Assessing the potential of electric vehicles for commutes in Portugal

Miguel Amorim Santiago
miguel.santiago@ist.utl.pt

Instituto Superior Técnico, Lisboa, Portugal
October 2016

Abstract

Considering that the transportation sector is one of the most polluting and energy consuming sectors, this work focusses on assessing the potential use of electric vehicles for commuting by estimating energy consumption. Three different scenarios were considered: the use of new conventional cars (baseline), a partial shift in the fleet to BEVs with batteries of 24 kWh considering only at home recharging (Scenario 1) and considering combined at home and at work recharging (Scenario 2). When analysing 18 Portuguese municipalities, energy savings of up to 37% for scenario 1 and 52% for scenario 2 could be obtained when compared to the baseline scenario, with Lisboa being the municipality which benefits the most from the shift to electric mobility reaching savings of 48% (Scenario1) and 56% (Scenario2). If BEVs with 60ºkWh battery are considered, energy savings would increase to 55% of the total baseline scenario energy demand and 99.9% of daily commuters could use a BEV. Furthermore, the municipalities where BEVs should be deployed were identified, in order to maximize energy savings, if only a fraction of BEVs could be replaced. The replacement of 10% of the vehicles that could be BEVs could lead to savings of 6.9% (Scenario1) and 12.1% (Scenario). Finally, assessing the different scenarios enables a comprehensive analysis of charging needs locally, with potential impacts in the definition of local policies.

Keywords: commuting patterns; battery electric vehicles; energy savings; EV range

1. Introduction and Policy Context

The transportation sector is currently one of the most energy consuming and polluting sectors. The transportation sector accounts for about a quarter of all GHG emissions being the main cause of air pollution in urban context and has only seen its emissions decrease in 2007, however still remaining significantly high [1].

Several policies and directives have been settled, setting mandatory emission reduction targets at the European level. One of the most important examples of such directives is the 2020 package which established three key targets in order to fulfil climate and energy targets for 2020 [2]:

- 20% cut in GHG emissions (from 1990 levels);
- 20% of EU energy from renewables; and
- 20% improvement in energy efficiency.

Regarding the 20% cut in GHG emissions, a European Community directive [3] promotes reductions of GHG emissions in a cost-effective and economically efficient manner by establishing a scheme for GHG emissions allowance trading within the Community.

Concerning the 20% improvement in energy efficiency, the directive [4] requires all EU countries to use energy more efficiently. Examples of specific measures and policies include a requirement of 1.5% of energy savings per year for distributors or retail sales companies and a requirement for the purchase of energy efficient products and services for the public sector in EU.

Another example is the renewable energy directive [5], which requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020, to be achieved through the accomplishment of individual national targets. The directive also ensures that at least 10% of transportation fuels come directly from renewables by 2020.

Regarding vehicle energy efficiency in the transport sector, the 2021 target for CO_2 per kilometre for the fleet average in new vehicle sales is of 95 g/km, meaning a 4.1 l/100 km fuel consumption for petrol or a 3.6 l/100 km fuel consumption for diesel vehicles. The 2015 target already represented a 18% reduction compared with 2007 and the 2021 target aims for a 40% decrease [6].

Concerning alternative fuels infrastructure, the final directive [7] requires member countries to develop national policies for the market development of alternative fuels infrastructures. Also, it imposes standardized technical specifications for recharging and refuel stations, while paving the way to the establishment of appropriate consumer information on alternative fuels, including a price comparison methodology.

Furthermore, some cities have implemented local incentives to the use of more efficient and less polluting ways of transportation. Numerous cities have already adopted free parking for EVs and access to bus lanes. Besides these policies, different cities and countries have established different policies. In Norway, electric and hybrid vehicles are exempted from paying ferryboat trips. Also, in some countries electric powered vehicles are exempted from paying tolls on highways. In Lisbon, the charging of EVs in public charging stations is free of charge until the beginning of the commercial phase [8].

2. Methods, key assumptions and data.

2.1. Methodology

The main goals of the developed methodology are to estimate the energy consumed in commuting to urban areas, identify the potential use of electric vehicles for commuting and estimate the potential savings that can be obtained from that shift to electric mobility. The developed methodology consists of four main steps: i) estimate the number of cars commuting; ii) characterize mobility patterns; iii) determine daily commuters; iv) assess the impacts of switching to BEVs. These steps are described in detail in the following subsections.

2.1.1. Estimate number of cars commuting

To identify the number of cars that commute to each municipality, it was first necessary to create an Origin/Destination (O/D) matrix. In this work, this was performed through the analysis of Census data [9], which characterize how many people commute between each parish and all municipalities in the country. With the O/D matrices defined, it was then necessary to limit the sample number from the total number of people commuting to the ones that commute by driving a car. This was done using statistics that characterize the transportation modes used for commuting in each parish [9], with which was possible to estimate the number of cars commuting for each entry of the O/D matrix. The percentage of cars used for commuting can then be calculated using equation 1.

$$\%cars = \frac{number\ of\ drivers\ commuting}{Total\ number\ of\ commuters} \qquad (1)$$

By multiplying the percentage of cars by the total number of commuters for each entry of the O/D matrix, the final number of cars is obtained.

2.1.2. Characterization of mobility patterns

The second step consisted in the characterization of mobility patterns, by developing specific Matlab [10] code connected to the Google Maps API System [11] to breakdown the trip corresponding to each entry of the O/D matrix in segments and obtain distance, time and road grade for each segment. The start and end locations representative of each O/D matrix entry were introduced in the Google Maps API Directions System and values for distance, time, street name and geographic coordinates for the start and end were obtained for every segment of the trip, according to the travelled street. All queries to the Google Maps API Directions System [12] were performed in off-peak hours, to guarantee free flow driving conditions. From the obtained distance and time values, an average speed for each segment was then calculated.

The geographic coordinates of the start and end points of each segment were also used in the Google Maps API Elevations System [13], to obtain the elevation of the two points of every segment of the trip. From these elevations, the elevation difference of each trip segment was calculated. Using the elevation difference and travelled distance, the average road grade of each segment was calculated by dividing both parameters, as shown in equation 2. This road grade is necessary to estimate the energy consumed in each segment.

$$Road\ Grade = \frac{Elevation\ Difference}{Travelled\ Distance} \qquad (2)$$

Both go and return journeys were considered separately when introducing data on Google Maps due to orography differences and potentially different defined paths, which can result in different assessments for the energy consumption in each trip.

2.1.3. Determine daily commuters

Due to the low vehicle range of most current electric vehicles technologies (typically below 120 km per charge), a distinction must be made between local and long-distance commuters. In this work, it was assumed that a local commuter is someone who commutes every day between their main residence and place of work and a long-distance commuter is someone who commutes weekly between those places. As generally no information is available to distinguish local from long-distance commuters, a threshold to divide the total number of commuters was defined. Several parameters may be used to differentiate these two sets of people such as distance, time or even percentage of commuters. In this work, a maximum total commute time per day of two hours was defined as this threshold.

2.1.4. Assess the impacts of BEVs

For the evaluation of the impacts of the shift to electric mobility, the energy consumption associated to the baseline fleet was calculated. The considered baseline fleet can be defined based on: the current existing fleet (for each location or national average) if the aim is to estimate the energy and emissions reductions from their current levels; or based on new vehicle sales if the aim is to estimate the reductions in the case of a fleet renovation program. In this case, the baseline fleet is based on the new vehicles sales.

After defining the fleet, energy consumption was estimated using the vehicle specific power (VSP) methodology, accounting for the impacts of speed and road grade. VSP stands for Vehicle Specific Power and is defined as “the instantaneous power per unit mas of the vehicle” used to overcome exterior forces such as drag and rolling resistance [14]. Due to the limited data available from the evaluation of mobility patterns previously presented, only speed and road grade was available. As a result, a simplified VSP equation in W/kg was used, as presented in equation 3, in which $grade(\%)$ is the road grade (%), V is the vehicle speed (m/s) and V_w is the headwind into the vehicle (m/s).

$$VSP\left(\frac{W}{Kg}\right) = \frac{V}{3.6} \times (9.81 \times grade(\%) + 0.132) + 3.02 \times 10^{-4} \times \left(\frac{V}{3.6}\right)^3 \quad (3)$$

The estimation of energy consumption was based on the modal VSP energy consumption for different vehicle technologies (SI – spark ignition, CI – compressed ignition, BEV – battery electric vehicle) available in the literature [15]. This data is based on experimental data [15] and is representative of Euro 5 vehicles. Since no data on this VSP approach was available for Euro 6 vehicle technologies, the Euro 5 vehicles were considered representative. This is a fair assumption since it is estimated that the fuel consumption reduction from Euro 5 to Euro 6 has not been significant [16]. Table 1 includes different regimes for BEVs, considering energy production ones, such as regenerative braking, for low VSP modes, as presented by negative values for energy consumptions in both VSP modes 1 and 2 for BEVs.

Table 1 - Fuel consumption distribution according to VSP and engine technology (SI – spark ignition, CI – compressed ignition, BEV – battery electric vehicle)

VSP mode	VSP	SI	CI	BEV
	W/kg	g/s	g/s	Wh/s
1	VSP<-2	0.129	0.037	-2.241
2	-2≤VSP<0	0.153	0.099	-0.434
3	0≤VSP<1	0.167	0.139	0.275
4	1≤VSP<4	0.472	0.457	2.567
5	4≤VSP<7	0.629	0.646	3.976
6	7≤VSP<10	0.901	0.846	5.260
7	10≤VSP<13	1.071	1.064	6.122
8	13≤VSP<16	1.308	1.299	7.876
9	16≤VSP<19	1.411	1.549	9.217
10	19≤VSP<23	1.589	1.860	10.656
11	23≤VSP<28	1.810	2.218	12.553
12	28≤VSP<33	1.930	2.570	14.862
13	33≤VSP<39	2.015	2.932	17.365
14	VSP≥39	2.046	3.340	20.957

Using the previously defined baseline fleet it was possible to calculate the fleet’s energy consumption by using equation 4.

$$\text{Fleet FC}\left(\frac{\text{MJ}}{\text{s}}\right) \quad (4)$$
$$= \frac{\text{SI FC}\left(\frac{\text{g}}{\text{s}}\right) \times \text{Petrol LHV}\left(\frac{\text{MJ}}{\text{l}}\right) \times \text{\%of Petrol cars}}{\text{Petrol density}\left(\frac{\text{g}}{\text{l}}\right)} + \frac{\text{CI FC}\left(\frac{\text{g}}{\text{s}}\right) \times \text{Diesel LHV}\left(\frac{\text{MJ}}{\text{l}}\right) \times \text{\%of Diesel cars}}{\text{Diesel density}\left(\frac{\text{g}}{\text{l}}\right)} + \text{BEV FC}\left(\frac{\text{Wh}}{\text{s}}\right) \times 0.0036 \times \text{\%of BEV cars}$$

Where SI FC, CI FC and BEV FC are the fuel consumption from a SI, CI and BEV engine (as obtained from the Portuguese total sales in 2015; CI – 69%; SI – 30%; Others – 1%[17]), LHV is the low heating value (31.76 MJ/l for petrol and 35.95 MJ/l for diesel), the petrol density is 0.73 g/l, and the diesel density is 0.82 g/l.

Consequently, the total energy consumed in each segment of a trip for a specific fleet was then calculated by multiplying the value obtained from equation 4 with the time spent on the segment, obtained in section 2.1.2. Equation 5 describes the calculation of the total energy consumption from commuters to a specific destination by applying this methodology for every segment *j* in every commute *i* on both go and return journeys, and multiplying by the number of vehicles that perform that daily commute *i* (obtained in section 2.1.3). This allowed estimating the total daily energy consumption (in MJ) for different fleet compositions.

$$Total\ FC\ (MJ) = \sum_i \left[\sum_j \left(Fleet\ FC_j \times time_j\right)_{go} + \sum_j \left(Fleet\ FC_j \times time_j\right)_{return}\right] \times number\ of\ cars\ commuting_i \quad (5)$$

It should be noted that only the vehicle usage energy consumption was considered in this study (Tank-to-Wheel stage). The authors acknowledge the importance of accounting for the electricity generation impacts, however, in this case they would homogenously affect the municipalities considered.

2.2. Data

In this work, the proposed methodology was applied to study the commutes of 18 municipalities in Continental Portugal, with the regions of Madeira and Azores not being included. The chosen municipalities were: **Aveiro, Beja, Braga, Bragança, Castelo Branco, Coimbra, Évora, Faro, Guarda, Leiria, Lisboa, Portalegre, Porto, Santarém, Setúbal, Viana do Castelo, Vila Real and Viseu**. These are the Portuguese district capitals and were found to be a good approximation of the Portuguese reality. This section describes the data used to perform the developed methodology. It should be highlighted that the assessment of these municipalities considers only the in-bound commuting movements, i.e., considering the municipality as the destination of commuters.

The O/D matrix for people that live in one place and work in a different municipality was available based on the Portuguese 2011 census [9]. The commutes to the 18 municipalities account for 46% of the total commuters in the country. The total number of people that commute to each municipality is shown in Figure 1. Also, in Figure 1, the percentage of people commuting from outside the municipality per total number of inhabitants per municipality is shown.

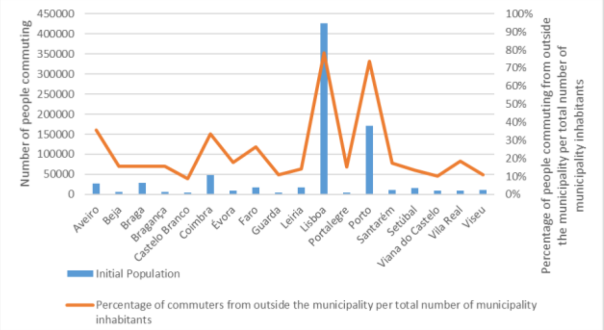

Figure 1 - Total initial number of people commuting and Percentage of people commuting from outside the municipality per total number of municipality inhabitants

It is noticeable that Lisboa is the municipality that accounts for the biggest share of people, around 48% of the entire studied commuting population, followed by Porto, 23%, Coimbra 6%, Aveiro, 4%, and Braga 4%. The other 12% are distributed between the remaining 13 municipalities. When analysing the percentage of commuters per total inhabitants, the values for Lisboa (78%) and Porto (74%) standout. On the other hand, Castelo Branco shows the lowest percentage (9%) followed by Viana do Castelo (10%).

Information regarding the transport mode share was also available in the Portuguese 2011 census [9]. The data available characterizes the share of people that use each mode of transportation as their main mobility product to commute to each parish in Portugal. Based on this data, it was possible to calculate for each parish the share of people that drive a car in their commute (which can be used to calculate the number of cars that are used in commutes from that parish) and the average occupation rate. Figure 2 shows the distribution of both parameters for all parishes in Portugal.

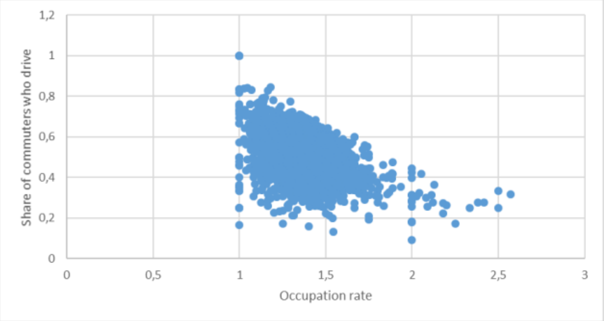

Figure 2 - Scatter graph "Occupation rate" VS "Percentage of cars commuting"

As can be seen, higher occupation rates result in lower shares of people driving a car, with a large diversity across parishes. As such, different values for occupation rate and percentage of cars commuting were used for each of the parishes considered. Overall, the Portuguese average percentage of drivers is around 53% of the total amount of commuters, with an average occupation rate of 1,37 people per car.

The baseline fleet considered in this work is based on the diesel and gasoline vehicles sales in Portugal, resulting in a partition of 70% of diesel and 30% of gasoline, calculated from the vehicle retailers' data available online [17]. All other technologies were not considered due to a lack of data or very low share in the market (below 1%). While all new vehicles are Euro 6, Euro 5 data was used due to availability of specific energy consumption data. This assumption has a very low impact on the results, as the consumption of Euro 5 and Euro 6 vehicles is very similar [16]. Table 2 presents the energy consumption by second for each VSP mode for the baseline fleet.

Table 2 – Energy consumption by second for each VSP mode for the baseline fleet

VSP mode	Energy consumption (kJ/s)
1	2.82
2	5.02
3	6.43
4	20.20
5	28.02
6	37.72
7	46.63
8	56.93
9	65.95
10	77.82
11	91.70
12	104.07
13	116.29
14	129.21

For the assessment of energy consumption of BEVs, an average BEV with a battery capacity of 24 kWh was considered, based on the current electric vehicles fleet in Portugal [18]. Furthermore, it was assumed that not all the capacity of the battery was available for the commute. Of the total capacity, only 80% should actually be used by the vehicle, as the state of charge of the battery should not go below 20%. Furthermore, it was assumed that only 90% of the remaining battery could be used for commutes, with the remaining 10% being available for detours or other trips within the commuters' destination. This resulted in a 72% availability of the battery for commuting.

As previously mentioned, the threshold for daily commutes was defined in this work as maximum time of go and return of 2 hours.

2.3. Definition of scenarios

To assess the potential energy savings from shifting to electric vehicles, three scenarios were considered:

- Baseline – All commutes are made with new conventional vehicles;
- Scenario 1 – The commutes for which only one BEV battery charge is sufficient for a go and return trip, i.e. no charging is made during the day, are made with BEVs;
- Scenario 2 – In addition to the trips made with BEVs in Scenario 1, the commutes for which one BEV charge is sufficient to perform the go trip and another charge is sufficient to perform the return trip, i.e. there is one recharging period during the day, are also made with BEVs.

A sensitivity analysis on the impact of the battery size of BEVs is also made. Battery capacities of 24, 30, 60 and 100 kWh were considered.

3. Results and discussion

The results obtained are analysed in terms of the characterization of the Portuguese mobility patterns; the impacts of the shift to electric mobility concerning each of the described scenarios; and the optimal distribution of BEVs for different shares of BEVs. The results of a sensitivity analysis on the capacity of BEVs batteries are also presented.

3.1. Characterization of the Portuguese mobility pattern

The four parameters analysed in this section are the number of commuters, distance of commute, average speed and time. For each of the last three parameters, a quartile distribution is shown, by quantifying average, maximum and minimum values. The first result deals with the number of commuters and the number of daily cars commuting. Table 3 shows, for each municipality as destination, the total number of commuters, the total number of commuters by car, the number of daily commuters by car, the number of cars commuting and the number of cars commuting daily.

The results show that approximately 73% of the total commutes are made by car and 61% of the total commuters travel by car daily. The municipality presenting the highest percentage of daily commuters by car is Santarém (73%) and the lowest percentage is found for the municipality of Bragança (19%). Furthermore, the number of cars commuting and the number of cars commuting daily are only 52% and 43% of the total number of commuters, respectively. Out of all the cars used for commuted, only 41% are used for daily commutes, ranging between 91% for Porto and 21% for Bragança.

Table 3 – Sample assessment

Municipality	**Total commuters**	**Commuters by car**	**Daily commuters by car**	**Cars commuting**	**Daily cars commuting**
Aveiro	27923	23617	19338	17414	14024
Beja	5548	4665	2536	3589	1871
Braga	28347	22105	20363	15824	14399
Bragança	5531	4848	1060	3817	805
Castelo Branco	4827	4264	2050	3405	1539
Coimbra	47380	39347	27832	28902	20298
Évora	9869	8364	4781	6239	3410
Faro	16811	14559	11870	10746	8533
Guarda	4640	4175	2452	3321	1853
Leiria	17882	15476	12515	11669	9268
Lisboa	425747	282044	243533	202225	174155
Portalegre	3775	3372	1830	2638	1353
Porto	171738	127628	116996	90060	82188
Santarém	10559	9053	7662	6623	5460
Setúbal	16409	11623	10120	8551	7266
Viana do Castelo	8989	7237	6374	5335	4606
Vila Real	9496	7866	4428	5891	3158
Viseu	10727	9001	6055	6872	4500
Total	826198	599244	501795	433121	358686

Concerning distance, Figure 3 shows the quartile distribution of the commutes for every municipality in study. The municipalities showing the lowest values for average distance are Porto and Lisboa with values of 42 km and 45 km, respectively. On the other hand, Bragança and Castelo Branco account for the highest values for average distance, with 101 km and 102 km respectively. The average commute for all the studies municipalities is of about 51 km.

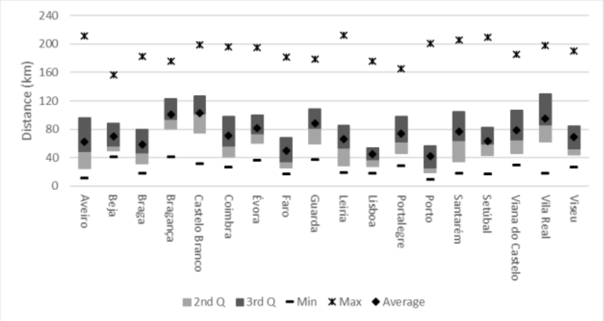

Figure 3 - Quartile distribution of distance

The quartile distribution of travel time for each municipality is shown in Figure 4. The average daily commute for the studied municipalities was found to take approximately 52 minutes, considering go and return. Municipalities such as Porto and Lisboa present the lowest values of time in commute, 42 and 52 minutes respectively. Once again, Castelo Branco and Bragança represent the highest averages, 79 minutes and 88 minutes respectively, for the daily commute. It is important to point out that inner-municipality commutes were not taken into account (since this data is not available) leading to a certain overestimation of commute times. The maximum time for all municipalities is naturally 120 minutes, equivalent to 2 hours, which was the threshold defined for the daily commute.

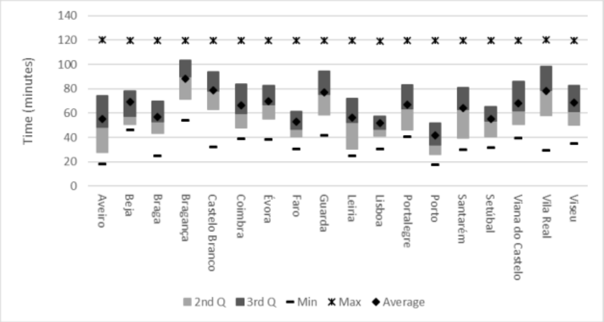

Figure 4 - Quartile distribution of time

Additionally, Figure 5 shows the quartile distribution of commuting average speed for each municipality. The highest average speed value was 91 km/h in the municipality of Castelo Branco and the lowest average speed value, 62 km/h, was registered in the municipality of Faro. The average speed for the considered municipalities was found to be approximately 69 km/h.

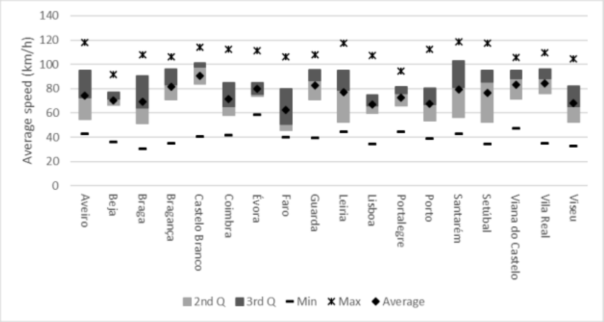

Figure 5 – Quartile distribution of speed

Lisboa and Porto are the municipalities which present the shorter commutes whether in time or distance, while Bragança and Castelo Branco present the longest commutes on both parameters. Also, concerning average speed, higher speeds tend to be associated to larger distances due to utilization of highways. However, optimal speeds for fuel consumption are considered to be from60ºkm/h to 80 km/h [16], which may have an impact in energy demand.

It is also worth mentioning that data collection for this study was performed in off-peak hours in order to obtain free flow driving conditions, which certainly benefits regions where intense traffic exists, such as Lisboa and Porto. In these regions, the travel times in peak hours could increase significantly while the average speed would decrease. Another less expected impacted could be the change in optimal routes to perform the commute, in order to avoid traffic.

3.2. Impacts of the shift to electric mobility

Taking into consideration the described scenarios, an assessment of the impacts of the utilization of BEVs will be performed regarding energy consumption and number of vehicles. The results are analysis in terms of the geographic distribution of energy demand, the total energy demand, the share of energy demand that is due to BEVs, the charging needs at origin and destination locations, and, finally, the number of commuters that could shift to BEVs.

3.2.1. Geographic distribution of energy demand

The following figures present the quartile distribution of energy consumption (in MJ) for the three considered scenarios. Figure 6 shows the quartile distribution for energy consumption for the Baseline Scenario. The total average energy consumption of all 18 municipalities is of 81.3 MJ per vehicle for a daily commute. The total average energy consumption presents a wide variability, showing minimum average values for Porto and Lisboa (representing 66.4 MJ and 72.5 MJ respectively) and higher values for Castelo Branco and Bragança (reaching 165.9MJ and 159.2 MJ respectively).

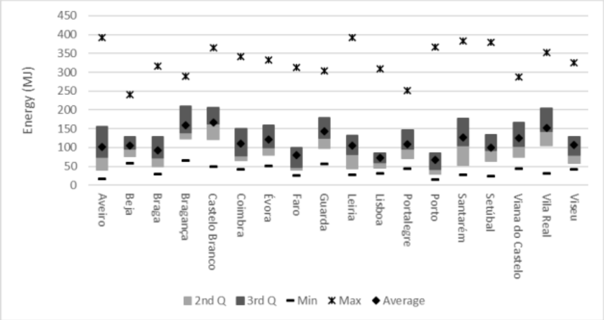

Figure 6 - Quartile distribution of energy consumption for baseline scenario

Figure 7 and Figure 8 show the quartile distribution of energy consumption for the scenarios including electric mobility, Scenario 1 and Scenario 2, respectively. When comparing the results of Scenario 1 (Figure 7) to the Baseline Scenario (Figure 6), there is a noticeable decrease in average energy consumption (on average 37% lower). However, the maximum energy consumption is unaltered. This result is explained by the use of BEV for shorter distances, where energy consumption is lower, decreasing the average energy consumption but without changing maximum values for which conventional vehicles account for. The lowest average energy consumption is obtained for Lisboa, with an average of 37.5 MJ per commute, whilst the highest value for average fuel consumption is obtained for Castelo Branco, with 149.6 MJ per commute. The total Portuguese average energy consumption for Scenario 1 is of 51.2 MJ accounting for an approximate decrease of 30.1 MJ when compared to the Baseline Scenario.

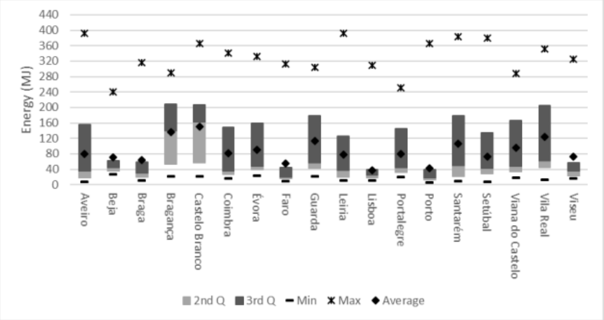

Figure 7 - Quartile distribution of energy consumption for Scenario 1

As expected, a further reduction of the average energy consumption values is observed (on average 23% lower) for Scenario 2 (Figure 8). Again, the maximum values for energy consumption remain untouched, mainly because they represent commutes done by internal combustion engine vehicles (ICEV) which a BEV, with 24 kWh battery, cannot travel. For Scenario 2, the average Portuguese energy consumption is of 38.5 MJ, 15.7 MJ lower when compared to scenario 1 and 45.8 MJ lower than the baseline. Porto and Lisboa, with 31.5 MJ and 32.1 MJ respectively, show the lowest values for average energy consumption, while Vila Real, with 101.0 MJ, represents the highest value for average energy consumption.

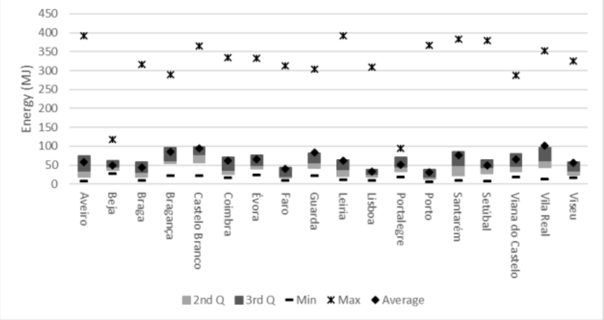

Figure 8 - Quartile distribution of energy consumption for scenario 2

More peripheral municipalities (such as Bragança and Castelo Branco) show higher values for average energy consumption in all Scenarios, mainly due to poor road infrastructure which limits speed and increases energy consumption. Also, the need to travel further and at higher speeds, in order to commute to more economically developed areas, increases energy consumption drastically.

3.2.2. Total energy demand

As expected, the Baseline Scenario was found to be the one with the highest values for energy demand. Table 4 shows the estimated total demand and average demand by car in the Baseline Scenario for each municipality under analysis. As expected, the municipalities with higher number of cars commuting were found to be responsible for the larger shares of energy demand. However, it is interesting to see that the average energy demand by car varies between 66,4 MJ for Porto and 165,9 MJ for Castelo Branco, which are also the municipalities with the lowest and highest average distance travelled, respectively.

Table 4 - Total energy demand and average demand by car for the baseline scenario per municipality

Municipality	Total energy demand (GJ)	Average energy demand by car (MJ/car)
Aveiro	1427.8	101.8
Beja	197.4	105.5
Braga	1342.0	93.2
Bragança	128.1	159.1
Castelo Branco	255.3	165.9
Coimbra	2259.3	111.3
Évora	415.8	121.9
Faro	684.2	80.2
Guarda	264.8	142.9
Leiria	982.7	106.0
Lisboa	12633.1	72.5
Portalegre	146.8	108.5
Porto	5455.7	66.4
Santarém	693.5	127.0
Setúbal	730.8	100.6
Viana do Castelo	577.3	125.3
Vila Real	482.3	152.7
Viseu	480.3	106.7

Figure 9 presents the estimated total energy demand of Scenarios 1 and 2 when compared to the Baseline Scenario. It is interesting to notice that, if it is considered that electric vehicles can only charge at home (Scenario 1), only the municipality of Lisboa would reduce the energy demand by almost 50%. All other municipalities would only reduce by at most 33% (Porto), with four of them (Bragança, Castelo Branco, Santarém and Vila Real) not reducing more than 20%. However, if it is considered that electric vehicles can charge within the municipality (Scenario 2), the savings achieved would be higher than 40%, apart from Santarém which would nonetheless be very close.

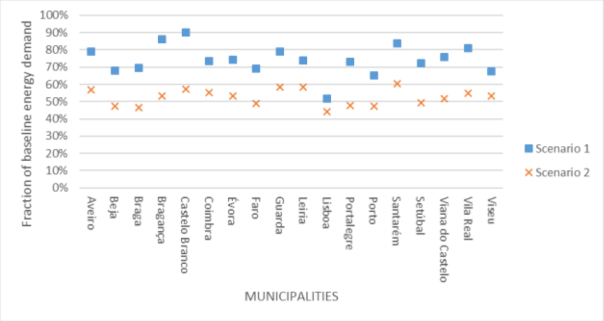

Figure 9 - Fraction of baseline total energy demand per municipality for scenarios 1 and 2

3.2.3. Share of energy demand consumed by BEVs

The share of energy demand consumed accountable to BEVs was also assessed, as is presented in Figure 10.

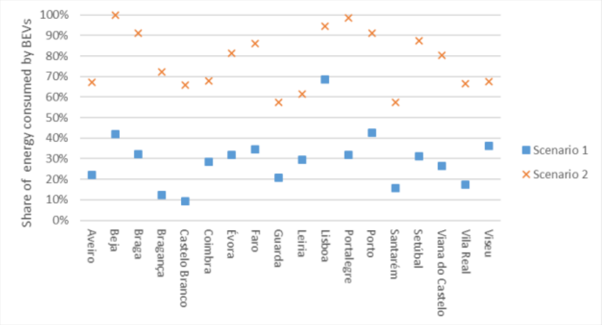

Figure 10 - Share of energy consumed by BEVs per scenario

For Scenario 1, Lisboa is the municipality accounting for the highest share of energy consumed by a BEV (with 69%), whilst for Scenario 2 the highest share is 100% for Beja. The 100% share means that all people travelling to Beja may already commute daily using an EV because their energy needs are satisfied. The lowest shares of energy consumed by BEVs are seen for the municipalities of Castelo Branco (9%) and Bragança (12%) for Scenario 1, however, for Scenario 2, Santarém with 57% and Guarda with 58% represent the lowest values. Analyzing total values, the average share of energy consumed by BEVs in Scenario 1 is of 45%, while for Scenario 2 it is of 85% of total consumed energy.

3.2.4. Municipalities and parishes charging needs

Table 5 summarizes the charging needs at the origin and destination for each municipality under analysis and for both Scenarios 1 and 2.

Table 5 - Total charging needs (kWh) at parish and municipality level for Scenario 1 and Scenario 2

Municipality	Scenario 1	Scenario 2		Total Parish
	Parish	Parish	Municipality	
Aveiro	69526	109133	42042	69526
Beja	15544	21008	5015	15544
Braga	83490	123548	35009	83490
Bragança	3779	9196	4471	3779
Castelo Branco	6020	15822	11002	6020
Coimbra	131334	180931	54441	131334
Évora	27395	38799	11375	27395
Faro	45223	62742	17612	45223
Guarda	11956	19354	5365	11956
Leiria	59636	78159	20363	59636
Lisboa	1243207	1352158	114205	1243207
Portalegre	9452	14756	4455	9452
Porto	421190	534550	120554	421190
Santarém	25036	46558	20111	25036
Setúbal	45786	66489	21318	45786
Viana do Castelo	32118	48140	18228	32118
Vila Real	19037	34367	14637	19037
Viseu	32633	40351	7821	32633

While Scenario 1 considers only the possibility of BEVs charging at the origin of their trips (in this cases parishes), Scenario 2 considers that charging is necessary both at the origin (parish) and destination (municipality), which would result in an increase in electricity demand at both locations. This analysis allows municipalities to better understand how electricity demand would increase if they support the shift to BEVs and what type of investments in infrastructure would be required. However, it is also noticeable that most of the electricity demand would occur at the parish level (origin), with the estimated total energy needs in parishes being 5,3 times higher than the total energy needs in the municipalities for Scenario 2.

3.2.5. Share of commuters using BEVs

The share of cars commuting that could switch to BEVs in each scenario is shown in Figure 11. The lowest shares are observed for Castelo Branco in Scenario 1 (30%) and Guarda for scenario 2 (86%) following the same results obtained in Figure 10. For Scenario 1, Lisboa had the highest value with a share of 93 % of BEVs and for Scenario 2 Beja achieved 100%, in line with the results obtained in Figure 10. It should be noted, nonetheless, that the percentages of BEVs on the road are higher than the percentages of energy consumed by BEVs, as the commutes that require more energy would still be performed using conventional vehicles. Overall, 85% and 98% of the total cars commuting could be BEVs in Scenario 1 and Scenario 2, respectively. At the municipal level, the increase between both scenarios was found to range between 6% for Lisboa and 190% for Castelo Branco. Once again, it is also important to refer that all inner-municipality commutes are not taken into account, underestimating the number of cars commuting to each municipality.

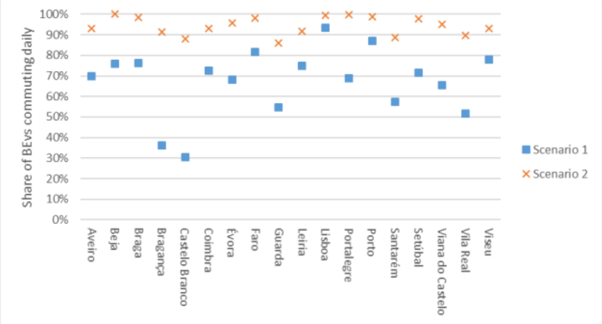

Figure 11 - Share of BEVs commuting daily per scenario

3.3. Optimal distribution of BEVs

Recognizing that a complete shift to BEVs might not be feasible to support due to numerous reasons, such as budgetary constraints, it is important to identify in which municipalities should BEVs be deployed in order to maximize energy savings if only a fraction of the potential BEVs could be replaced. Figure 12 (Scenario 1) and Figure 13 (Scenario 2) show this optimal distribution of BEVs per municipality, to maximize energy savings, for levels of implementation that range between 10% and 100% of the total potential BEVs that could be introduced in each scenario.

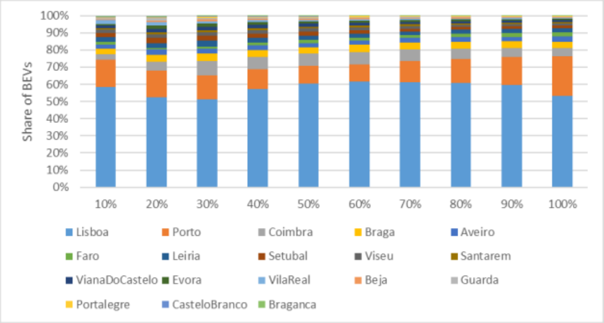

Figure 12 – Distribution of BEVs per municipality for Scenario 1 according to fraction of BEVs replaced

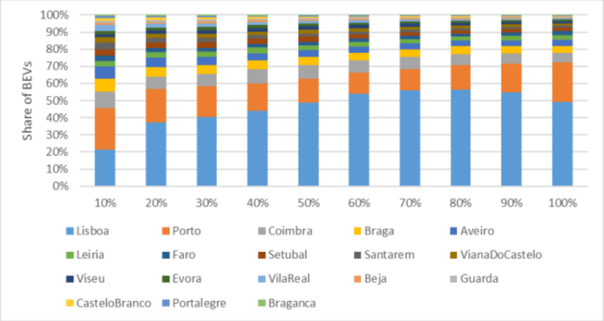

Figure 13 - Distribution of BEVs per municipality for Scenario 2 according to fraction of BEVs replaced

While for Scenario 1, Lisboa is the municipality that accounts for the highest percentages of BEVs for all fractions of BEV replaced, in Scenario 2 the percentages are more spread. In Scenario 1, Lisboa reaches its highest share of BEVs of 61.5%, for a replacement rate of 60%. On the other hand, based inFigure 13 , for a 10% fraction of BEV replaced, the top three municipalities are Porto (24%), Lisboa (21%) and Coimbra (9%). With higher fractions, the preponderance of Lisboa becomes noticeable, reaching its highest share of BEVs (56.5%) for an 80% BEV fraction.

Figure 14 presents the obtained energy savings resulting from each of the studied fractions of potential BEVs that could be replaced for Scenario 1 and Scenario 2. Naturally, for higher BEV fractions, higher savings are obtained from the utilization of BEVs. However, this increase is non-linearity for both curves since in this analysis it is considered that the first vehicles to be replaced correspond to the vehicles in which higher energy savings would be obtained from shifting to BEVs.

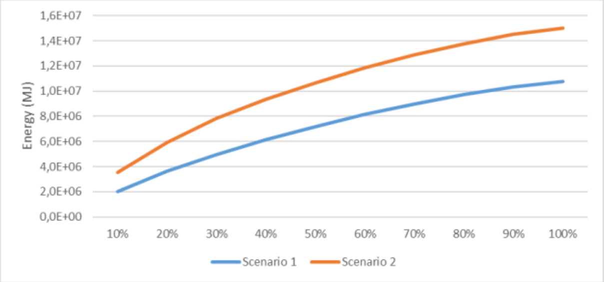

Figure 14 - Energy savings for different fraction of BEVs replaced for Scenarios 1 and 2

3.4. *Battery capacity sensitivity analysis*

A sensitivity analysis on the considered battery capacity was also performed. The battery capacity variable was established at 24 kWh based on the current vehicle market, but it is expected that battery capacity may increase in the future. As such, the impact of having higher capacity batteries was considered, using the following values: 30 kWh, 60 kWh and 100 kWh. The results for potential total savings for the 18 municipalities based on this variation are shown in Figure 15.

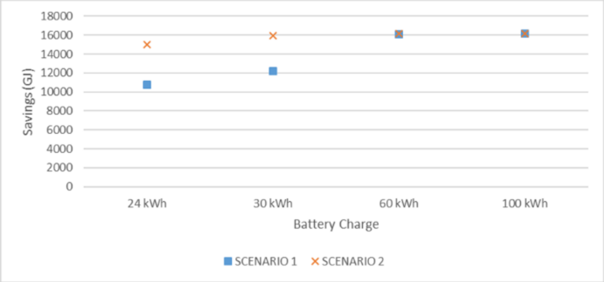

Figure 15 - Total savings per battery charge and per scenario

As expected, the total savings increase with the increase in battery capacity. However, when a charge of 60 kWh per battery is reached, Scenario 1 and Scenario 2 present almost the same result as the share of BEVs on the road is practically 100%, as can be seen in Figure 15.

4. Conclusions

The main objective of this work was to define a generic methodology to assess the impacts of using BEVs in regional commuting patterns. The presented methodology was applied to the municipalities of the 18 capitals of districts in mainland Portugal. For a regular battery of 24 kWh, energy savings of up to 37%, when compared to the Baseline Scenario, can be achieved in the case that all commutes done by BEVs use only a single battery charge for go and return trips (Scenario 1). For Scenario 2, which in addition to Scenario 1 accounts for commutes that could be done using a BEV if the vehicle is recharged at the destination of the commute, a reduction of up to 51.5% in energy consumption can be obtained. This would result in energy savings of 10790GJ in Scenario 1 and 15028GJ in Scenario 2.

This study focused on daily commutes, taking into consideration that about 98% (Scenario 2) and 85% (Scenario 1) of people that were assumed to commute daily to the 18 studied municipalities are suited to use BEVs. This shows that BEVs may already be a viable alternative to ICEV. Moreover, BEVs result in zero local emissions and, with a stable development of renewable based electricity production systems, these saving may also represent reductions in terms of life cycle emissions. Furthermore, using the obtained results, it is possible to evaluate the applicability of BEVs in different regions. For each region, the charging needs at the parish and municipality levels were quantified for the considered scenarios, with the results showing the charging needs in the origin parishes would be more than five times higher than those at the destination municipalities.

It is important to note that the obtained results for total energy demand and savings might be explained by different socio-economic conditions of the municipalities such as proximity to employment areas, access to public transportation and road infrastructure, but also orography. The municipalities of Castelo Branco, Bragança and Vila Real present the highest values for average energy consumption, not only due to their peripheral location, but also due to poorer road infrastructures which limit commuting and thus increase energy consumption. Also, the proximity to mountains in the referred municipalities, increases fuel consumption.

On the other hand, for municipalities that have big metropolis, such as Porto and Lisboa, and where road infrastructures are better, the average commute to employment areas was found to be shorter. As such, for Scenario 2, Lisboa and Porto could achieve savings of 55.7% and 52.5% of their total energy demand in the Baseline Scenario. These are also the municipalities which account for 71% of the total cars commuting daily (of the 18 municipalities) and, therefore, represent the higher results for total potential energy demand decrease in absolute values from the shift to electric mobility.

When evaluating the optimal distribution of EVs between the municipalities considered to maximize energy demand reduction, 10 different replacement rates ranging between 10% and 100% of total BEVs replaced were considered. The results show that the total savings when accounting for the 18 municipalities may rise to 6.8% (Scenario 1) and 12.4% (Scenario 2) of the total Baseline Scenario energy demand for a 10% replacement, while for 20% values of 12.4% (Scenario 1) and 20.4% (Scenario 2) could be achieved.

In order to determine the impact that the current battery capacity had on the results, a sensitivity analysis was performed. The results demonstrated that if the battery capacity of BEVs reaches values of 60 kWh, almost 100% of the vehicles used for commutes could be BEVs and might not require the recharging of the vehicles at the destination municipality.

5. References

[1] E. European Comission, “Reducing emissions from transport/ Transport.” [Online]. Available: http://ec.europa.eu/clima/policies/transport/.

[2] E. European Comission, “2020 climate & energy package.” [Online]. Available: http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm. [Accessed: 01-Jan-2016].

[3] E. Parliament, “DIRECTIVE 2009/29/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009,” *Off. J. Eur. Union*, vol. 140, pp. 63–87, 2009.

[4] European Parliament, “Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency,” *Off. J. Eur. Union Dir.*, no. October, pp. 1–56, 2012.

[5] European Parliament, “Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009,” *Off. J. Eur. Union*, vol. 140, no. 16, pp. 16–62, 2009.

[6] E. European Comission, “Reducing CO2 emissions from passenger cars.” [Online]. Available: http://ec.europa.eu/clima/policies/transport/vehicles/cars/index_en.htm.

[7] Europen Commission, “DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure,” *Off. J. Eur. Union*, vol. 12, no. April, pp. 1–38, 2014.

[8] MOBI.E Mobilidade Eléctrica, “MOBI.E Chraging Prices.” [Online]. Available: https://www.mobie.pt/o-carregamento.

[9] S. P. Instituto Nacional de Estatística, “Census,” 2011.

[10] T. MathWorks, “Matlab R2015b.” 2015.

[11] Google, “Google Maps API System,” 2016. .

[12] Google, “Google Maps API Directions,” 2016. [Online]. Available: https://developers.google.com/maps/documentation/directions/intro.

[13] Google, “Google Maps API Elevations,” 2016. [Online]. Available: https://developers.google.com/maps/documentation/elevation/start.

[14] J. L. Jiménez-Palacios, “Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing,” no. 1993, p. 361, 1999.

[15] H. A. C. Martins, “Definição e avaliação de ciclos de condução representativos de condições reais de utilização em diferentes contextos urbanos,” Instituto Superior Técnico, 2016.

[16] EMISIA, “COPERT 4.” 2015.

[17] European Envirnoment Agency, “Monitoring of CO2 emissions from passenger cars - Data 2015.” 2015.

[18] A. Associação Automóvel de Portugal and Auto Informa, “Estatísticas do Sector Automóvel,” 2015.