 2016 – 2018. February, 2015.

City of Amsterdam (2015b). Duurzaam Amsterdam. Agenda voor duurzame energie, schone lucht, een circulaire economie en een klimaatbestendige stad. March, 2015.

City of Amsterdam (2017a). Baseline document: Operational pilot in Amsterdam. April, 2017.

City of Amsterdam (2017b). Dashboard for data of EV charging in Amsterdam. June, 2017.

Coenen, P., van der Maas, C., Zijlema, P., Arets, E., Baas, K., ... & Oude Voshaar, S. (2016). Greenhouse gas emissions in the Netherlands. National Institute for Public Health (RIVM), 2016.

Cuijpers, M., Staats, M., Bakker, W. & Hoekstra, A. (2016). Eindrapport Toekomstverkenning elektrisch vervoer. Ecofys, December 2016.

ECN (2016). Energietrends 2016. ECN Policy Studies, September 2016 (ECN-O--16-031). Publication by ECN, Energie Nederland and Netbeheer Nederland.

EEA (2014). Air pollution fact sheet 2014 Netherlands. European Environment Agency, 2014.

ENTSO-E (2017). Actual generation per production type. Obtained in May 2017, from https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show.

EV Database (2017). Elektrische Voertuigen Database. Retrieved in June 2017, from https://ev-database.nl/cheatsheet/snelladen-elektrische-auto.

Geerts, F., Vertelman, B., Kelder, M. & Schuring, F. (2016). Consortium Project plan Smart Charging Amsterdam. December 23, 2016. Confidential.

Van der Giessen, A. & van der Linden, C. (2016). Electric mobility is here. Published in March 2016.

Helmus, J., & Van den Hoed, R. (2015). Unraveling User Type Characteristics: Towards a Taxonomy for Charging Infrastructure. In Proc. 28th Int. Electric Vehicle Symp. and Exhibition (EVS 28), Goang, Korea (pp. 3-6).

iCarus (2017). Dataset electricity production of eight PV systems. Obtained from iCarus, May 2017.

IDO-Laad (2017). Consortiummeeting 6. Amsterdam University of Applied Sciences. July, 2017.

Janssens, H. & Wielders, L. (2014). $CO_2$-uitstootrapportage. Gemeente Amsterdam, September 2014.

KNMI (2017). Klimatologie. Uurgegevens van het weer in Nederland. Obtained in May 2017, from http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi.

Knol, A. (2016). Wat ademen wij in? Milieudefensie, May 2016.

Milieudefensie (2016). Actieplan gezonde lucht in Amsterdam. July 2016.

PVOutput, 2017. Solar power production statistics. Retrieved in July 2017, from https://pvoutput.org/.

Raad van State, 2017. Provincie mocht vergunningen voor windturbines in Amsterdams havengebied weigeren. Retrieved in August 2017, from **https://www.raadvanstate.nl/pers/persberichten/tekst-persbericht.html?id=1074**.

Readaar (2017). Inventarisatie PV Amsterdam. Research of Readaar BV, commissioned by the City of Amsterdam. May 2017.

SEEV4-City (2017). Smart, clean Energy and Electric Vehicles for the City. Retrieved in May 2017, from http://www.northsearegion.eu/seev4-city/

Steinbuch, M. (2017). Schatting verkopen Elektrisch Vervoer Nederland t/m 2025. Retrieved in July 2017, from https://steinbuch.wordpress.com/2016/01/22/schatting-verkopen-elektrisch-vervoer-nederland-tm-2025/.

Twidell, J., & Weir, T. (2015). Renewable energy resources. Routledge.

Van Vuuren, D., Stehfest, E., Gernaat, D., Doelman, J., van den Berg, M., et al. (2016). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change 42, pp. 237-250.

Van Sark (2014). Opbrengst van zonnestroomsystemen in Nederland. Een analyse ten behoeve van de bepaling van een nieuw kengetal zon-PV voor het Protocol Monitoring Hernieuwbare Energie. Universiteit Utrecht, March 2014.

Windstats (2017). Statistieken over windenergie in Nederland. Obtained in May 2017, from http://windstats.nl/turbines.php?gemeente=Amsterdam.

# Appendix

## A.1 Energy supply and demand per neighbourhood combination

| Neighbourhood combination | Solar Power (kW) | Solar electricity (MWh) | Wind Power (kW) | Wind electricity (MWh) | EV (MWh) |
|---|---|---|---|---|---|
| Amstel III/Bullewijk | 1,131.8 | 1,047.0 | | | NA |
| Apollobuurt | 144.0 | 133.2 | | | 174.7 |
| Banne Buiksloot | 988.0 | 913.9 | | | 25.1 |
| Bedrijventerrein Sloterdijk | 1,096.0 | 1,013.8 | 6,600 | 10,560 | 19.1 |
| Betondorp | 24.0 | 22.2 | | | 14.4 |
| Bijlmer Centrum (D,F,H) | 657.0 | 607.7 | | | 36.3 |
| Bijlmer Oost (E,G,K) | 939.2 | 868.8 | | | 42.1 |
| Buiksloterham | 491.0 | 454.2 | 2,000 | 4,700 | 16.0 |
| Buikslotermeer | 479.0 | 443.1 | | | 30.9 |
| Buitenveldert-Oost | 189.7 | 175.5 | | | 59.5 |
| Buitenveldert-West | 824.9 | 763.0 | | | 137.8 |
| Burgwallen- Nieuwe Zijde | 117.0 | 108.2 | | | 40.4 |
| Burgwallen-Oude Zijde | 21.0 | 19.4 | | | 40.5 |
| Centrale Markt | 200.0 | 185.0 | | | 29.9 |
| Chassébuurt | NA | NA | | | 40.5 |
| Da Costabuurt | 49.0 | 45.3 | | | 27.4 |
| Dapperbuurt | 234.0 | 216.5 | | | 39.4 |
| De Eendracht | 81.6 | 75.5 | | | 1.3 |
| De Kolenkit | 283.0 | 261.8 | | | 47.0 |
| De Krommert | 112.0 | 103.6 | | | 30.8 |
| De Omval | 125.0 | 115.6 | | | 70.9 |
| De Punt | 47.2 | 43.7 | | | 13.0 |
| Diamantbuurt | 55.0 | 50.9 | | | 37.8 |
| Driemond | 125.9 | 116.5 | | | 0.3 |
| Erasmuspark | 66.0 | 61.1 | | | 19.5 |
| Frankendael | 684.0 | 632.7 | | | 62.2 |
| Frederik Hendrikbuurt | 86.0 | 79.6 | | | 38.0 |
| Gein | 310.8 | 287.5 | | | 30.8 |
| Geuzenveld | 323.7 | 299.4 | | | 49.1 |
| Grachtengordel-West | 34.0 | 31.5 | | | 151.8 |
| Grachtengordel-Zuid | 31.0 | 28.7 | | | 153.5 |
| Haarlemmerbuurt | 32.0 | 29.6 | | | 51.6 |
| Helmersbuurt | 110.0 | 101.8 | | | 59.5 |
| Holendrecht/Reigersbos | 560.5 | 518.5 | | | 20.1 |
| Hoofddorppleinbuurt | 282.0 | 260.9 | | | 140.4 |
| Hoofdweg e.o. | 36.0 | 33.3 | | | 17.9 |
| Houthavens | 244.0 | 225.7 | | | NA |
| IJburg-West | 739.3 | 683.9 | | | 123.8 |
| IJburg-Zuid | 273.8 | 253.3 | | | 48.9 |
| IJplein/Vogelbuurt | 75.0 | 69.4 | | | 29.1 |

| | | | | | |
|---|---|---|---|---|---|
| IJsselbuurt | 35.0 | 32.4 | | | 13.2 |
| Indische Buurt Oost | 219.0 | 202.6 | | | 30.7 |
| Indische Buurt West | 219.0 | 202.6 | | | 39.3 |
| Jordaan | 52.0 | 48.1 | | | 142.0 |
| Kadoelen | 255.0 | 235.9 | | | 4.9 |
| Kinkerbuurt | 135.0 | 124.9 | | | 24.5 |
| Landlust | 384.0 | 355.2 | | | 65.0 |
| Lutkemeer/Ookmeer | 104.4 | 96.6 | | | 2.5 |
| Middelveldse Akerpolder/Sloten | 810.1 | 749.4 | | | 82.2 |
| Middenmeer | 497.0 | 459.7 | | | 126.1 |
| Museumkwartier | 266.0 | 246.1 | | | 210.5 |
| Nellestein | 123.9 | 114.6 | | | 5.9 |
| Nieuwe Pijp | 123.0 | 113.8 | | | 81.5 |
| Nieuwendammerdijk/Buiksloterdijk | 185.0 | 171.1 | | | 8.5 |
| Nieuwendammerham | 280.0 | 259.0 | | | 44.0 |
| Nieuwendam-Noord | 204.0 | 188.7 | | | 59.5 |
| Nieuwmarkt/Lastage | 249.0 | 230.3 | | | 35.1 |
| Oostelijk Havengebied | 379.0 | 350.6 | | | 101.0 |
| Oostelijke Eilanden/Kadijken | 263.0 | 243.3 | | | 60.9 |
| Oosterparkbuurt | 165.0 | 152.6 | | | 58.4 |
| Oostzanerwerf | 259.0 | 239.6 | | | 29.7 |
| Osdorp-Midden | 87.9 | 81.3 | | | 135.4 |
| Osdorp-Oost | 197.5 | 182.7 | | | 52.7 |
| Oude Pijp | 138.0 | 127.7 | | | 127.1 |
| Overtoomse Sluis | 84.0 | 77.7 | | | 48.4 |
| Overtoomse veld | 654.0 | 605.0 | | | 41.3 |
| Rijnbuurt | 71.0 | 65.7 | | | 61.2 |
| Scheldebuurt | 665.0 | 615.1 | | | 136.3 |
| Schinkelbuurt | 21.0 | 19.4 | | | 44.0 |
| Sloter-/Riekerpolder | 990.7 | 916.4 | | | 113.1 |
| Sloterdijk | 27.0 | 25.0 | | | 11.3 |
| Slotermeer-Noordoost | 98.9 | 91.5 | | | 26.0 |
| Slotermeer-Zuidwest | 236.3 | 218.6 | | | 57.8 |
| Slotervaart | 610.2 | 564.4 | | | 59.1 |
| Spaarndammer- en Zeeheldenbuurt | 134.0 | 124.0 | | | 75.0 |
| Staatsliedenbuurt | 183.0 | 169.3 | | | 31.3 |
| Stadionbuurt | 100.0 | 92.5 | | | 65.7 |
| Station Zuid/WTC e.o. | 188.0 | 173.9 | | | 54.0 |
| Transvaalbuurt | 115.0 | 106.4 | | | 34.3 |
| Tuindorp Buiksloot | 4.0 | 3.7 | | | 5.8 |
| Tuindorp Nieuwendam | 43.0 | 39.8 | | | 4.2 |
| Tuindorp Oostzaan | 284.0 | 262.7 | | | 21.5 |
| Van Galenbuurt | 28.0 | 25.9 | | | 10.9 |
| Van Lennepbuurt | 52.0 | 48.1 | | | 22.6 |

| | | | | | |
|---|---|---|---|---|---|
| Volewijck | 133.0 | 123.0 | | | 15.3 |
| Vondelbuurt | 44.0 | 40.7 | | | 29.7 |
| Waterland | 202.0 | 186.9 | 160 | 90 | 3.8 |
| Weesperbuurt/Plantage | 138.0 | 127.7 | | | 84.1 |
| Weesperzijde | 181.0 | 167.4 | | | 29.9 |
| Westelijk Havengebied | 296.0 | 273.8 | 57,600 | 140,040 | 8.3 |
| Westindische buurt | 47.0 | 43.5 | | | 20.2 |
| Westlandgracht | 44.3 | 40.9 | | | 30.3 |
| Weteringschans | 45.0 | 41.6 | | | 107.4 |
| Willemspark | 98.0 | 90.7 | | | 119.1 |
| Zeeburg/Nieuwe Diep | 109.3 | 101.1 | | | 3.1 |
| **Total** | **23,861** | **22,071** | **66,360** | **155,390** | **5,348** |

## A.2 EV charging characteristics

Correlation between EV charging volume and battery capacity.

| EV battery (kWh) | Mean charging volume per session (kWh) | Standard deviation (kWh) |
|---|---|---|
| 50+ | 37.2 | 20.5 |
| 40-50 | 25.5 | 14.3 |
| 30-40 | 18.3 | 11.1 |
| 20-30 | 11.1 | 7.2 |
| <20 | 8.3 | 4.5 |

## A.3 Annual hourly electricity supply and demand

The tables present the annual sum of the daily distribution of electricity supply by solar and wind power, and demand by EVs. In addition, it shows the potential uptake of solar and wind power by EVs and the frequency of renewable surplus, which implies production exceeds consumption.

*a. 2016*

| | Production (kWh) | | Demand (kWh) | | Charge per source (kWh) | | | | | | Frequency of surplus by source (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Charging | Static Smart Charging | Regular Charging Scheme | | | Static Smart Charging Scheme | | | Regular Charging Scheme | | | Static Smart Charging Scheme | | |
| Time | Solar | Wind | | | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable |
| 00:00-01:00 | 0 | 125427 | 14834 | 19283 | 0 | 10046 | 10046 | 0 | 12681 | 12681 | 0.0 | 68.4 | 68.4 | 0.0 | 65.1 | 65.1 |
| 01:00-02:00 | 0 | 122900 | 13865 | 16888 | 0 | 9043 | 9043 | 0 | 10739 | 10739 | 0.0 | 67.4 | 67.4 | 0.0 | 65.1 | 65.1 |
| 02:00-03:00 | 0 | 124500 | 12486 | 11948 | 0 | 7994 | 7994 | 0 | 7330 | 7330 | 0.0 | 66.6 | 66.6 | 0.0 | 65.1 | 65.1 |
| 03:00-04:00 | 0 | 121318 | 9919 | 7232 | 0 | 6377 | 6531 | 0 | 4491 | 4612 | 0.0 | 67.2 | 67.9 | 0.0 | 67.1 | 68.4 |
| 04:00-05:00 | 242 | 121076 | 7307 | 3957 | 192 | 4847 | 5480 | 89 | 2735 | 3023 | 1.4 | 69.5 | 76.2 | 4.4 | 69.3 | 79.0 |
| 05:00-06:00 | 280 | 115523 | 4678 | 1858 | 280 | 3287 | 4002 | 139 | 1389 | 1629 | 20.0 | 72.2 | 86.3 | 27.1 | 72.1 | 88.1 |
| 06:00-07:00 | 1515 | 116811 | 3115 | 1388 | 893 | 2269 | 2809 | 502 | 988 | 1296 | 43.6 | 76.6 | 93.4 | 49.2 | 76.6 | 94.3 |
| 07:00-08:00 | 6954 | 125527 | 4118 | 3331 | 2343 | 3128 | 3960 | 1957 | 2528 | 3202 | 63.4 | 80.4 | 96.6 | 67.6 | 80.3 | 96.8 |
| 08:00-09:00 | 21240 | 139981 | 8044 | 8198 | 5955 | 6518 | 7977 | 5934 | 6628 | 8129 | 80.1 | 81.6 | 98.8 | 82.7 | 81.2 | 98.8 |
| 09:00-10:00 | 39394 | 162853 | 12977 | 15554 | 10708 | 11157 | 12929 | 12054 | 13251 | 15426 | 88.0 | 84.5 | 99.2 | 87.8 | 82.7 | 98.7 |
| 10:00-11:00 | 56495 | 189161 | 13462 | 14461 | 12100 | 11963 | 13403 | 12861 | 12719 | 14348 | 87.8 | 88.8 | 98.9 | 85.5 | 87.8 | 98.7 |
| 11:00-12:00 | 67757 | 213402 | 12336 | 12030 | 11561 | 11232 | 12259 | 11197 | 10900 | 11927 | 89.1 | 91.6 | 99.3 | 88.3 | 91.5 | 99.3 |
| 12:00-13:00 | 71600 | 231372 | 12471 | 12686 | 11767 | 11288 | 12364 | 11768 | 11450 | 12557 | 91.0 | 91.2 | 99.0 | 91.6 | 90.8 | 99.1 |
| 13:00-14:00 | 71264 | 244630 | 12899 | 13658 | 11845 | 11848 | 12780 | 12347 | 12487 | 13461 | 88.6 | 92.3 | 98.4 | 88.4 | 91.7 | 98.1 |
| 14:00-15:00 | 66664 | 254291 | 12976 | 13962 | 11238 | 11736 | 12496 | 11854 | 12544 | 13424 | 82.8 | 90.8 | 96.4 | 81.6 | 89.5 | 96.1 |
| 15:00-16:00 | 54744 | 251335 | 13920 | 14648 | 10640 | 12141 | 12787 | 11015 | 12764 | 13444 | 73.7 | 88.9 | 93.8 | 73.6 | 88.1 | 92.9 |
| 16:00-17:00 | 41189 | 240387 | 15874 | 15165 | 10428 | 13510 | 14032 | 9927 | 12933 | 13394 | 61.2 | 86.0 | 89.2 | 60.9 | 86.6 | 89.9 |
| 17:00-18:00 | 29762 | 226275 | 19234 | 14866 | 10340 | 16199 | 16470 | 8490 | 12684 | 12903 | 42.7 | 82.8 | 84.9 | 44.4 | 86.3 | 87.7 |
| 18:00-19:00 | 19292 | 205943 | 25956 | 22233 | 9723 | 20226 | 20497 | 8852 | 17615 | 17831 | 18.4 | 75.3 | 76.5 | 23.4 | 77.9 | 79.2 |
| 19:00-20:00 | 10530 | 185026 | 28081 | 27875 | 5877 | 20485 | 20651 | 5787 | 20320 | 20481 | 1.5 | 69.3 | 69.6 | 2.0 | 69.1 | 69.6 |
| 20:00-21:00 | 3959 | 157067 | 23831 | 27654 | 1874 | 16849 | 17019 | 1884 | 18941 | 19126 | 0.1 | 66.5 | 66.7 | 0.1 | 63.8 | 63.9 |
| 21:00-22:00 | 837 | 138438 | 18841 | 18297 | 355 | 12912 | 12912 | 338 | 12286 | 12286 | 0.0 | 67.1 | 67.1 | 0.0 | 67.7 | 67.7 |
| 22:00-23:00 | 277 | 130385 | 15702 | 17299 | 226 | 10960 | 10960 | 231 | 12074 | 12074 | 0.0 | 70.0 | 70.0 | 0.0 | 68.8 | 68.8 |
| 23:00-24:00 | 245 | 128179 | 14953 | 18355 | 115 | 10257 | 10257 | 120 | 12408 | 12408 | 0.0 | 68.8 | 68.8 | 0.0 | 65.8 | 65.8 |

*b. 2020*

| | Production (kWh) | | Demand (kWh) | | Charge per source (kWh) | | | | | | Frequency of surplus by source (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Charging | Static Smart Charging | Regular Charging Scheme | | | Static Smart Charging Scheme | | | Regular Charging Scheme | | | Static Smart Charging Scheme | | |
| Time | Solar | Wind | | | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable |
| 00:00-01:00 | 0 | 284328 | 178699 | 249183 | 0 | 86265 | 87162 | 0 | 107630 | 108818 | 0.0 | 45.7 | 45.7 | 0.0 | 46.9 | 46.9 |
| 01:00-02:00 | 0 | 278600 | 166174 | 218571 | 0 | 80946 | 82016 | 0 | 95763 | 96969 | 0.0 | 45.3 | 45.3 | 0.0 | 50.5 | 50.5 |
| 02:00-03:00 | 0 | 282226 | 148472 | 158247 | 0 | 72214 | 73168 | 0 | 71006 | 71706 | 0.0 | 48.1 | 48.1 | 0.0 | 54.0 | 54.0 |
| 03:00-04:00 | 0 | 275014 | 128847 | 103060 | 0 | 66527 | 68425 | 0 | 53674 | 55086 | 0.0 | 52.7 | 53.8 | 0.0 | 57.7 | 61.3 |
| 04:00-05:00 | 1674 | 274464 | 104262 | 59014 | 3199 | 58191 | 65004 | 7868 | 34204 | 38410 | 1.8 | 59.8 | 65.5 | 5.3 | 60.8 | 71.0 |
| 05:00-06:00 | 2321 | 261878 | 74778 | 28817 | 13604 | 45809 | 56029 | 10923 | 17910 | 22545 | 13.2 | 65.9 | 81.0 | 20.9 | 64.9 | 81.2 |
| 06:00-07:00 | 12242 | 264796 | 48922 | 15665 | 23421 | 32529 | 41943 | 9274 | 10355 | 13780 | 38.6 | 74.4 | 91.7 | 41.2 | 71.8 | 89.9 |
| 07:00-08:00 | 49791 | 284554 | 37017 | 21151 | 25247 | 27496 | 34149 | 15015 | 14585 | 18918 | 60.4 | 77.7 | 96.8 | 60.5 | 77.6 | 96.6 |
| 08:00-09:00 | 141865 | 317321 | 51743 | 56476 | 26189 | 38653 | 49388 | 42363 | 39429 | 52785 | 82.5 | 77.1 | 98.2 | 84.7 | 73.0 | 96.4 |
| 09:00-10:00 | 260005 | 369168 | 85071 | 146881 | 41436 | 64840 | 81513 | 108677 | 100279 | 136770 | 89.2 | 74.9 | 98.2 | 86.0 | 69.2 | 95.7 |
| 10:00-11:00 | 379028 | 428806 | 102092 | 138129 | 69634 | 79373 | 97728 | 105468 | 100401 | 129807 | 86.6 | 75.7 | 97.8 | 79.8 | 72.2 | 95.8 |
| 11:00-12:00 | 457730 | 483758 | 111238 | 125064 | 83603 | 89708 | 106486 | 98625 | 93987 | 117766 | 86.8 | 78.3 | 97.9 | 83.2 | 74.9 | 96.3 |
| 12:00-13:00 | 496706 | 524493 | 116911 | 132928 | 91117 | 95552 | 111525 | 102681 | 103662 | 124320 | 86.9 | 76.8 | 97.0 | 86.3 | 77.3 | 95.3 |
| 13:00-14:00 | 491591 | 554548 | 135699 | 155823 | 94582 | 110033 | 127537 | 108128 | 118692 | 141541 | 84.0 | 76.5 | 94.1 | 82.7 | 74.9 | 93.2 |
| 14:00-15:00 | 459301 | 576448 | 150456 | 175547 | 101143 | 117230 | 134999 | 102045 | 130285 | 152088 | 75.5 | 73.1 | 89.7 | 75.8 | 71.0 | 89.0 |
| 15:00-16:00 | 372044 | 569747 | 162485 | 181825 | 97437 | 121916 | 136565 | 85353 | 129020 | 146319 | 65.1 | 70.3 | 83.6 | 64.1 | 70.6 | 83.1 |
| 16:00-17:00 | 275154 | 544929 | 182699 | 171042 | 83505 | 127896 | 140946 | 61142 | 114603 | 128187 | 52.3 | 64.1 | 74.0 | 53.2 | 63.0 | 73.4 |
| 17:00-18:00 | 190382 | 512938 | 213081 | 112280 | 66932 | 135280 | 146779 | 28814 | 79310 | 85002 | 30.4 | 57.6 | 62.7 | 29.9 | 56.2 | 62.2 |
| 18:00-19:00 | 116137 | 466849 | 254873 | 167035 | 39169 | 146204 | 151976 | 11899 | 105657 | 109677 | 10.6 | 45.5 | 47.3 | 12.1 | 42.8 | 45.1 |
| 19:00-20:00 | 57545 | 419433 | 272110 | 253440 | 12569 | 142801 | 144331 | 2492 | 129181 | 130789 | 1.2 | 39.5 | 39.9 | 2.7 | 48.4 | 49.2 |
| 20:00-21:00 | 18980 | 356051 | 254067 | 323612 | 2541 | 123691 | 124576 | 1539 | 138087 | 139281 | 0.2 | 37.4 | 37.8 | 2.1 | 71.8 | 73.4 |
| 21:00-22:00 | 3605 | 313823 | 228304 | 214212 | 1598 | 107847 | 108756 | 1452 | 97280 | 98437 | 0.5 | 39.2 | 39.2 | 4.0 | 64.5 | 64.5 |
| 22:00-23:00 | 1695 | 295568 | 204835 | 238692 | 1552 | 99571 | 100474 | 1533 | 107660 | 109001 | 0.0 | 42.3 | 42.3 | 0.0 | 60.3 | 60.3 |
| 23:00-24:00 | 1318 | 251362 | 151882 | 195433 | 1563 | 74041 | 74747 | 1528 | 86234 | 87239 | 0.0 | 46.0 | 46.0 | 0.0 | 49.2 | 49.2 |

### *c. 2025*

| | Production (kWh) | | Demand (kWh) | | Charge per source (kWh) | | | | | | Frequency of surplus by source (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Charging | Static Smart Charging | Regular Charging Scheme | | | Static Smart Charging Scheme | | | Regular Charging Scheme | | | Static Smart Charging Scheme | | |
| Time | Solar | Wind | | | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable |
| 00:00-01:00 | 0 | 528172 | 1021561 | 1424489 | 0 | 307974 | 305455 | 0 | 357074 | 351955 | 0.0 | 25.4 | 25.7 | 0.0 | 20.8 | 21.2 |
| 01:00-02:00 | 0 | 517532 | 949959 | 1249495 | 0 | 287977 | 285968 | 0 | 327201 | 322793 | 0.0 | 25.3 | 25.5 | 0.0 | 22.9 | 23.4 |
| 02:00-03:00 | 0 | 524267 | 848760 | 904641 | 0 | 263777 | 262112 | 0 | 258643 | 255151 | 0.0 | 27.8 | 28.2 | 0.0 | 30.5 | 31.4 |
| 03:00-04:00 | 0 | 510870 | 736573 | 589156 | 0 | 257428 | 259210 | 0 | 207624 | 207175 | 0.0 | 30.8 | 31.3 | 0.0 | 38.1 | 40.1 |
| 04:00-05:00 | 3870 | 509848 | 596029 | 337363 | 3203 | 235216 | 257698 | 17210 | 137185 | 150057 | 1.2 | 36.0 | 39.6 | 4.8 | 49.4 | 56.8 |
| 05:00-06:00 | 5365 | 486468 | 427482 | 164734 | 6889 | 196745 | 248000 | 34299 | 75879 | 99060 | 4.6 | 45.6 | 58.1 | 18.1 | 62.2 | 77.6 |
| 06:00-07:00 | 28298 | 491889 | 279671 | 89550 | 32135 | 146383 | 203025 | 36262 | 44127 | 64974 | 21.9 | 58.4 | 78.4 | 38.6 | 70.8 | 89.5 |
| 07:00-08:00 | 115091 | 528592 | 211614 | 120910 | 80662 | 128328 | 175112 | 63635 | 63724 | 95380 | 46.6 | 65.9 | 90.4 | 61.7 | 72.1 | 93.6 |
| 08:00-09:00 | 327920 | 589460 | 295799 | 322851 | 103376 | 181423 | 257683 | 176860 | 174266 | 262119 | 70.0 | 65.7 | 92.7 | 78.9 | 66.4 | 91.6 |
| 09:00-10:00 | 601000 | 685772 | 486322 | 839666 | 116061 | 288455 | 424246 | 420917 | 384049 | 646028 | 78.8 | 61.3 | 91.6 | 80.0 | 51.2 | 82.5 |
| 10:00-11:00 | 876123 | 796557 | 583622 | 789634 | 185734 | 346507 | 507966 | 421946 | 400269 | 631204 | 74.5 | 60.1 | 91.0 | 63.4 | 56.0 | 84.9 |
| 11:00-12:00 | 1058042 | 898636 | 635906 | 714949 | 304945 | 388492 | 552639 | 406839 | 386103 | 589195 | 74.9 | 59.9 | 90.5 | 69.4 | 58.8 | 87.4 |
| 12:00-13:00 | 1148135 | 974306 | 668339 | 759905 | 367193 | 417579 | 576653 | 423658 | 426876 | 615282 | 74.6 | 58.7 | 87.3 | 71.4 | 59.1 | 85.8 |
| 13:00-14:00 | 1136312 | 1030136 | 775741 | 890785 | 403496 | 478108 | 639591 | 407687 | 485824 | 669353 | 70.1 | 56.4 | 81.8 | 67.9 | 57.3 | 79.0 |
| 14:00-15:00 | 1061674 | 1070818 | 860103 | 1003538 | 413829 | 496783 | 648990 | 357840 | 529807 | 689056 | 57.7 | 53.8 | 74.9 | 53.7 | 52.9 | 72.5 |
| 15:00-16:00 | 859979 | 1058371 | 928869 | 1039431 | 426309 | 508282 | 628703 | 276943 | 520117 | 639912 | 42.6 | 48.2 | 66.4 | 42.6 | 49.5 | 65.5 |
| 16:00-17:00 | 636017 | 1012268 | 1044424 | 977784 | 385357 | 511053 | 607473 | 170888 | 449423 | 537604 | 28.4 | 40.8 | 51.9 | 29.8 | 44.5 | 54.7 |
| 17:00-18:00 | 440067 | 952842 | 1218110 | 641864 | 299778 | 513149 | 567845 | 79592 | 332878 | 363809 | 11.0 | 31.9 | 37.5 | 16.6 | 48.8 | 54.7 |
| 18:00-19:00 | 268451 | 867226 | 1457018 | 954882 | 197157 | 486213 | 502337 | 25952 | 394861 | 407531 | 2.6 | 21.7 | 22.4 | 9.4 | 31.1 | 32.4 |
| 19:00-20:00 | 133015 | 779145 | 1555558 | 1448828 | 93297 | 450274 | 447566 | 5295 | 418703 | 414541 | 0.3 | 16.5 | 16.5 | 1.0 | 20.5 | 20.7 |
| 20:00-21:00 | 43871 | 661406 | 1452410 | 1849973 | 26752 | 398963 | 395084 | 3278 | 419909 | 413718 | 0.2 | 17.7 | 17.7 | 0.0 | 17.2 | 17.3 |
| 21:00-22:00 | 8333 | 582963 | 1305131 | 1224574 | 5295 | 364890 | 361644 | 3278 | 335457 | 331102 | 0.3 | 19.9 | 19.9 | 0.3 | 24.9 | 24.9 |
| 22:00-23:00 | 3917 | 549052 | 1170967 | 1364518 | 3331 | 342974 | 340126 | 3110 | 359327 | 354602 | 0.1 | 21.0 | 21.2 | 0.0 | 19.8 | 19.8 |
| 23:00-24:00 | 2935 | 437639 | 848662 | 1091478 | 3331 | 253292 | 251064 | 3110 | 271743 | 268147 | 0.2 | 33.6 | 34.0 | 0.0 | 30.7 | 30.8 |

*d. 2030*

| | Production (kWh) | | Demand (kWh) | | Charge per source (kWh) | | | | | | Frequency of surplus by source (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Charging | Static Smart Charging | Regular Charging Scheme | | | Static Smart Charging Scheme | | | Regular Charging Scheme | | | Static Smart Charging Scheme | | |
| Time | Solar | Wind | | | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable |
| 00:00-01:00 | 0 | 602302 | 2579554 | 3596993 | 0 | 474967 | 467743 | 0 | 503798 | 490326 | 0.0 | 13.3 | 13.6 | 0.0 | 10.5 | 11.0 |
| 01:00-02:00 | 0 | 590168 | 2398752 | 3155113 | 0 | 448324 | 441862 | 0 | 471981 | 459730 | 0.0 | 14.7 | 14.9 | 0.0 | 12.8 | 13.6 |
| 02:00-03:00 | 0 | 597848 | 2143213 | 2284318 | 0 | 415827 | 409878 | 0 | 394954 | 384460 | 0.0 | 16.2 | 16.7 | 0.0 | 18.6 | 19.6 |
| 03:00-04:00 | 0 | 582571 | 1859928 | 1487685 | 0 | 412767 | 412947 | 0 | 330594 | 325959 | 0.0 | 16.8 | 17.5 | 0.0 | 27.8 | 29.7 |
| 04:00-05:00 | 6066 | 581406 | 1505038 | 851878 | 4875 | 388513 | 429362 | 26155 | 228868 | 248799 | 1.2 | 19.7 | 22.3 | 4.8 | 41.4 | 47.9 |
| 05:00-06:00 | 8410 | 554745 | 1079439 | 415972 | 10563 | 344260 | 461298 | 57153 | 129789 | 179911 | 3.7 | 30.3 | 42.5 | 18.1 | 56.6 | 71.0 |
| 06:00-07:00 | 44359 | 560926 | 706200 | 226123 | 49587 | 273625 | 418439 | 69319 | 74859 | 128372 | 16.6 | 46.0 | 66.7 | 37.2 | 67.6 | 86.4 |
| 07:00-08:00 | 180413 | 602781 | 534349 | 305312 | 144797 | 247974 | 393072 | 132229 | 114691 | 202624 | 39.9 | 54.6 | 84.6 | 59.5 | 67.3 | 89.5 |
| 08:00-09:00 | 514037 | 672191 | 746925 | 815234 | 210123 | 344248 | 579341 | 365605 | 310130 | 550870 | 64.0 | 51.4 | 85.8 | 75.1 | 55.6 | 84.1 |
| 09:00-10:00 | 942109 | 782020 | 1228018 | 2120249 | 252906 | 513000 | 925668 | 797863 | 599482 | 1264302 | 69.7 | 45.2 | 80.8 | 71.8 | 37.5 | 65.1 |
| 10:00-11:00 | 1373381 | 908354 | 1473711 | 1993913 | 402760 | 604129 | 1100681 | 837622 | 628143 | 1264964 | 63.7 | 43.6 | 78.8 | 50.3 | 40.9 | 70.0 |
| 11:00-12:00 | 1658552 | 1024760 | 1605732 | 1805324 | 642625 | 685650 | 1201539 | 812052 | 633232 | 1189882 | 62.5 | 41.6 | 76.8 | 56.5 | 44.0 | 72.1 |
| 12:00-13:00 | 1799779 | 1111050 | 1687630 | 1918843 | 772002 | 736764 | 1240843 | 842140 | 712488 | 1280950 | 61.3 | 40.7 | 74.0 | 59.7 | 41.7 | 72.8 |
| 13:00-14:00 | 1781246 | 1174717 | 1958832 | 2249331 | 856730 | 832479 | 1333487 | 758226 | 805160 | 1322659 | 54.9 | 36.4 | 65.8 | 52.9 | 37.4 | 62.8 |
| 14:00-15:00 | 1664246 | 1221108 | 2171855 | 2534045 | 867212 | 859199 | 1313647 | 637563 | 839112 | 1297049 | 39.5 | 31.4 | 55.4 | 41.2 | 31.4 | 51.9 |
| 15:00-16:00 | 1348076 | 1206914 | 2345496 | 2624678 | 838186 | 864146 | 1206226 | 468763 | 831151 | 1173353 | 26.0 | 27.9 | 44.8 | 29.9 | 29.8 | 44.5 |
| 16:00-17:00 | 996999 | 1154341 | 2637285 | 2469013 | 713511 | 815433 | 1053092 | 278366 | 701715 | 902292 | 14.9 | 20.3 | 28.1 | 19.5 | 27.3 | 35.5 |
| 17:00-18:00 | 689835 | 1086574 | 3075863 | 1620777 | 526454 | 767999 | 884802 | 129306 | 573957 | 647696 | 5.5 | 14.5 | 16.6 | 12.3 | 29.7 | 35.9 |
| 18:00-19:00 | 420816 | 988941 | 3679131 | 2411181 | 317529 | 681290 | 706380 | 39568 | 601911 | 618554 | 1.4 | 8.6 | 9.0 | 6.2 | 15.9 | 16.8 |
| 19:00-20:00 | 208510 | 888499 | 3927957 | 3658450 | 143412 | 612404 | 605093 | 8048 | 582355 | 569802 | 0.3 | 7.1 | 7.1 | 0.8 | 10.0 | 10.0 |
| 20:00-21:00 | 68771 | 754235 | 3667495 | 4671385 | 40724 | 561471 | 552231 | 4982 | 561477 | 546472 | 0.2 | 8.0 | 8.0 | 0.0 | 7.2 | 7.2 |
| 21:00-22:00 | 13062 | 664782 | 3295599 | 3092184 | 8060 | 521533 | 513367 | 4982 | 484153 | 471973 | 0.3 | 9.5 | 9.5 | 0.3 | 13.8 | 13.8 |
| 22:00-23:00 | 6140 | 626112 | 2956820 | 3445559 | 5070 | 501635 | 493854 | 4726 | 507158 | 494238 | 0.1 | 11.8 | 11.9 | 0.0 | 10.5 | 10.5 |
| 23:00-24:00 | 5954 | 615518 | 2806898 | 3668020 | 5070 | 496345 | 488630 | 4726 | 504925 | 492124 | 0.3 | 12.4 | 12.7 | 0.0 | 9.6 | 9.6 |

*e. 2035*

| | Production (kWh) | | Demand (kWh) | | Charge per source (kWh) | | | | | | Frequency of surplus by source (%) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Regular Charging | Static Smart Charging | Regular Charging Scheme | | | Static Smart Charging Scheme | | | Regular Charging Scheme | | | Static Smart Charging Scheme | | |
| Time | Solar | Wind | | | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable | Solar | Wind | Sustainable |
| 00:00-01:00 | 0 | 676431 | 4143841 | 5778273 | 0 | 572083 | 565057 | 0 | 589601 | 581574 | 0.0 | 9.1 | 9.4 | 0.0 | 7.4 | 7.8 |
| 01:00-02:00 | 0 | 662804 | 3853398 | 5068429 | 0 | 550507 | 544069 | 0 | 559810 | 552655 | 0.0 | 10.5 | 10.8 | 0.0 | 9.7 | 10.1 |
| 02:00-03:00 | 0 | 671429 | 3442896 | 3669569 | 0 | 512687 | 506818 | 0 | 476064 | 469479 | 0.0 | 13.3 | 13.6 | 0.0 | 16.5 | 17.3 |
| 03:00-04:00 | 0 | 654272 | 2987822 | 2389843 | 0 | 516538 | 519030 | 0 | 402340 | 402315 | 0.0 | 13.6 | 14.1 | 0.0 | 24.2 | 26.0 |
| 04:00-05:00 | 8262 | 652964 | 2417720 | 1368472 | 6817 | 486126 | 546734 | 36774 | 285906 | 317961 | 1.2 | 15.5 | 17.4 | 4.8 | 39.8 | 46.0 |
| 05:00-06:00 | 11455 | 623021 | 1734029 | 668225 | 14771 | 444976 | 627257 | 81678 | 163972 | 240642 | 3.6 | 25.5 | 35.8 | 18.1 | 55.7 | 68.5 |
| 06:00-07:00 | 60420 | 629963 | 1134452 | 363248 | 69401 | 367943 | 608733 | 103303 | 93668 | 183095 | 14.0 | 41.1 | 62.3 | 36.7 | 67.1 | 85.1 |
| 07:00-08:00 | 245735 | 676969 | 858388 | 490459 | 210474 | 335284 | 594032 | 203025 | 149198 | 299850 | 37.1 | 49.5 | 79.9 | 58.9 | 65.8 | 87.2 |
| 08:00-09:00 | 700153 | 754923 | 1199874 | 1309606 | 319481 | 458697 | 876363 | 561920 | 398020 | 809887 | 61.4 | 45.4 | 81.2 | 74.0 | 50.1 | 80.7 |
| 09:00-10:00 | 1283217 | 878269 | 1972710 | 3406006 | 394815 | 661962 | 1380559 | 1182476 | 724604 | 1776478 | 66.5 | 38.5 | 74.9 | 68.9 | 32.3 | 57.7 |
| 10:00-11:00 | 1870640 | 1020152 | 2367396 | 3203057 | 627403 | 769710 | 1626880 | 1264531 | 767400 | 1815614 | 59.0 | 36.3 | 72.7 | 45.3 | 35.9 | 63.5 |
| 11:00-12:00 | 2259062 | 1150885 | 2579476 | 2900105 | 988441 | 881854 | 1776756 | 1233880 | 787894 | 1720994 | 58.1 | 34.0 | 70.4 | 52.1 | 38.1 | 67.1 |
| 12:00-13:00 | 2451423 | 1247795 | 2711039 | 3082465 | 1184083 | 950294 | 1833093 | 1266684 | 884414 | 1857582 | 56.0 | 32.0 | 67.7 | 55.8 | 35.1 | 64.2 |
| 13:00-14:00 | 2426181 | 1319297 | 3146702 | 3613366 | 1315580 | 1056636 | 1931118 | 1124797 | 986749 | 1869997 | 48.7 | 26.2 | 56.8 | 48.6 | 28.9 | 54.0 |
| 14:00-15:00 | 2266818 | 1371398 | 3488907 | 4070736 | 1323667 | 1077641 | 1852051 | 930146 | 1013398 | 1772054 | 33.7 | 22.7 | 46.0 | 37.3 | 25.3 | 43.5 |
| 15:00-16:00 | 1836172 | 1355457 | 3767847 | 4216329 | 1249740 | 1087699 | 1660579 | 673818 | 1007021 | 1572763 | 21.4 | 18.8 | 35.1 | 26.7 | 22.3 | 34.2 |
| 16:00-17:00 | 1357982 | 1296414 | 4236581 | 3966267 | 1042977 | 992394 | 1368676 | 396514 | 846213 | 1179976 | 11.3 | 12.0 | 19.0 | 16.7 | 20.1 | 28.1 |
| 17:00-18:00 | 939603 | 1220306 | 4941121 | 2603645 | 759847 | 905685 | 1084844 | 184354 | 729888 | 861416 | 4.0 | 7.0 | 9.1 | 10.4 | 22.1 | 27.1 |
| 18:00-19:00 | 573180 | 1110657 | 5910222 | 3873365 | 448497 | 791039 | 832394 | 55632 | 726596 | 763837 | 1.3 | 5.0 | 5.2 | 5.7 | 10.5 | 11.2 |
| 19:00-20:00 | 284005 | 997853 | 6309940 | 5876999 | 200880 | 707482 | 701859 | 11315 | 685023 | 679524 | 0.3 | 4.5 | 4.5 | 0.8 | 5.9 | 5.9 |
| 20:00-21:00 | 93671 | 847064 | 5891530 | 7504197 | 56948 | 655482 | 646688 | 7005 | 641814 | 632983 | 0.2 | 4.9 | 4.9 | 0.0 | 5.1 | 5.1 |
| 21:00-22:00 | 17791 | 746601 | 5294109 | 4967340 | 11271 | 619282 | 611409 | 7005 | 574406 | 567322 | 0.3 | 6.8 | 6.8 | 0.3 | 9.5 | 9.5 |
| 22:00-23:00 | 8364 | 703172 | 4749889 | 5535008 | 7090 | 604563 | 596863 | 6645 | 593695 | 586262 | 0.1 | 7.7 | 7.8 | 0.0 | 7.4 | 7.4 |
| 23:00-24:00 | 7571 | 672477 | 4100070 | 5331015 | 7090 | 573623 | 566149 | 6645 | 565974 | 558740 | 0.3 | 8.9 | 9.2 | 0.0 | 7.8 | 7.8 |

## A.4 Assumptions

- All renewable electricity is available for EV charging, electricity demand by others is not considered.
- National growth rate for EVs is handled in order to determine future EV charging demand.
- From 2020, all EVs are assumed to be large battery FEVs. Moreover, based on literature these FEVs have a charging frequency of 2.4 per week, charge with 22 kW and charge an average of 32 kWh per session.
- Solar and wind power growth is based on targets set by the City of Amsterdam, where linear growth values are considered.
- Future solar and wind power production is based on the production profile established for 2016.