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EDITOR'S NOTE

To see the figures in a better resolution, open the article online and click on “Original” below them.

List of Abbreviations

- 1 BAU: Business as usual
- 2 BEV: Battery Electric Vehicle
- 3 CBC: Choice-based conjoint
- 4 CO₂: Carbon Dioxide
- 5 DMCLP: Dynamic Maximal Covering Location Problem
- 6 EU: European Union

- 7 EV: Electric Vehicle
- 8 E2SFCA: Enhanced two-step floating catchment area method
- 9 MCLP: Maximal Covering Location Problem
- 10 NO_x: Nitrogen Oxides
- 11 PHEV: Plug-in hybrid electric vehicle
- 12 PM: Fine dust
- 13 POI: Point of interest

Introduction

- 14 Passenger transportation is a major contributor to climate change because of its use of fossil fuel engines. In Europe, passenger cars are responsible for 12 % of all CO₂ emissions [European Commission, 2018], but in addition to CO₂, other greenhouse gases are emitted that can cause even more damage in densely populated cities. These more local emissions are, for example, nitrogen oxides (NO_x) or fine dust (PM) [Van Mierlo, *et al.*, 2017]. In addition to being harmful to the environment, these emissions are also harmful to citizens' health. In the Brussels-Capital Region, these emissions are mainly emitted by road transportation. In 2012, road transportation was responsible for 67 % of NO_x emissions, 47 % of PM_{2.5} emissions and 27 % of CO₂ emissions [Willocx, 2015]. A switch from fossil fuel engines to alternative lower emissions vehicle technologies could reduce these values. One of the alternatives to conventional fuel vehicles are the electric vehicles (EVs). Since these vehicles do not emit any local emissions, they could offer a solution to improve Brussels-Capital Region's air quality. The low emission zone introduced in the Region on 1 January 2018 demonstrates the Region's will to tackle this problem. This zone should encourage the inhabitants of Brussels to make the vehicle fleet greener by purchasing alternative vehicle technologies. Today, however, the use of electric vehicles is still limited. One of the possible causes could be the availability of the charging infrastructure. Initially, the roll-out of charging stations is slow, as charging station operators without users run the risk of a loss-making business case and consumers do not want to purchase an EV without being sure of finding a charging station to recharge their vehicle. The latter is even more appropriate for the Brussels-Capital Region, where 22 % of families have a private parking space to recharge at home [Ermans, 2019]. In this situation, a large network of charging stations should stimulate the switch to electromobility [Mersky *et al.*, 2016]. The lack of an extensive charging infrastructure in the Brussels-Capital Region is therefore an impeding factor to the use of EVs. In this regard, the Brussels-Capital Region published a vision on charging infrastructure in June 2020, which foresees 11 040 charging stations by 2035 [Brussels Environment, 2020]. This vision also emphasizes the Region's ambition to organize the planning of the roll-out on the basis of cartographies. Meanwhile, since 2018, the Region has been rolling out a basic network of public charging infrastructure, of which 162 charging stations have been installed and 25 are pending government approval [Charge.brussels, 2021]. This vision and the need for charging infrastructure in the Brussels-Capital Region are the starting point of this paper.

- 15 The roll-out of the charging infrastructure also fits within the context of the recent mobility strategy developed by the Brussels-Capital Region – Good Move – which aims, among other things, to improve air quality through adjustments in Brussels mobility [Brussels-Capital Region, 2019]. Although this plan deals more broadly with the various facets of mobility, such as improvements in public transportation, the promotion of the sharing economy, etc., the car is the most popular means of transportation in the Region and this aspect of mobility also needs to be improved (46 % of journeys are made by car in the Brussels-Capital Region [Derauw *et al.*, 2019]). To achieve this, the Region aims to reduce the number of cars and make the Brussels car fleet greener. Since EVs are better for air quality in an urban context [Hooftman *et al.*, 2018], a shift in vehicle technologies from fossil fuels to electricity is a step towards better air quality in the Region.
- 16 In this paper, we propose two complementary analyses to identify locations for installing public charging infrastructure for passenger cars in the Brussels-Capital Region. Both analyses outline an evolution of the charging infrastructure in the Brussels-Capital Region between 2015 and 2020. These analyses were carried out on behalf of the Brussels-Capital Region authorities between 2014 and 2016 in the context of two policy preparatory studies.
- 17 The first analysis describes the charging infrastructure's accessibility in the Brussels-Capital Region and proposes a method to extend the public charging infrastructure for occasional charging, ie recharging the vehicle that is parked while the user is carrying out an activity (such as shopping, visiting a tourist attraction, eating or drinking...). So this analysis focuses on both residents and visitors and can also be used for planning charging infrastructure for electric shared cars. The second analysis focuses on residential charging, for example for EVs that are parked along the public road at night. For this type of charging, a location model is used that proposes optimal locations based on the inhabitants' socio-demographic characteristics. Since socio-demographic characteristics of the inhabitants are used as a basis, this analysis mainly focuses on the use of the charging stations for private vehicles of Brussels residents. Both analyses can be performed separately for their specific purpose, but the results can be considered complementary. Since this paper focuses on normal charging (maximum 22 kW), electric taxis are outside the scope. Electric taxis generally use fast charging stations to remain operational longer and faster and benefit less from normal charging infrastructure. Also, the quantification of the impact of the increasing number of EVs on the electricity grid is not studied in this paper. However, the location of low-voltage cabins is taken into account in order to limit the costs related to the installation of the charging stations.
- 18 The next section first outlines the Brussels situation in terms of the number of electric vehicles and compares these figures with predictions made in 2015 for the number of EVs in 2020. Section 2 describes the two methods used in this paper to determine the infrastructure's locations for public occasional charging and residential charging. The results of both methods are discussed in section 3. Finally, this paper concludes with some recommendations.

1. Electric vehicles in the Brussels-Capital Region

- 19 At the beginning of 2015, 7 402 851 vehicles were registered in Belgium, of which 637 809 in the Brussels-Capital Region [FEBIAC, 2017]. The number of newly registered vehicles in the Brussels-Capital Region was 78 470 in 2014 and 82 889 in 2015. Of these new registrations, 434 in 2014 and 542 in 2015 were electric vehicles (both battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV)) [Denys *et al.*, 2020]. Numbers from 2016 to 2019 show that the number of purchased EVs continues to increase. In 2016, 2017, 2018 and 2019, respectively 1 016, 1 666, 1 823 and 2 357 new EVs were registered in the Brussels-Capital Region [Denys *et al.*, 2020].
- 20 Based on the results of a previously performed choice-based conjoint (CBC) study for Flanders [Lebeau *et al.*, 2012], the market share of BEVs and PHEVs was predicted for the newly registered vehicles between 2016 and 2020 based on consumer preferences regarding vehicle properties (such as purchase price, charging speed or driving range) and the expected evolution of the properties. When we take into account the real sales of 2014 and 2015, we obtain the cumulative number of BEVs and PHEVs for the next five years in the Brussels-Capital Region (assuming that a similar trend is present in the Region as in Flanders). This forecast was executed in 2016 and includes 3 scenarios: business as usual (BAU), subsidy policy, and subsidy-and-infrastructure policy. In the BAU scenario, sales are forecast on the assumption that no policies are in place to drive EV uptake. This results in a total number of 14 000 vehicles in 2020. In the subsidy policy scenario, it is assumed that a financial incentive is given (an eco-bonus) to stimulate market development. In 2016 the bonus would be € 6 000 and would decrease over time, namely € 3 000 in 2017, € 2 000 in 2018 and € 1 500 in 2019. The effect of this incentive measure, compared to the BAU scenario, is a faster uptake of EVs and therefore a higher cumulated number of EVs in the Brussels-Capital Region, namely more than 16 000. The subsidy and infrastructure policy scenario builds on the subsidy policy scenario with the additional assumption that the focus will be on charging infrastructure, with the number of charging stations increasing by 100 each year. The combination of these measures was also analysed with the results of the CBC study. It would initially lead to the same effects as the subsidy scenario, but in the longer term, from 2019 on, the total number of EVs would rise to more than 18 000. This delayed effect can be explained by the in time progressive number of charging stations in combination with the in time degressive financial incentive. The results of this scenario-based demand forecast are depicted in Figure 1.

Figure 1. Forecast number of EVs in Brussels-Capital Region 2016-2020

Sources: MOBI for the projections and visualization and [Denys et al., 2020] for the historical data)

- 21 If we compare the predicted numbers with the BAU scenario, we notice that the forecast is more positive than the actual numbers. The historical numbers also indicate an increase in the number of registered vehicles, but the number of annual registered vehicles was on average 500 units lower than predicted. Taking into account people who exchanged their EV for a new EV or another type of vehicle or means of transportation, the total number of EVs registered in the Brussels-Capital Region at the end of 2019 amounts to 6 672 EVs [Denys et al., 2020]. The actual total number of EVs in 2019 lies between the 2017 and 2018 forecasts of the BAU scenario and is 35 % smaller than predicted. This comparison with the actual numbers demonstrates the difficulty of making accurate predictions for a market that is in the early stages of its development. Several factors play a role: the greater uncertainty surrounding the evolution of vehicle properties is a major challenge in this regard. Changes in vehicle properties, such as purchase price, running costs, driving range, density of the charging infrastructure, or even charging speed, can all have an impact on the final forecast and must be accurately estimated for the coming years. It is not an easy job and requires a good knowledge of the technology and the trends in the field. Another possible factor that could have influenced the forecast is that the measured preferences for Flemings would not be fully transferable to the inhabitants of Brussels. These preferential differences can be observed in the EVs' market share evolution between 2014-2019 for Flanders and Brussels (see Table 1) [Denys et al., 2020]. It can therefore be concluded that one should be careful with the use of CBC data for making predictions, both in terms of technological evolution and in the way to apply the most correct preference.

Table 1. Evolution of the market shares of electric vehicles in Flanders and the Brussels-Capital Region [Denys et al., 2020]

	2014	2015	2016	2017	2018	2019
Brussels-Capital Region	0,55 %	0,66 %	1,31 %	2,18 %	2,42 %	3,01 %

Flanders	0,50 %	1,01 %	2,38 %	3,55 %	3,09 %	3,99 %
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- 22 When comparing the spatial distribution of the adoption with the predictions per municipality for 2020, shown in Figure 2, one notices that the trends are broadly correct¹. The municipalities of Brussels, Ixelles, Woluwe-Saint-Lambert, Woluwe-Saint-Pierre and Uccle show the highest adoption rates as predicted. On the other hand, there are municipalities that show a lower adoption rate than predicted, such as Evere, Auderghem, Molenbeek-Saint-Jean and Watermael-Boitsfort. The latter municipality in particular has a slower adoption than predicted, as this municipality was considered a possible frontrunner. Saint-Josse-ten-Noode, on the other hand, shows a much stronger adoption than predicted. The adoption in this municipality is mainly due to the increasing number of many electric commercial vehicles. Except for the municipalities of Watermael-Boitsfort and Saint-Josse-ten-Noode, the spatial distribution of adoption follows the predicted pattern, but as mentioned above, to a lesser extent than predicted in terms of numbers. The spatial distribution of demand in the location model can still be regarded as quite adequate, with those exceptions. This leads us to three conclusions regarding the use of EV projections to forecast demand: demand is overestimated due to the unpredictable nature of the EV market (which is in an initial phase), vehicle preferences need to be better tailored to the specific Brussels context and the spatial distribution of demand was reasonably well predicted. Since the spatial distribution of the prediction is more important than accurately predicting the number of vehicles, the use of this method is not a problem as long as it is taken into account that the numbers are an overestimation.

Figure 2. Number of electric vehicles in the Brussels Capital Region end 2018 and mid 2019 compared to the forecast made in 2015 for 2020

Source: FPS Mobility for the historical data and MOBI for the projection and visualization

2. Methodology

- 23 These sections describe the methodology for public occasional charging, public residential charging and the location model.

2.1. Public occasional charging

- 24 The “enhanced two-step floating catchment area method” (E2SFCA) is used to identify the accessibility of charging locations for public occasional charging [Luo and Qi, 2009; Marion *et al.*, 2015]. In the scientific literature, the term accessibility is defined as “the relative ease with which a facility or activity can be reached from a given location” [Luo and Wang, 2003]. In other words, accessibility expresses the relationship between supply and demand for the use of a particular type of facility.
- 25 In this analysis, accessibility will measure the ratio between the number of charging points (supply) and the number of address points (demand). This method takes into account the distance between demand and supply by measuring the amount of demand within a defined area around the charging station. The size of the area is determined by a threshold value that is equal to a walking distance of 9 minutes from the charging station. The demand is therefore equal to the number of address points that are located in the area of a charging station. An address point is a reference to one or more house numbers within a building. The address point can be used for multiple purposes, eg residences, shops, offices, schools, recreation, etc. For each address point, a score is calculated that indicates to what extent it is served. Since an address point can have different functions, the accessibility of address points is not only calculated for Brussels residents, but also for visitors or commuters planning an activity (shopping, visiting family or friends, work...) at an address point. The motives or profiles of the potential users are therefore not taken into consideration, only their quantity by means of the number of address points. This emphasizes the applicability of this method for public occasional charging and the different segments of the target audience.
- 26 The first step in calculating the scores resides in first calculating an accessibility score for each charging station based on the amount of address points located in the area. A score is calculated for each address point by summing the accessibility scores of the charging points in their range (usually 2 charging points per charging station). This score is adjusted by the walking distance from the address point to the charging station and the number of other addresses in the range of the charging points. This means that the further an address is located from a charging station or the more other addresses there are in the area of the charging station, the less accessible this charging station will be for this address. The result of this method is a score per address point in the range of one or more charging stations. This score therefore indicates how accessible the charging infrastructure is for the address points in the Brussels-Capital Region.
- 27 Three datasets are necessary for the implementation of the E2SFCA method, namely, a dataset of charging stations, a network of the streets and the addresses of the buildings in the Brussels-Capital Region. In this study, the administrative database of UrbIS [CIBG, 2021] was used for the street and address details. Since there was no official overview of the charging infrastructure in the Brussels-Capital Region in 2015, a list of the existing charging infrastructure was drawn up by consulting 5 different charging

infrastructure databases (ASBE, Chargemap, Oplaadpunten.nl, Oplaadpunten.org and Openchargemap). This initial list was supplemented with data obtained from some charging station operators and was eventually validated by conducting a field study of all listed charging stations. In total, 144 charging points for 220 004 address points were identified in the Brussels-Capital Region.

2.2. Public residential charging: splitting up the EV demand by building blocks

- 28 The previously performed CBC analysis [Lebeau *et al.*, 2012], discussed in section 1, was used to forecast EV adoption in the Brussels-Capital Region. Given the inherent spatial nature of the location analysis, the predicted EV demand should be more finely assigned to spatial entities. Ideally, all data is available at the same spatial level, but in practice this is not the case and therefore a step-by-step approach is applied. As a result, the number of registered EVs is uniformly distributed, starting from metropolitan Region level up to the building blocks that form the smallest spatial entity in our analysis. We calculate an EV suitability score for each district to account for spatial socio-demographic differences. The remainder of this calculation is based on the results of the BAU scenario.
- 29 In the first allocation phase, the total number of predicted EVs is distributed proportionally among the 19 municipalities according to the number of newly registered electric vehicles by private individuals in each municipality in the year 2015. Since one of the objectives of this study is to optimally locate the public charging infrastructure for the benefit of residents, only electric vehicles sold to private individuals are taken into account (see appendix for more details).
- 30 The distribution of this number is presented on the map in Figure 3. Note that in 2 municipalities, Berchem-Sainte-Agathe and Saint-Gilles, no private EVs were registered; the highest number was registered in Uccle. In order to simulate the uptake of EVs in the first mentioned municipalities, a small correction factor was applied so that a valid prognosis for the future is obtained.

Figure 3. Number of registered EVs by private individuals per municipality in 2015

Source: FPS Mobility for the historical data and MOBI for the visualisation

- 31 In the next phase, the demand for EVs (both PHEVs and BEVs) is distributed over the different neighbourhoods in a municipality. This step is crucial to take into account the spatial variation with regard to socio-demographic characteristics of the inhabitants. The Brussels Neighbourhood Monitoring database was used as a source for this information.
- 32 Note that the Brussels-Capital Region is divided into 118 residential districts (in which 99,7 % of the population lives), 6 industrial zones and stations, 18 green areas and 3 cemeteries. In our analysis we exclude the 3 cemeteries and there is no information about building blocks in the neighbourhoods Parc des Étangs and Parc Astrid (in Anderlecht), Schaerbeek Station and Parc du Cinquantenaire (in Brussels).
- 33 Note also that the boundaries of the Monitor neighbourhoods do not necessarily coincide with the boundaries of the municipalities, therefore the demand of a neighbourhood is calculated based proportionally on the area it comprises within two (or sporadically three or four) municipalities.
- 34 In order to take into account the socio-demographic profiles of the inhabitants, the variables income, living area per inhabitant and household size are used to break down the demand at the municipality level to the demand at neighbourhood level. An indicator – EV suitability score – was calculated for each district. This score is multiplicatively proportional to the average income and living area per inhabitant in a neighbourhood and inversely proportional to the average household size. In the scientific literature Plötz *et al.* [2014]; Axsen *et al.* [2016]; Hardman *et al.* [2016] high income and multi-person households are often cited as characteristic of households that own an EV. Income is also mentioned as planning criteria for the roll-out planned in the vision of the Brussels-Capital Region [Brussels Environment, 2020]. The living area per inhabitant is not explicitly mentioned in the literature. The study by Plötz *et*

al. [2014] does determine that smaller or medium-sized cities are considered more perfect for EV adoption than large cities. The reasons are that vehicle ownership is higher there and that there are also more households owning a private parking space. These characteristics can be found in the municipalities with a larger living area per inhabitant such as Uccle, Auderghem, Woluwe-Saint-Lambert, Woluwe-Saint-Pierre and Watermael-Boitsfort [BISA, 2018]. The average predicted demand per neighbourhood ranges from 14,68 EVs in 2016 to 69,45 in 2020; the median from 9,18 to 43,43 (see Figure 4).

- 35 In the final step towards creating question points for the location model, the demand per district is allocated uniformly to the number of building blocks in a district. A building block is delimited by streets or by municipal boundaries. 4 992 building blocks are taken into account in the analysis. Average forecast demand per block ranges from 0,6 EVs in 2016 to 2,81 EVs in 2020; the median from 0,26 to 1,23. We do not depict the building blocks individually, but they can be identified by the centroids in Figure 5, ranging from yellow (low predicted demand) to brown (high predicted demand). As mentioned in Section 1, the demand per block is spread in a similar way to the actual adoption of EVs in the Region for mid-2019 (with the exceptions of Saint-Josse-ten-Noode and Watermael-Boitsfort). This validates for the other municipalities the spatial distribution of the demand and the locations that are gradually identified in the dynamic location model.

Figure 4. Prognosis EV uptake per neighbourhood

Source: MOBI

Figure 5. Forecast EV uptake per building block

Source: MOBI

2.3. Location models for public residential charging

- 36 The aim of this analysis is to provide – from the perspective of the public authorities – a maximal service to the inhabitants of the Brussels-Capital Region by installing or having installed a given number of charging stations. To model this mathematically, the Maximal Covering Location Problem (MCLP) is applied [Church and ReVelle, 1974].
- 37 We consider $d_i > 0$ to be the above predicted demand for public charging infrastructure in building block $i \in I$. Public charging stations are opened at candidate locations $j \in J$. A given budget B is available for opening new charging stations that will serve the EV owners. The N_i set indicates which candidate locations are within distance d of block i .

$$N_i = \{j \in J : d_i \geq d\} \quad \forall i \in I \quad (1)$$

- 38 The MCLP model is fully formulated below:

$$\max \sum_{i \in I} d_i x_i \quad (2)$$

$$s.t. \sum_{j \in N_i} y_j \geq x_i \quad \forall i \in I \quad (3)$$

$$\sum_{j \in J} y_j \leq B \quad (4)$$

$$x_i \in 0, 1 \quad \forall i \in I \quad (5)$$

$$y_j \in 0, 1 \quad \forall j \in J \quad (6)$$

- 39 where x_i indicates whether a building block is served by one or more public charging stations and y_j indicates which candidate locations were chosen. The objective function is to maximize the degree of service for all building blocks given the constraint on the sets coverage (3) and the constraint on the budget (4).
- 40 The MCLP model allows to use the demand predicted above at building block level. In the first scenario, the candidate locations for a charging station are the 1 292 existing cabins of the grid operator that are already equipped with a 400 V connection and a low voltage panel and for which no substantial costs have to be incurred for the power supply of a charging station. In the second scenario, the candidate locations for a charging station are also the grid operator's existing cabins, but in this scenario investments are needed to make the cabin compliant. These are 2 345 cabins. In both scenarios, the electricity grid is therefore taken into account, which is also mentioned as planning criteria in the vision of the Brussels-Capital Region [Brussels Environment, 2020]. A radius d is determined that indicates how far a resident has to walk to the charging station (via the road network); the basic principle is that the residents of a block in the radius of 350 m can meet with their charging needs. The model maximizes the charging stations service by placing the given number of charging stations at the greatest expected demand.
- 41 The starting point is the roll-out by 2020 of 500 charging stations, each equipped with 2 charging points, i.e. 1 000 charging points. This corresponds to the rule of thumb of 1 charging point per 10 EVs when the forecast of 14 000 vehicles is used and it is assumed that semi-public infrastructure can also serve the demand. To simulate the rollout over several years, the Dynamic Maximal Covering Problem (DMCLP) is applied [Gunawardane, 1982]. Since the solution must be optimal in the long term, the solution of the MCLP in the year 2020 will be used as a starting point. An overview is then provided for each year $t \in T$ (2016-2019) of the charging stations that will be opened.

$$\min \sum_{i \in I, t \in T} d_{it} x_{it} \quad (7)$$

$$s.t. \sum_{j \in N_i} y_{jt} + x_{it} \geq 1 \quad \forall i \in I, t \in T \quad (8)$$

$$\sum_{j \in J} y_{jt} \leq B_t \quad \forall t \in T \quad (9)$$

$$y_{jt} \geq y_{jt-1} \quad \forall j \in J, t \in T \quad (10)$$

$$x_{it} \in 0, 1 \quad \forall i \in I, t \in T \quad (11)$$

$$y_{jt} \in 0, 1 \quad \forall j \in J, t \in T \quad (12)$$

3. Results

- 42 In this section, the results of the applications of the models for the public occasional charging (section 3.1) and residential charging (section 3.2) are discussed separately.

3.1. Public Occasional Charging

- 43 Figure 6 shows the result of the E2FSCA method for the public charging infrastructure in 2015. The squares on the Region's map represent the charging points. The yellow, orange and red zones represent the address points that are located at a walking distance of 9 minutes from a charging station. The charging infrastructure's accessibility is illustrated by the address points' score based on the demand (number of other addresses in the area) and the number of charging stations that are accessible from the address points. This accessibility score can therefore be interpreted as the number of charging points that are accessible per address point, taking into account the distances between the address points and the charging points. A score of 1 is equal to an address point that would have a charging point on its doorstep without any competition from other address points. In other words, the darker the red colour of the address points, the more accessible the charging infrastructure in their vicinity. The following factors (alone or combined) promote the charging infrastructure's accessibility for an address point, namely, a short distance to charging infrastructure from the address point, more supply of charging infrastructure from the address point or a smaller number of other address points in the area around the charging point. In total, 36 % of the addresses were served by the infrastructure in 2015, i.e. slightly more than one third of the Brussels addresses.

Figure 6. The charging infrastructure's accessibility in 2015

Source: MOBI

- 44 The highest accessibility scores are obtained in neighbourhoods that are well served by the charging infrastructure. According to the metric, the charging infrastructure is very accessible in the western part of the Brussels Region. This can be explained by a low degree of competition, as there are very few buildings for the number of charging points. An example of a charging station located in this area is the charging station at

IKEA. This charging station is therefore typically a charging station that will be used for occasional charging. It is a charging station located in an environment with few other buildings and in a commercial zone. In contrast to the charging stations in the centre of the Capital Region, which are also located at an economic core and are characterized by a reasonable degree of accessibility due to the large number of charging stations in the same neighbourhood. Lower accessibility scores can be found at charging stations where there is little charging infrastructure and many buildings in their vicinity. Such cases lead to a higher degree of competition for using the charging points in those neighbourhoods.

- 45 In order to stimulate occasional charging, we could install new public charging infrastructure at the important poles (POI) for public transportation according to the Iris-2 plan [Brussels-Capital Region, 2011] and public car parks in the Brussels-Capital Region. These important poles are specific locations in the Brussels Region where public transportation and multimodality need to be improved. A large number of these poles are discussed in detail in the *Ontwerp van Gewestelijk Plan voor Duurzaam Ontwikkeling (Draft of the Regional Plan for Sustainable Development)* [Brussels-Capital Region, 2013]. These locations include economic centres (commercial centres, centres of activity such as offices or industry...), universities, hospitals, major train stations, etc... This POI-based strategy identifies locations that are potential destinations for EV users (in addition to their work and their place of residence) [Wagner *et al.*, 2013]. These locations then allow the EV users to charge during their activities at these POIs. Placing charging stations at POIs would change the coverage of the charging infrastructure as can be seen in Figure 7. 4 charging points are allocated per location, this corresponds to two charging stations with two charging points each. In total, there are 620 charging points serving about 65 % of the address points in the Region, almost two-thirds of the addresses in Brussels. Note also that the scores in this figure are higher than in Figure 6. This means that the accessibility of the infrastructure has improved in general.

Figure 7. Charging infrastructure's accessibility after a POI approach

Source: MOBI

3.2. Public Residential Charging

- 46 In the first scenario, it is assumed that the charging stations to be installed must be placed in the immediate vicinity of a low-voltage cabin.
- 47 The result of the optimization is shown in Figure 8: the blue dots indicate the optimal locations for charging stations in 2020.

Figure 8. Optimal locations for charging stations in 2020 based on low-voltage cabins

Source: MOBI

- 48 Based on this configuration of the public charging stations' network, approximately 11 800 of the estimated 14 000 EV owners in 2020 will have access to a charging station within 350 m walking distance. This must of course be immediately nuanced, as only two cars can connect per charging station at the same time, and the service level will therefore be much lower in practice than the figures above suggest.
- 49 The roll-out of the infrastructure (as a result of the dynamic model) over the years 2016-2019 is shown in Figure 9. It is clear that first there will be an extensive roll-out near the places where the estimated EV adoption is high (south-eastern municipalities). Later on, a more balanced distribution of the charging infrastructure over the Region will follow. That is to say, the charging infrastructure will be first and mainly made available in neighbourhoods with affluent residents. Although these neighbourhoods more often have houses with a private parking space where families can charge their vehicle, there are also other families who have the financial means to buy an EV but do not have a private parking space. When a public charging point becomes available in a neighbourhood, households without a private parking space may be easier inclined to switch to electric driving. It is important to note that even if charging infrastructure is initially provided in more affluent neighbourhoods, the benefits of an increasing number of EVs in the Region are available to all thanks to better air quality and a reduction in noise pollution. This roll-out strategy also has the beneficial effect that the business case is more interesting for the charging station suppliers in the start-up years than a geographically uniform roll-out without taking the predicted adoption into account. A favourable business case is important to ensure that these investments are made, because the vision of the Brussels-Capital Region assumes that the charging station suppliers themselves will have to invest without being subsidized. Possibly, a "vehicle first and station later" strategy could supplement the need for charging infrastructure in neighbourhoods where there would be a lack of coverage and the

demand for infrastructure would come from residents. This strategy is currently used by PitPoint and the Brussels-Capital Region and is described in the Regional vision [Brussels Environment, 2020]. In a later phase, the DMCLP model ensures that the charging infrastructure is further rolled out in neighbourhoods with less wealthy residents. Finally, the POI approach proposed for occasional charging provides complementarity to this method. This approach does not take into account the income of the households in the vicinity of the POI and could be implemented simultaneously to combat social inequality.

Figure 9. Optimal locations for the roll-out of charging stations in 2016-2019 based on low-voltage cabins

Source: MOBI

- 50 Since the number of charging stations determines the quality of the solution, i.e. the level of service, a sensitivity analysis on this parameter was also performed. If the number of charging stations that are rolled out per year would be limited to 50 (resulting in 250 new charging stations in 2020), the service level logically turns out to be significantly lower than with the reference scenario of 100 charging stations per year. Figure 10 shows how the service level evolves over the years using the DMCLP with parameters 50, 75, 100 and 125 new charging stations, with the last group of bars representing the total number of predicted EVs per year that was used as input for the model (and would therefore represent a 100 % service level).

Figure 10. Sensitivity analysis with regard to charging stations parameter

Source: MOBI

- 51 Figure 11 shows what the laying out of the 500 charging stations looks like when all cabins are considered as possible locations. Given the more even distribution over the territory of the cabins that are not yet compliant, the distribution of the charging stations is also less concentrated, although the general pattern is similar to the optimal configuration of Figure 8.

Figure 11. Optimal locations for charging stations in 2020 based on all cabins

Source: MOBI

- 52 Since there are more possibilities with regard to possible locations for the charging stations, the service level with this laying out is also somewhat higher than in scenario 1. 13 281 of the 14 028 estimated owners of an EV in 2020 have access to a charging station within a walking distance of 350 m. Again, the nuance must be made that this only guarantees accessibility, and not availability, given the charging points/EVs ratio is less than 1 in 14.

Conclusion

- 53 This paper proposes two different analyses identifying locations for the roll-out of public charging infrastructure for passenger cars. The first analysis aims at implementing a charging infrastructure network for public occasional charging based on important mobility poles and public car parks. The second analysis locates charging stations on the basis of socio-demographic information from the residents, in order to maximize the service level. Fast charging infrastructure falls outside the scope of this paper.
- 54 Wagner *et al.* [2013] indicates that POIs are a good location to install charging stations for occasional charging. Placing charging infrastructure at important mobility poles and public car parks improves accessibility by one third of the coverage of the number of Brussels addresses compared to the situation in 2015. The infrastructure's accessibility is also improved as can be seen from the higher accessibility scores. This confirms that a good starting point to further roll out charging infrastructure are the locations of important POIs in the Brussels-Capital Region. Since the demand for a possible location is measured on the basis of the number of address points within a walking distance of 9 minutes, and not on the basis of usage motives or profiles, the analysis applies to residents of Brussels as well as to visitors or commuters.
- 55 The second analysis examines where new charging locations can be implemented for residential charging. The location model uses the predicted demand down to the spatial level of building blocks as input. The demand is equal to the predicted number of electric vehicles per block between 2015 and 2020. As a control for the use of the data in the analysis, the demand forecast was tested against the latest numbers of electric vehicles in the Brussels-Capital Region. The result of this comparison indicates that the predictions were too optimistic. On the other hand, the spatial distribution of the demand largely corresponds to the spatial distribution of the forecast. Using spatial optimization models MCLP and DMCLP, the service level of new charging stations to be localized was maximized, using the existing 400 V network. Two scenarios were developed: on the one hand, on the basis of the existing low-voltage cabins, and on the other, on the basis of the cabins that are not yet fully compliant. Both approaches provide insight into the proposed location of the new charging stations. Hereby, the greater availability of non-compliant cabins compared to low voltage cabins will result in a greater service level for EV owners in 2020, although conforming these cabins to provide a connection to a charging station entails an additional cost.
- 56 In summary, the combination of both methods focuses on neighbourhoods where the EV adoption of residents is expected to be higher, but also covers most areas of the Region through a complementary POI approach. This complementarity ensures that the

infrastructure is provided at relevant locations for visitors, commuters and residents alike.

- 57 A number of recommendations can be formulated in connection with the data and assumptions used in the methods. In the first place, in 2015, there was no official overview of all existing charging infrastructure in the Brussels-Capital Region available yet. In the meantime, the situation has partly changed, as the Region has awarded a concession to PitPoint (Total) for the expansion of the charging infrastructure network since 2018. An overview of the public charging infrastructure is now available on the charge.brussels website [Charge.brussels, 2021]. However, this is also not the complete overview of the charging infrastructure in the Brussels-Capital Region. This dataset contains all public charging stations that PitPoint has installed, but not the semi-public charging stations (charging stations that are not on public roads but are still available to users) that we listed in 2015. A dataset that contains both types of charging stations would provide a more complete picture of the current situation in the Region. In second place, with regard to predicting numbers of EVs, one can conclude that the resulting numbers should be handled with care. The numbers can easily be overestimated, especially if the market is still in its early development, such as the EV market in 2015.
- 58 A possible avenue for further research is to integrate the results of the accessibility analysis into the location model. In other words, the accessibility score resulting from the analysis could be added to the model to take into account not only the distance between the points but also the number of surrounding addresses representing the demand. Another option could be to consider the POI as fixed charging stations in the location model. This could constitute an additional scenario if the Brussels-Capital Region would like to carry out a complementary POI-oriented roll-out. Since the planning criteria mentioned for the cartography of the Regional vision are similar to the parameters in the proposed location model, a similar model can be used in the future for the roll-out of the 11 040 charging stations from the Regional vision. However, for the amount of charging stations that the Region wishes to install by 2035, this will only be possible if some adjustments are made in the parameters such as e.g. finding other candidate locations (e.g. streets or parking spaces), defining a smaller radius to cover the demand and using a demand that is distributed at a finer level. A final avenue of research is to work with CBC data that is specifically tailored to Brussels residents. This data, coupled with the most recent EV numbers, would make it easier to predict the preferences and adoption of EVs by the inhabitants of Brussels. Hereby, the announced transition to zero-emission mobility can also be taken into account, both at the EU level [European Commission, 2021] and at the Brussels level [Brussels Environment, 2021], with the aim of achieving a zero-emission fleet for passenger cars by 2035.

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APPENDIXES

Table 2. Number of registered EVs per municipality in 2015 and 2018

Municipality	NIS	2015			2018			2020 forecast
		Company	Private	Total	Company	Private	Total	Total
Anderlecht	21001	30	5	35	137	16	153	958
Auderghem	21002	13	3	16	49	13	62	575
Berchem-Sainte-Agathe	21003	7	0	7	30	10	40	19
Brussels	21004	119	6	125	1978	42	2020	1150
Etterbeek	21005	10	2	12	77	13	90	383
Evere	21006	132	4	136	62	7	69	767
Forest	21007	10	1	11	72	16	88	192
Ganshoren	21008	6	1	7	24	7	31	192
Ixelles	21009	132	4	136	273	19	292	767
Jette	21010	30	1	31	58	4	62	192
Koekelberg	21011	2	1	3	16	2	18	192
Molenbeek-Saint-Jean	21012	17	4	21	61	5	66	767
Saint-Gilles	21013	12	0	12	52	9	61	19
Saint-Josse-ten-Noode	21014	33	1	34	395	1	396	192
Schaerbeek	21015	69	2	71	154	12	166	383
Uccle	21016	71	20	91	311	78	389	3833
Watermael-Boitsfort	21017	16	7	23	72	14	86	1342
Woluwe-Saint-Lambert	21018	70	4	74	232	22	254	767
Woluwe-Saint-Pierre	21019	27	7	34	161	47	208	1342
Brussels Capital Region	04000	806	73	879	4214	337	4551	14032

NOTES

1. These detailed figures were personally provided by Mr Kwanten of FPS Mobility. The figures for mid-2019 are an underestimate of the 2019 numbers of EVs per municipality.

ABSTRACTS

The impact of transport on climate change is becoming increasingly significant, making switching to sustainable vehicles an important step in emission reduction. The use of electric vehicles could be stimulated by a large network of charging stations. However, in Brussels, this network is still limited. In this paper, we propose two complementary methods that can support the deployment of a charging infrastructure. The analysis for public occasional charging is a point of interest (POI) based approach as it demonstrates that the accessibility of the charging infrastructure is improved if charging stations are installed at important Brussels mobility poles. Locations for public residential charging are identified by means of location models that take into account demand forecasts for EVs. The resulting roll-out is first pushed through where the estimated EV adoption is high and then spreads evenly across the entire Region. The combination of both methods offers a solution for residents (location models), as well as for visitors or commuters (POI approach).

L'impact du transport sur le changement climatique ne cesse de s'intensifier, faisant des véhicules durables une étape importante pour réduire les émissions. Dans ce contexte, un grand réseau de bornes de recharge permettrait de stimuler l'adoption de la voiture électrique, mais ce réseau demeure trop limité à Bruxelles. Dans cet article, nous présentons deux méthodes complémentaires susceptibles de soutenir le déploiement d'une infrastructure de recharge. L'analyse pour la recharge opportuniste publique consiste en une approche basée sur un point d'intérêt (*point of interest*, POI) qui démontre que l'accessibilité de l'infrastructure de recharge tend à s'améliorer avec l'installation de bornes à proximité d'importants pôles de mobilité bruxellois. Pour la recharge résidentielle publique, des emplacements sont identifiés sur la base de modèles de localisation tenant compte des prévisions de la demande en véhicules électriques (VE). Le déploiement qui en résulte s'impose en premier lieu dans les quartiers où l'adoption escomptée de VE est forte, et s'étend ensuite de manière équilibrée sur l'ensemble du territoire de la Région. La combinaison des deux méthodes offre une solution tant aux habitants (modèles de localisation) qu'aux visiteurs et aux navetteurs (approche POI).

De impact van vervoer op de klimaatverandering wordt steeds aanzienlijker waardoor het overschakelen naar duurzame voertuigen een belangrijke stap is om emissies te reduceren. Een groot netwerk van laadpalen zou de adoptie van elektrische voertuigen (EV's) kunnen stimuleren. Dit netwerk blijft echter nog beperkt in Brussel. In deze paper stellen we twee complementaire methodes voor die de uitrol van laadinfrastructuur kunnen ondersteunen. De analyse voor publiek gelegenheidsladen is een point of interest (POI) gebaseerde aanpak die aantoonst dat de toegankelijkheid van de laadinfrastructuur verbeterd wordt als er laadpalen komen bij belangrijke Brusselse mobiliteitspolen. Locaties voor publiek residentieel laden worden geïdentificeerd a.d.h.v. locatiemodellen die rekening houden met voorspellingen van de vraag naar EV's. De resulterende uitrol wordt eerst doorgedreven waar de geschatte EV adoptie hoog is en spreidt zich vervolgens evenwichtig uit over het volledige Gewest. De combinatie van beide methodes biedt een oplossing voor zowel inwoners (locatiemodellen), als voor bezoekers of pendelaars (POI-aanpak).

INDEX

Mots-clés: mobilité, infrastructures urbaines

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