Optimal Location of Charging Stations for Electric Vehicles in a Neighborhood in Lisbon, Portugal

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Economic and social development over the past 40 years has contributed to increasing per capita income and to the expansion of cities into the suburbs. Other behavioral factors have also helped to increase individual motorized transportation, thereby altering the pattern of urban mobility. All these factors have adverse impacts on the environment and on the quality of city life (*1, 2*). Motorized transportation is responsible for 40% of carbon dioxide emissions and 70% of other greenhouse gas emissions in urban areas (*2*).

In light of such impacts, electric mobility is an alternative that is being introduced in several countries. Electric vehicles (EVs) are more efficient in energy consumption, more environmentally friendly, and cheaper in terms of fuel consumption. The use of such vehicles can help reduce carbon dioxide and other greenhouse gas emissions and almost completely eliminate local pollutant emissions during operation. Whereas carbon dioxide emissions depend on the energy mix of the electric grid from which the vehicles recharge, the introduction of renewable energy sources such as wind and solar, as well as lower carbon-intensive power plants fueled by natural gas or nuclear power in some locations, has contributed to a gradual decrease in carbon dioxide emissions caused by the electric system (*3*). EVs also have the advantage of being silent, thus moderating noise pollution in cities.

An electric mobility system was recently launched in Portugal as a component of the country's efforts to reduce its dependence on fossil energies (*4*). A key issue in this system is recharging the batteries and, consequently, the location of charging stations.

This paper describes a study carried out to define the location of charging stations in a neighborhood of Lisbon, Portugal, called Avenidas Novas, which is characterized by a large concentration of population and employment, thus including both residential and workplace environments. The study was conducted with the objective of maximizing demand coverage and involved a detailed assessment of the potential demand for charging station services.

The remainder of the paper is organized as follows. The process of electric mobility implementation in the European Union (EU) and in Portugal is described, and then the basic characteristics of EV charging systems are presented. In the following sections, the neighborhood dealt with in this study is introduced, and detailed information is provided on how the demand for charging stations was estimated and on how the locations of charging stations were chosen. The final part of the paper summarizes the main conclusions of the work.

IMPLEMENTATION OF ELECTRIC MOBILITY

The roots of the electric mobility efforts currently being made by the EU date back to 1998, the year when the Kyoto Protocol to the United Nations Framework Convention on Climate Change was signed.

With respect to this protocol, the EU has the goal of reducing greenhouse gas emissions by at least 20% by the end of 2020 compared with 1990 levels and has recently taken a number of initiatives in favor of environmentally friendly transportation technologies. The European Green Cars Initiative, launched in November 2008, is an example of such initiatives, which focus on EVs (*5*). Another example is the European Strategy on Clean and Energy-Efficient Vehicles, put forward in April 2010 with the objective of cutting carbon emissions from road transportation by 85% to 90% by 2050. This objective is to be met by promoting clean and energy-efficient vehicles based on conventional internal combustion engines and by facilitating the deployment of breakthrough technologies in ultra-low-carbon vehicles—namely, vehicles powered by liquid biofuels (ethanol and biodiesel), vehicles powered by gaseous fuels (liquefied petroleum gas and compressed natural gas), battery EVs, and hydrogen fuel-cell EVs (*6*).

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Portugal is among the EU countries that are paying more attention to these issues because of its large dependence on fossil fuels. This dependence has increased sharply in recent years, partly as a consequence of the rapid growth in the rate of car ownership, which increased 41.2% in Portugal between 1995 and 2009 (from 252 to 355 cars per 1,000 inhabitants), about 36% faster than in the EU (*7*).

The main initiative of the Portuguese government to promote the popularization of EVs was creation of the Program for Electric Mobility in February 2009 (*8, 9*). This program is managed by a bureau under the Ministry of Economy and Innovation called the Office for Electric Mobility in Portugal, whose main function is the installation and operation of a network of charging stations. The program is divided into three stages: pilot, growth, and consolidation. The main objective of the pilot stage is construction of an experimental charging station network by the end of 2011. The pilot network will be installed in 25 municipalities (mainly district capitals) and on major highways, integrating intelligent charging when possible. The growth stage will start in 2012, and the consolidation stage will start as soon as the demand for EVs reaches a sustainable level. This initiative was complemented by publication in April 2010 of the legal regime for electric mobility (*10*). According to this legal regime, the construction or reconstruction of buildings that incorporate parking spaces must add an electricity supply point that meets the requirements for charging EVs.

Another important recent initiative in favor of electric mobility, taken in March 2010 within the framework of the 2010 to 2013 plan for stability and growth, is the decision to provide tax benefits for purchasing EVs, while the purchase of internal combustion vehicles is discouraged (*11*).

CHARGING OF ELECTRIC VEHICLES

EVs use electricity as a propulsive engine element, as opposed to internal combustion vehicles, which use fossil fuels. Vehicles may be partially or completely electric, and there are different types of EVs: battery EVs, hybrid EVs, plug-in hybrid EVs, and hydrogen fuel-cell EVs (*12*).

EVs are refueled at stations, which can have more than one supply point to allow several vehicles to be charged simultaneously; stations with two and four points are the most common sizes. Each supply point needs from 2 to 3 kW, which means that large stations are a great burden on the power grid. Charging stations can be public with public access, private with public access, or private with private access.

Three types of systems can be used to refuel an EV: battery replacement (which realistically applies only to fleets that can effectively manage this type of system), slow (or normal) charging, and fast charging. Slow charging takes 5 to 8 h (Table 1), which makes this system especially suited to areas where people leave their cars parked for long periods, such as residential and workplace areas. Fast charging takes 20 to 30 min. For slow charging, a single-phase low-voltage 230- to 400-V 16- to 32-A system is needed; for fast charging, a three-phase 400-V up to 200-A system is required (*13*). That difference has implications not only in the power grid but also in a more expensive installation.

Supply points can be activated with an electronic card. In Portugal, users can receive real-time information about charging operations via the MOBI.E portal (*14*) or Short Message Service. Also, users can know the location and availability of charging stations (*15*). This solution is similar to that in use in the United States (*16*).

The autonomy of EVs is still very low. Taking into account information from the automobile industry and research institutions, one can say that, in real-world conditions, it currently ranges between 60 and 160 km [a recent, thorough study on this topic is provided elsewhere (*17*)]. The difference depends on the vehicle, the driving, the topography, and the weather. EVs have to be refueled much more frequently than internal combustion vehicles.

The location of charging stations should be carefully chosen to ensure the best possible access for users. Locations can be selected efficiently with the support of a particular type of optimization model, called facility location models, whose decision variables represent the location, the capacity, and the coverage area of any kind of facility. The reader is referred to Daskin (*18*) for a textbook presentation of these models and to ReVelle and Eiselt (*19*) and Daskin (*20*) for recent surveys.

Several types of objective can be considered in a facility location model, such as the minimization of total costs, the minimization of transportation costs, and the maximization of demand coverage. The first type of objective is dealt with through fixed-charge models, the second through *p*-median models, and the third through maximal covering models. Depending on whether capacity constraints apply to the facilities, the models are classified as capacitated or uncapacitated.

Maximal covering models are especially well suited to cope with EV charging stations. These models were introduced by Church and ReVelle (*21*). The application of these models allows for determining, for a given number of facilities, the locations that maximize the demand lying within a given maximum acceptable distance, d_{max}, of at least one facility. A closely related model introduced by Berman et al. (*22*), in which coverage decays beyond a given maximum desirable distance, d^*, is especially interesting. According to this model, a demand area j located at a distance d_j from a facility is totally covered by the facility if $d_j \leq d^*$, is partly covered if $d^* < d_j \leq d_{max}$, and is not covered if $d_j > d_{max}$. For this model to be fully applicable to charging stations, it needs to include capacity constraints to take into account the maximum (and possibly the minimum) number of supply points to install in each station.

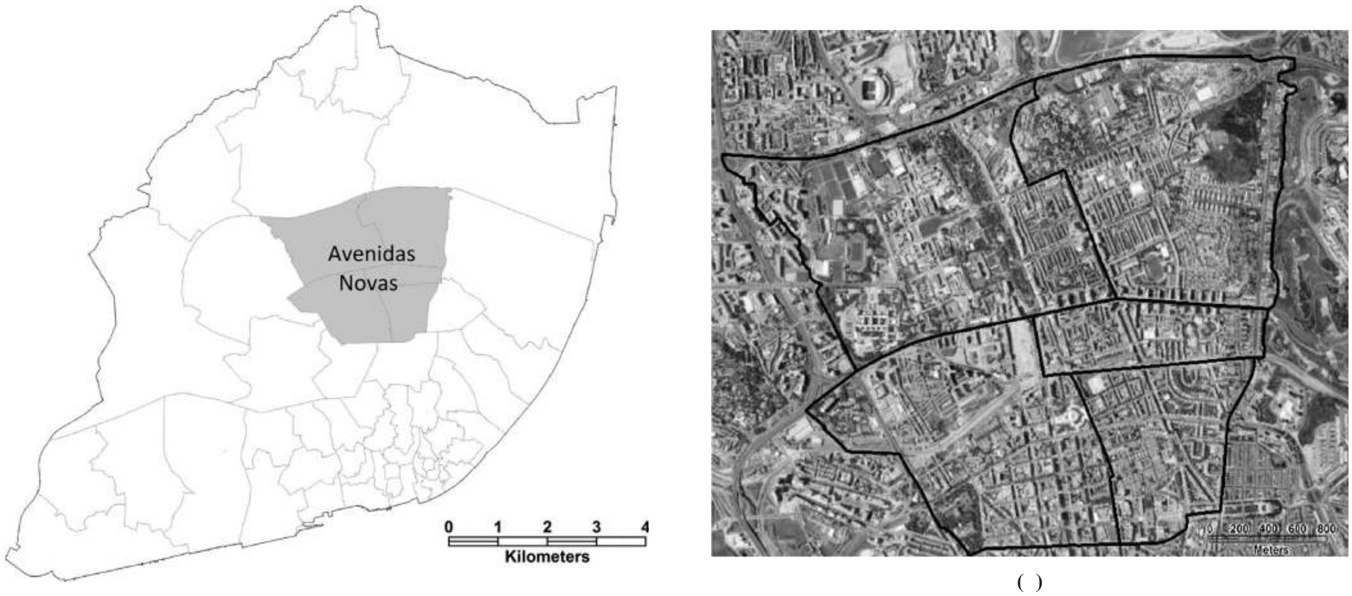
TABLE 1 Battery Capacity and Charging Time for Four EV Models

Vehicle	Battery Capacity (kWh)	Charging Time (3kW/240V/13A) (h)
Mitsubishi I MiEV Peugeot iOn Citroën C-ZERO	16	5.3
Nissan Leaf	24	8

DESCRIPTION OF STUDY AREA

The area dealt with in this study is the neighborhood of Avenidas Novas, one of the most important in Lisbon, the capital city of Portugal (Figure 1).

The neighborhood has an area of 8.07 km^2, spread across five *freguesias* (the freguesia is the smallest administrative jurisdiction in Portugal) and 387 census blocks. It is a mixed-use neighborhood where residences and workplaces are often combined in the same building. The population of the neighborhood in 2001, date of the latest census (*23*), was 60,290—about 11% of the total population



(a)

( )

FIGURE 1 Avenidas Novas: (*a*) location in Lisbon and (*b*) aerial view.

of the city of Lisbon (557,000). Avenidas Novas is a neighborhood where 56% of the residents older than 17 have completed high school and 86% of the working residents are employed in the tertiary sector (the equivalent percentages for Lisbon are 42% and 69%, respectively). The car-ownership rate for households in the neighborhood was 2.81 vehicles per household, which is clearly above the city's average (2.11).

The total number of buildings in Avenidas Novas was 4,510 (also in 2001). Despite the name of the neighborhood (*novas* means new in Portuguese), 92% of these buildings were constructed before 1980, at a time when car-ownership rates were much lower than today and most buildings did not have parking spaces. This situation makes street parking, parking lots, and parking garages the dominant parking solutions in the area and points to the importance of public access EV charging stations. The proportion of nonresidential and partly residential buildings was 32%, which is quite high compared with the equivalent number for the city of Lisbon (22%). The notable nonresidential buildings located in the neighborhood include Ministry of Labor and Social Solidarity, National Laboratory of Civil Engineering, National Bureau of Statistics, Hospital Júlio de Matos, Instituto Superior Técnico (a large engineering school), and Caixa Geral dos Depósitos (a large bank).

The number of nonresidential and partly residential buildings located in the neighborhood gives a clear indication of the large number of people who work there. This number was estimated at 122,500 in a mobility study published in 2005; the total for Lisbon was 469,000 (*24*). The employment-to-population ratio was therefore 2.4 times larger in Avenidas Novas than in the city, and confirms the importance of this neighborhood with regard to employment.

ESTIMATION OF REFUELING DEMAND

The first part of the study consisted of estimating the demand for EV refueling in each census block of Avenidas Novas. This operation is difficult because it deals with potential demand—that is, one cannot rely on observations of the behavior of actual users. Nighttime demand (7 p.m. to 7 a.m.) was estimated separately from daytime demand (7 a.m. to 7 p.m.) because the demands correspond to different types of users: the former demand is related to the population (households) living in the neighborhood and the latter demand is related to the employment (jobs) offered there. The measure used to assess demand was the number of charge-ups necessary each period of the day.

Nighttime Demand

To estimate the nighttime demand, first a relationship was established between the number of cars per household and the characteristics of households. This was done by using regression analysis and information available for the 51 municipalities of the Lisbon and Tagus Valley Region (Região de Lisboa e Vale do Tejo) (Figure 2).

Specifically, the number of cars per household, v_h, was assumed to be a (linear) function of the following variables: household size, building type, average age, education level, and employment sector of household members:

$$v_h = f\left(\text{size}_{\text{household}}, \text{type}_{\text{building}}, \text{pop}_{\text{age}}, \text{pop}_{\text{education}}, \text{pop}_{\text{employment}}\right) \qquad (1)$$

The regression equation was obtained after stepwise elimination of the nonsignificant variables and the intercept was forced to be 0:

$$v_h = 3.90 \times p_H - 1.18 \times p_T + 3.41 \times p_{20} + 3.28 \times p_{64} \qquad \left(R^2_{\text{adj}} = .99\right) \qquad (2)$$

where

p_H = proportion of population older than 17 years of age who completed high school,
p_T = proportion of residents working in the tertiary sector,
p_{20} = proportion of residents younger than 20 years of age, and
p_{64} = proportion of residents older than 64 years of age.

(a)

(b)

FIGURE 2 Maps of (*a*) Lisbon and Tagus valley region and (*b*) traffic zones of city of Lisbon.

This regression equation captures the relationship between the number of cars per household and the characteristics of households extremely well ($R^2_{\text{adj}} = .99$), and, as shown in Table 2, all variables are clearly significant (t-statistic > 2). As expected, households whose members have higher levels of education possess more vehicles on average. However, households with people working in the tertiary sector tend to own fewer vehicles, probably because the tertiary sector has a large presence in central areas, which are usually well served by public transport, thus reducing the need for a car. Finally, the results indicate that individuals younger than 20 years or older than 64 years are associated with a larger number of cars in the household.

Equation 2 was used to calculate the number of cars in each census block j during the nighttime, V_{Nj}, as follows:

$$V_{Nj} = v_{hj} \times H_j \tag{3}$$

where H_j is the number of households in census block j.

The next step consisted of estimating the number of EVs to refuel in each census block in the nighttime. This step took into account the forecasts of the European Commission, according to which the share of EVs will be 1% to 2% by 2020 (and 11% to 30% by 2030) (*6*). However, as the Portuguese government is putting a strong emphasis on electric mobility, it was assumed that the share of EVs in Portugal will be higher. Specifically, it was taken to be 2% by the end of 2011 and 4% by the end of 2012 in census blocks where the number of cars per household is lower than 2.0 and 1% more when the number of cars per household is higher than (or equal to) 2.0 to reflect the idea that a family with a larger number of cars is more likely to own an EV.

$$V_{ENj}(2011) = \begin{cases} 0.03 \times V_{Nj} \Leftarrow v_{hj} \geq 2 \\ 0.02 \times V_{Nj} \Leftarrow v_{hj} < 2 \end{cases} \tag{4a}$$

$$V_{ENj}(2012) = \begin{cases} 0.05 \times V_{Nj} \Leftarrow v_{hj} \geq 2 \\ 0.04 \times V_{Nj} \Leftarrow v_{hj} < 2 \end{cases} \tag{4b}$$

where V_{ENj} is the number of EVs to refuel in the nighttime in census block j.

Finally, to estimate the nighttime demand, it is necessary to know the average distance cars travel by day. According to the last mobility survey carried out in the metropolitan area of Lisbon (*25*), this distance is about 20 km. It is also necessary to select a value for the autonomy of an EV in the Lisbon area. Given the characteristics of the area, this value was assumed to be 60 km. An EV will thus need to be refueled once every 3 days. Consequently, the number of charge-ups necessary to refuel the EVs of census block j in the nighttime, u_{Nj}, is given by

$$u_{Nj} = 0.33 \times V_{ENj} \tag{5}$$

TABLE 2 Regression Results for Nighttime Demand

Variable	Coefficients	Standard Error	t-Statistic	P-Value
p_H	3.9	0.72	5.41	<.001
p_T	−1.18	0.43	−2.78	.008
p_{20}	3.41	0.72	4.71	<.001
p_{64}	3.28	0.48	6.76	<.001

Daytime Demand

Daytime demand was estimated according to the same steps as for nighttime demand, but in this case, the first step was to establish the relationship between the volume of employment and the type of buildings. Regression analysis was used as before, and information was available for the 40 traffic zones considered in the mobility study referred to above (*24*) (Figure 2).

The regression equation obtained by forcing the intercept to be 0 was as follows:

$$E = -1.42 \times B_R + 14.89 \times B_{RN} + 159.20 \times B_N \qquad (R^2 = .68) \qquad (6)$$

where

E = volume of employment,
B_R = number of residential buildings,
B_{RN} = number of mainly residential buildings, and
B_N = number of mainly nonresidential buildings.

This regression equation captures the relationship between the volume of employment and the type of buildings well enough ($R^2_{\text{adj}} = .68$), but, as shown in Table 3, variables B_R and B_{RN} are not significant. Accordingly, these variables should have been removed stepwise from the regression equation. However, they were the only variables that could be used for the estimation and the signs of the respective regression coefficients were as expected (i.e., employment increases with B_N and B_{RN} and decreases with B_R). Therefore, it was decided to keep these variables.

By using Equation 6 and taking into account that about 20% of the travel-to-work trips ending in the neighborhood are made by car (the equivalent figure for the city of Lisbon is about 40%, but Avenidas Novas is much better served by public transport than other neighborhoods), the number of cars in each census block j in the daytime, V_{Dj}, was calculated as follows:

$$V_{Dj} = 0.2 \times E_j \qquad (7)$$

where E_j is the volume of employment in census block j.

Finally, by using the same ideas as before, the number of EVs to refuel in each census block j in the daytime, V_{EDj}, and the number of charges necessary to refuel them, u_{Dj}, were calculated as follows:

$$V_{EDj}(2011) = 0.02 \times V_{Dj} \qquad (8a)$$

$$V_{EDj}(2012) = 0.04 \times V_{Dj} \qquad (8b)$$

$$u_{Dj} = 0.33 \times V_{EDj} \qquad (9)$$

TABLE 3 Regression Results for Daytime Demand

Variable	Coefficients	Standard Error	*t*-Statistic	*P*-Value
B_R	–1.42	2.04	–0.7	.49
B_{RN}	14.89	9.26	1.61	.12
B_N	159.2	42.76	3.72	.001

LOCATION OF CHARGING STATIONS

To determine where the EV charging stations should be located, it was necessary to address a number of supply-side issues.

First, the number of stations to install was decided. This number was chosen by taking into account that the government had already decided the total amount of stations to locate in the city of Lisbon: 406. Of these stations, 268 are to be installed by the end of 2011 and the other 138 stations by the end of 2012. With population as a weight measure, this total signifies that 43 stations are to be located in Avenidas Novas: 29 by the end of 2011 and the other 14 by the end of 2012.

Second, the possible locations for the stations were chosen. It was assumed that all 290 car parks located in Avenidas Novas either meet the requirements for the installation of charging stations, or if the car parks do not, the situation can be resolved by increasing the capacity of the local power supply. The locations of the car parks are depicted in Figure 3.

Third, capacity limits for charging stations were defined. It was assumed that each station would have at least two and at most 10 supply points (to avoid excessive burden on the power grid). Moreover, it was assumed that each refueling operation would take 6 h, meaning that during daytime there could be two charge-ups and that during nighttime there could also be two charge-ups but only if some business structure would take care of refueling operations. Otherwise, only one charge-up per night would be possible.

Fourth, the coverage area of a station was defined. The concept of gradual coverage was used, taking 400 m as the maximum desirable walking distance (d^*) and 600 m as the maximum acceptable walking distance ($d_{\max}$). As rectilinear distances were used instead of street distances (except where there were obstacles such as a railroad), those values were reduced by 50 m.

$$r_{jk} = \begin{cases} 1 \Leftarrow d_{jk} \le 350 \\ 2.75 - 0.005 \times d_{jk} \Leftarrow 350 < d_{jk} \le 550 \\ 0 \Leftarrow d_{jk} > 550 \end{cases} \qquad (10)$$

where r_{jk} is the level of coverage of census block j by a charging station located in k and d_{jk} is the distance between the centroid of census block j and a charging station located in k.

Taking these definitions into account, the problem of determining the maximal coverage solution for the location of charging stations in Avenidas Novas can be represented by the following model:

$$\max \sum_{j \in \boldsymbol{J}} \sum_{k \in \boldsymbol{K}} n_N r_{jk} u_{Nj} x_{jk} + \sum_{j \in \boldsymbol{J}} \sum_{k \in \boldsymbol{K}} n_D r_{jk} u_{Dj} x_{jk} - \sum_{k \in \boldsymbol{K}} 0.01 \times s_k \qquad (11)$$

subject to

$$\sum_{k \in \boldsymbol{K}} x_{jk} \le 1 \qquad \forall j \in \boldsymbol{J} \qquad (12)$$

$$x_{jk} \le r_{jk} y_k \qquad \forall j \in \boldsymbol{J},\ k \in \boldsymbol{K} \qquad (13)$$

$$\sum_{k \in \boldsymbol{K}} y_k = p \qquad (14)$$

FIGURE 3 Possible locations of charging stations (car parks).

$$y_{40} = 1 \qquad (15)$$

$$z_k \geq \sum_{j \in \boldsymbol{J}} u_{Nj} x_{jk} \qquad \forall k \in \boldsymbol{K} \qquad (16a)$$

$$z_k \geq \sum_{j \in \boldsymbol{J}} u_{Dj} x_{jk} \qquad \forall k \in \boldsymbol{K} \qquad (16b)$$

$$s_K \geq \frac{z_k}{n_N} \qquad \forall k \in \boldsymbol{K} \qquad (17a)$$

$$s_K \geq \frac{z_k}{n_D} \qquad \forall k \in \boldsymbol{K} \qquad (17b)$$

$$s_k \geq 2 y_k \qquad \forall k \in \boldsymbol{K} \qquad (18a)$$

$$s_k \leq 10 y_k \qquad \forall k \in \boldsymbol{K} \qquad (18b)$$

$$x_{jk}, z_k, s_k \geq 0 \qquad \forall j \in \boldsymbol{J}, k \in \boldsymbol{K} \qquad (19)$$

$$y_k \in \{0,1\} \qquad \forall k \in \boldsymbol{K} \qquad (20)$$

where

$\boldsymbol{J}$ = set of census blocks,
$\boldsymbol{K}$ = set of possible locations for charging stations,
n_N (n_D) = number of refueling operations in the nighttime (daytime),
x_{jk} = proportion of users from census block j covered by a charging station located in k,
y_k = 1 or 0 depending on whether a charging station is located in k,
p = number of stations to locate,
z_k = capacity (in terms of daily charge-ups) of a charging station located in k, and
s_k = number of supply points of a charging station located in k.

The Objective Function 11 of this mixed-integer optimization model maximizes demand coverage, distinguishing between nighttime and daytime demand. This function contains a penalty term to prevent the installation of unnecessary supply points. Constraint 12 guarantees that the demand covered from each census block does not exceed 100%. Constraint 13 defines the level of coverage provided by stations. Constraint 14 specifies the maximum number of stations to locate. Constraint 15 signifies that the station already existing in location k = 40 (Praça de Londres) will be kept. Constraints 16a and 16b ensure that charging stations will have enough capacity to accommodate both the nighttime and the daytime demand. Constraints 17a and 17b define the number of supply points to install in each charging station, and Constraints 18a and 18b set the minimum (2) and maximum (10) number of these points. Finally, Expressions 19 and 20 specify the domain of the decision variables.

This model was applied to Avenidas Novas by considering four scenarios, depending on the number of charging stations to install and on the number of nighttime charge-ups as explained in Table 4.

TABLE 4 Scenarios for Application of Optimization Model

Scenario	Number of Supply Points	Charge-ups in Nighttime
1	29	1
2	43	1
3	29	2
4	43	2

The results for the various scenarios can be summarized as follows:

Scenario 1. One hundred eighty supply points, providing only one charge-up at night, were installed in the 29 charging stations (average 6.2 supply points per station). Of the 387 census blocks, seven are partly covered and four are not covered, but the latter do not face any local demand (Figure 4).

Scenario 2. An additional 144 supply points need to be installed, both in the initial stations and in the 14 new ones, to meet increased demand. The number of supply points per station increases to 7.5. All demand is fully covered.

Scenario 3. Compared with Scenario 1, the number of supply points decreases by 43 because of the two charge-ups at night and the locations of charging stations differ in five cases.

Scenario 4. Compared with Scenario 2, the number of supply points decreases by 88 and the locations of charging stations differ in nine cases.

CONCLUSION

This paper presented a study on the location of EV charging stations for a neighborhood of Lisbon characterized by a mix of residential and business uses. It is an important part of the city, mainly developed before 1980, where most buildings do not have parking spaces. Therefore, EVs will mainly have to be refueled at public-access charging stations.

The methodology used in the study starts with the estimation of refueling demand and then determines the locations of charging stations that best allow coping with the estimated demand through the application of a maximal covering model. Because of the mixed-use nature of the neighborhood, there are two types of demand to consider: a nighttime demand associated with residences and a daytime demand associated with workplaces.

The main difficulties encountered in the development of the study have to do with the estimation of demand. The estimation is mostly on the basis of 2001 census data, which are now somewhat outdated. In particular, the estimation of daytime demand at the census-block level raised problems that were not fully overcome. Another aspect that deserves further (market) research before these results are used in practice is the penetration rate of EVs. On the supply side,

FIGURE 4 Optimum location of charging stations and coverage of census blocks (Scenario 1).

a number of issues require more consideration, such as vehicle autonomy, refueling time, and power supply improvements.

Despite these difficulties, it is believed that the methodology followed here can provide urban managers, in Lisbon and elsewhere, with good insight into where the EV charging stations of their cities should be located and therefore contributes significantly to the future planning of electric mobility systems.

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