TÉCNICO LISBOA

Assessing the potential of electric vehicles for commutes in Portugal

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Thesis to obtain the Master of Science Degree in

Mechanical Engineering

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October 2016

Acknowledgments

To Professors Patrícia Baptista and André Pina for their patience and understanding, but more importantly for their passion. I wish to thank them for opening my mind to new themes and reasonings.

My friends whom I owe the person I am today and the one I will always be. For their unconditional friendship and inspiration.

To my family for their never ending support and motivation throughout my life but also for inculcating in me values and principles I cherish so much.

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

Resumo

Tendo em conta que o sector dos transportes é um dos mais poluentes e consumidor de energia, este trabalho foca-se na avaliação do uso de veículos eléctricos para movimentos pendulares, estimando o consumo de energia associado. Foram considerados três cenários diferentes: o uso de novos carros convencionais (base), uma mudança parcial da frota para BEVs com baterias de 24ºkWh considerando carregamento em casa (cenário 1) e considerando uma combinação de carregamento em casa e no trabalho (Cenário 2). Avaliando 18 municípios portugueses, foi estimado que podem ser alcançadas poupanças energéticas de 37% para o cenário 1 e 52% para o cenário 2, sendo Lisboa o município que mais beneficia da mudança para mobilidade eléctrica alcançando poupanças de 48% (cenário 1) e 56% (cenário 2). Se forem considerados BEVs com 60ºkWh de bateria, a poupança energética aumentará para 55% do total de energia do cenário base e 99,9% dos viajantes diários de movimentos pendulares poderiam usar BEVs. Para além disso, os municípios onde os BEVs deveriam ser introduzidos foram identificados de modo a maximizar a poupança de energia se apenas uma fracção dos BEVs pudesse ser substituída. Com uma substituição de 10% dos veículos por BEVs poder-se-ia alcançar valores de 6.9% (cenário 1) e 12.1% (cenário 2) de poupança energética. Finalmente, a avaliação dos diferentes cenários permite analisar as necessidades de carregamento locais, com potenciais impactos na definição de politicas locais.

Palavras Chave: padrões de movimentos pendulares; veículos eléctricos; poupanças energéticas; alcance do EV

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Nomenclature

ACAP – Associação Automóvel de Portugal

ACEA – European Automobile Manufacturers Association

API – Application-programming Interface

BEV – Battery Electric Vehicle

CI – Compressed Ignition

CV – Conventional Vehicles

EU – European Union

EV – Electric Vehicle

GHG – Greenhouse Gases

HEV – Hybrid Electric Vehicle

ICEV – Internal Combustion Engine Car

IEA – International Energy Association

INE – National Statistics Institute

LNG – Liquefied Natural Gas

PHEV- Plug-in Hybrid Electric Vehicle

SI – Spark Ignition

VSP – Vehicle Specific Power

1. Introduction

1.1. Motivation

The transportation sector is currently one of the most energy consuming and polluting sectors, accounting for around 31,6% of the total final energy consumption and about a quarter of GHG emissions in Europe [1]. Since 2000, emissions and energy consumption have increased by 28% in this sector [2], and, unlike other sectors, has only seen a decrease in emissions in 2007 [3]. Therefore, the continuous search for energy efficiency and mitigation of environmental impacts is of vital importance and has been promoted through EU regulations [4], such as CO_2 reduction targets for new passenger cars [5].

Furthermore, 93% of the total final energy consumption for transportation comes from oil [2], justifying the need for the promotion of energy source diversification in this sector. This suggests that there is a huge unbalance in the transportation sector, which must be counteracted with alternative, cleaner and more efficient vehicle technologies or energy sources. Figure 1 presents the transport sector dependence on oil originated fuels such as diesel and petrol. Recent data [6] reveals an increase from 45.4% of the total 2252 Mtoe in 1973 to 63.8% of the total 3716 Mtoe in 2013 worldwide for the amount of energy spent by the transportation sector. Increasingly more and more energy is being consumed all over the world and its impacts are increasing substantially, justifying the need for future mitigation.

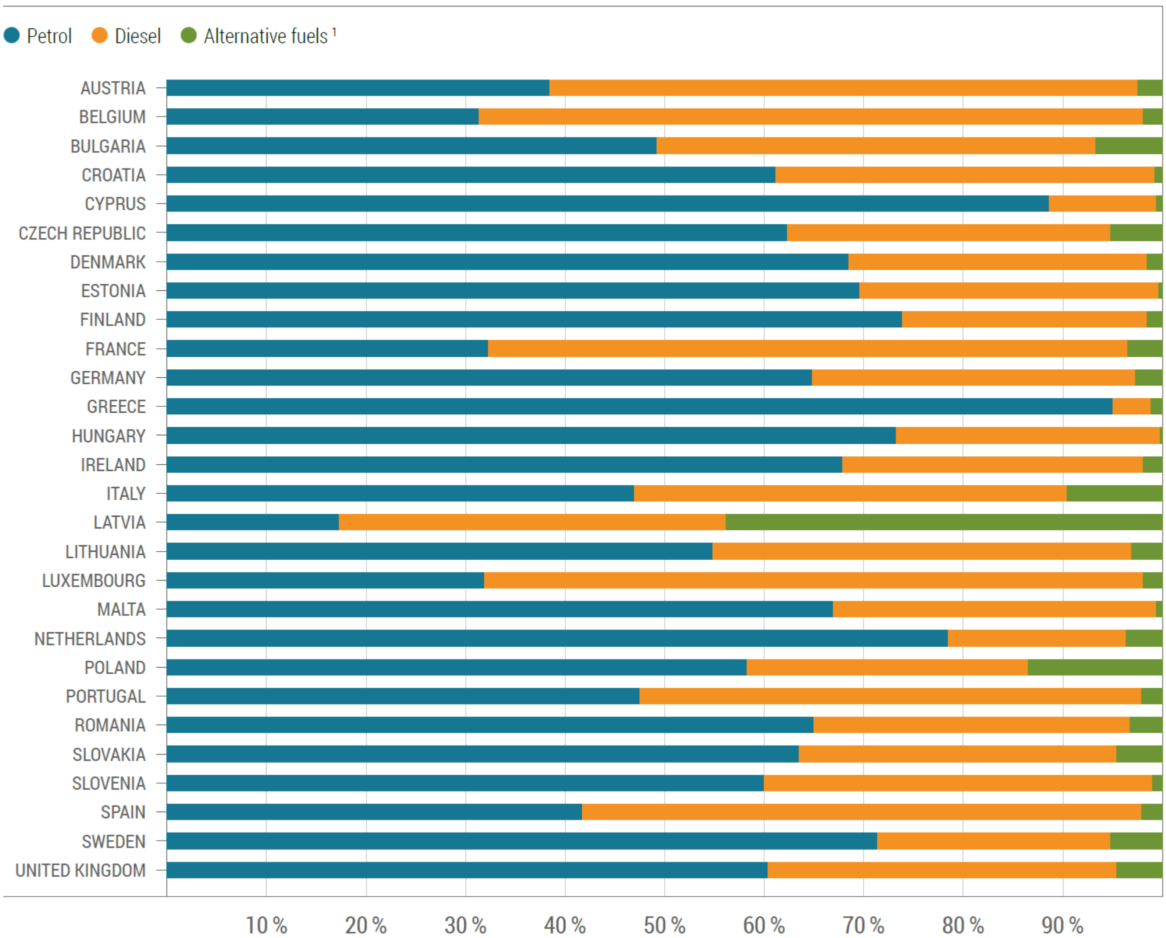


Figure 1 – Passenger car fleet by fuel type 2014 [7]

Consequently, today's transport sector is undergoing constant change to overturn the presented trends, mainly due to rapid improvements of current vehicle technologies and the introduction of alternative vehicle technologies and energy sources. Among the alternatives in transportation are the battery electric vehicles (BEV), hybrid vehicles, whether plug-in (PHEV) or full hybrid (HEV), extended-range electric vehicles (EREV) natural gas powered cars (NG), biofuel and hydrogen fuel cells. Also, other kinds of transportation models are flourishing, such as the shared mobility systems carsharing and bikesharing, which represent a viable inner city transportation [8].

In this context, BEVs is one of the most discussed options [9]. Besides being more efficient than an engine powered car, reaching efficiencies from 85% up to 90% [10], BEVs result in zero local emissions, and even when accounting for the electricity production stage they have the potential to be considerably lower [11]. Furthermore, their operational costs are approximately 25% lower than an internal combustion engine car [12]. However, they typically present higher purchase costs [10], making this technology dependant on utilization and incentives to become economically viable on the long-term when compared to conventional technologies. EVs are being considered increasingly more suited for day-to-day use and already present themselves as a valid alternative to conventional transportation as shown in the "Green e Motion Project Results" [13], which demonstrated that EVs in fleets already show a positive business case in some situations such as office cars, taxis, urban buses and urban deliveries.

Looking deeper into the performance of BEVs, they show great dependency on trip characteristics [14]. Range, weather, speed and road grade are all features which condition the effectiveness of BEVs. Some of these limitations hamper BEVs from fully complying with current transportation needs, mainly due to range limitations. Furthermore, refuelling/recharging infrastructures that allow ICEVs to travel freely, are still not available for BEVs.

Consequently, for BEVs to become an effective option, an increase of battery lifetime is needed and recharging infrastructure should be standardized and wider spread, as it will be later discussed in this work. This framework justifies the need for a better understanding of the possible suitability of BEVs according to current mobility patterns, in order to assess its potential impacts.

1.2. Objectives

The main objective of this thesis is to assess the potential impacts of a shift to electric mobility for daily commuting mobility patterns, applied to 18 cities in Portugal. To achieve this objective, the following specific goals were established:

- Develop a methodology to characterize mobility patterns of commuters taking into consideration distance, time, speed and road grade and estimate energy consumption;
- Estimate the potential impacts of using BEVs for commuting to the 18 cities considered, for different scenarios, in terms of number of commuters impacted, energy savings and charging needs;
- Determine the optimal locations for supporting BEVs for commutes;
- Perform a sensitivity analysis on battery size.

1.3. Thesis Outline

Chapter 1 introduces the motivation and the objectives considered for this work. A state-of-the-art on electric mobility is presented in Chapter 2, focusing on the current situation of the shift to electric mobility and policy context, as well as studies regarding the future impacts of EVs deployment. Chapter 3 presents the method and data used in this work, followed by the scenarios designed. The results obtained from applying the developed methodology are shown in Chapter 4, focusing on the number of commuters that could switch to electric mobility in each case study, the savings that could be obtained and the increase in electricity consumption for charging of BEVs. A sensitivity analysis on the battery capacity of BEVs is also performed. Finally, the main conclusions and suggestions for future work are presented in Chapter 5.

2. State-of-the-art

2.1. The shift to electric mobility

The shift to electric mobility all over the world has been slow, with electricity based technologies accounting for only 1.35% of total EU new vehicle registrations in 2015 [15]. PHEV sales have reached 0.94% of the total sold cars in 2015 and BEV only 0.41%, accounting for 56.818 sold vehicles [15].

In Europe, some countries have adopted BEVs and PHEVs at higher rates, namely, Norway and Netherlands. As seen in Figure 2, in 2015 Norway has greatly surpassed all the other European countries in terms of new registration of BEV and PHEV, with this market representing more than a quarter of total new vehicles sales [8].

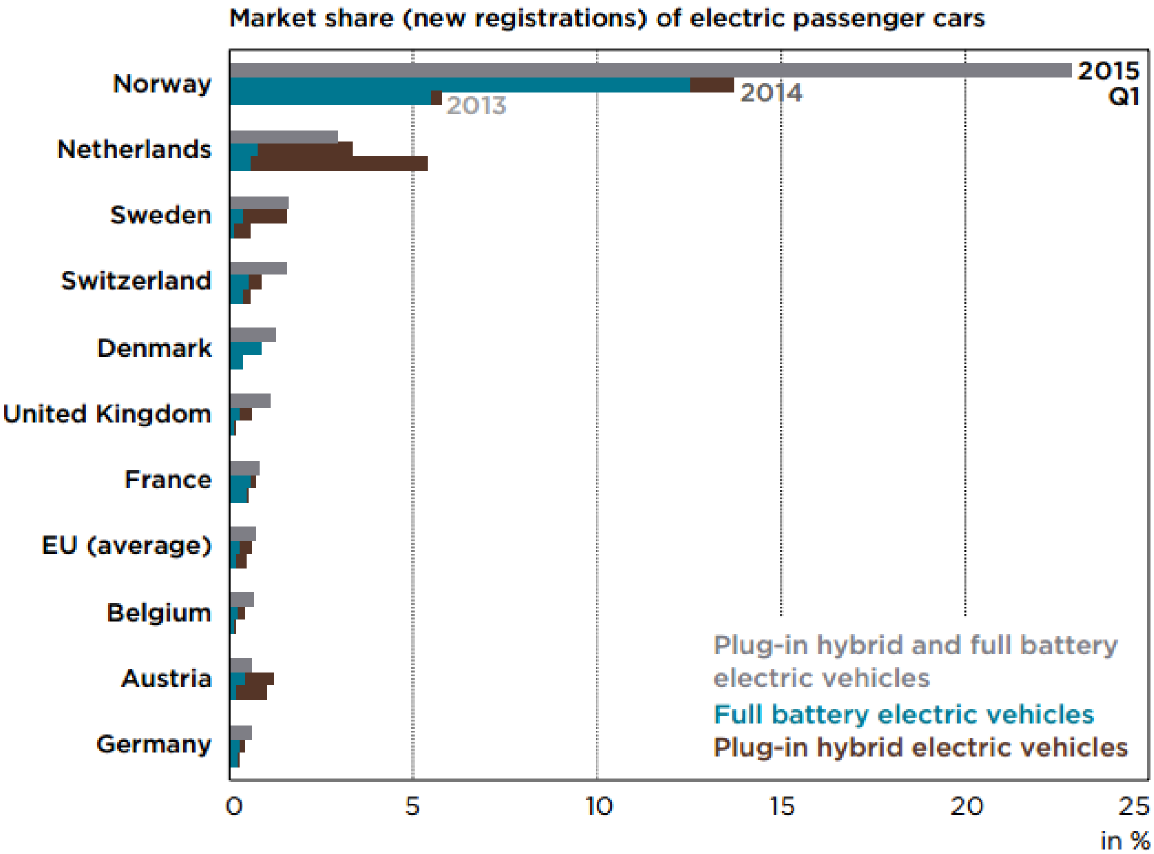


Figure 2 - 2013-2015 sales of electric vehicles [16]

This growth of BEV usage and sales is sustained by an increase of options with new automobile manufacturers and models appearing in the market. In Europe, in 2011, only two models of PHEVs were available in the market and only 2000 were sold. Nowadays, more than 30 different types of hybrid and PHEVs are available and more than 200.000 were sold in the EU (in 2015), even though this only accounts for 1.4% of total sales. In Japan, for instance, for every 5 cars sold one is a hybrid [16].

The following Figure 3 shows the newly registered cars in 2015 for five different regions. In countries such as China and the USA, it is clear that there is a slow acceptance of electric mobility.

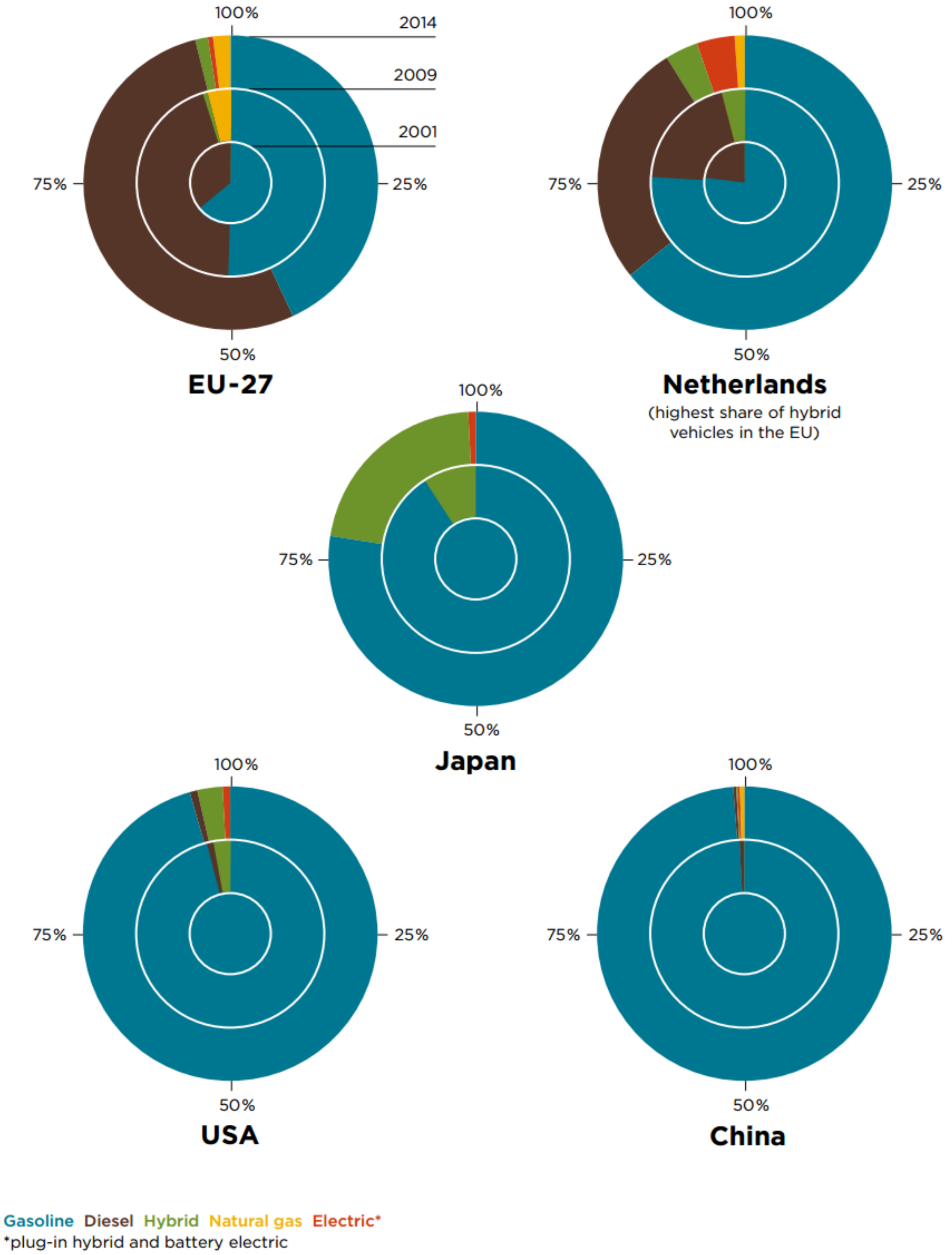


Figure 3 - Newly registered cars per type [16]

The main international organizations have assessed the expected adoption of electric mobility [17], pointing out a possible steep growth in non-petrol and non-diesel cars. One of those examples is the IEA BLUE Map Scenario

[17], which considers an increasing trend in sales until 2050, as shown in Figure 4. These predictions show a significant increase in PHEV and BEV sales, while conventional diesel and gasoline experience a steep decrease.

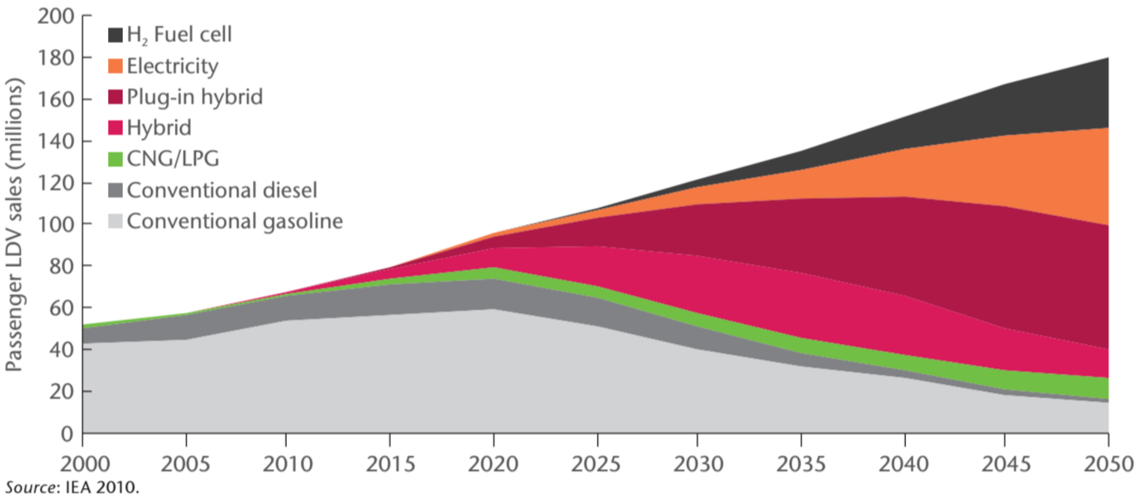


Figure 4 - Annual light-duty vehicle sales by technology type, BLUE Map Scenario [17]

All scenarios point out to an increase in EV sales mainly promoted by subsidies and incentives, falling battery costs, fuel economy regulations, growing commitments from car companies and rising interest of consumers. A study by McKinsey & Company [8] states that global EV sales have risen 60% in 2015. Also, comparing battery prices, the average priced lithium-ion batteries fell 65% over the period 2010-2015 continuing to drop due to scale economies, improvements in battery chemistry and better battery management systems. Figure 5 shows the growth of sales of electric vehicles from 2011 to 2015 and also the average battery pack price from 2010 to 2015.

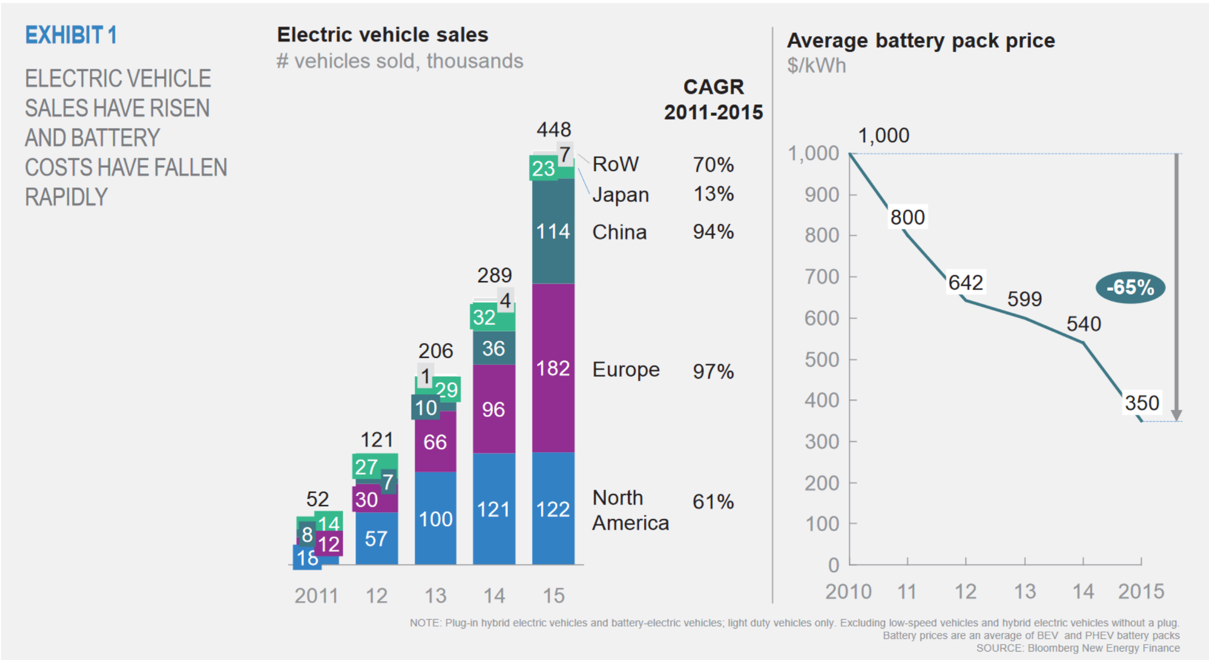


Figure 5 - Electric vehicles sales evolution from 2011 to 2015 and average battery pack price from 2010 to 2015 [8]

2.2. Policy context

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 [18]:

- 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 [19] 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 [20] 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 [21], 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 past 2015 target required a limit average emission of 130ºg/km, meaning a 5.6ºl/100 km fuel consumption for petrol or a 4.9ºl/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 [5].

Concerning alternative fuels infrastructure, the final directive [22] 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.

Also, building upon the 2020 package, the 2030 framework [23] sets three key targets for the EU near future:

- 40 % reduction of GHG emissions when compared to 1990;
- At least a 27% share of renewable energy consumption; and
- At least a 27% energy savings compared with the business-as-usual-scenario.

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 [24].

2.3. Evaluation of the impacts of electric mobility

Several studies have been conducted to evaluate the impacts of electric mobility, focusing on issues such as energy, emissions and influence on the grid, among others. A study conducted for the city of Beijing [14] concluded that the use of HEVs, PHEVs and BEVs could lead to a higher fuel reduction when compared to other countries' cities, such as in the U.S., reaching a maximum fuel reduction of 24,7% for PHEVs in China. These results, obtained with real-world driving cycles, are explained by the driving conditions of the Chinese city, characterized by low speeds, severe speed changes and short distance commutes. While conventional vehicles are more sensitive to these kind of conditions, electric vehicles are not, showing better results.

Another study performed the estimation of potential impacts of BEVs and PHEVs on climate change and urban air quality in the city of Dublin [25]. Three different scenarios were studied for the penetration of electric vehicles, to be compared to a baseline scenario: a high, medium and low penetration. Each of the examined scenarios was quantified in terms of net reduction of CO_2 emissions and tailpipe air pollutants. The baseline scenario projects a 6% emissions reductions on 2010 levels. The "high" and "medium" scenarios demonstrate that a reduction of 10% and 5% respectively could be achieved. Under the most probable scenario of a 10% penetrations of the EV, the possible net reduction of CO_2 is of 3%.

Another study by the European Union [26], divides the EVs (including PHEVs, BEVs and EREVs) penetration into three scenarios:

- Scenario 1 – The "most realistic" scenario based on current best estimations for costs and performance of EVs and conventional vehicles (CV). This scenario estimates 3.3 million EVs in the EU in 2020 increasing to more than 50 million in 2030;
- Scenario 2 – The EVs gain some market share, however remaining a fairly small part of the European fleet mainly due to increase in fuel efficiency of CVs, which therefore maintain their status. The predictions for 2020 are of about 2 million EVs increasing to 20 million in 2030; and
- Scenario 3 – This scenario accounts for a technological breakthrough in battery technology and, therefore, a market uptake in 2020, with EVs becoming competitive with CVs. This scenario's predictions point to a total of 5.5 million EVs in 2020 and 93 million in 2030, with EVs sales exceeding CVs in 2025.

The following figure shows the predictions according to the described scenarios.

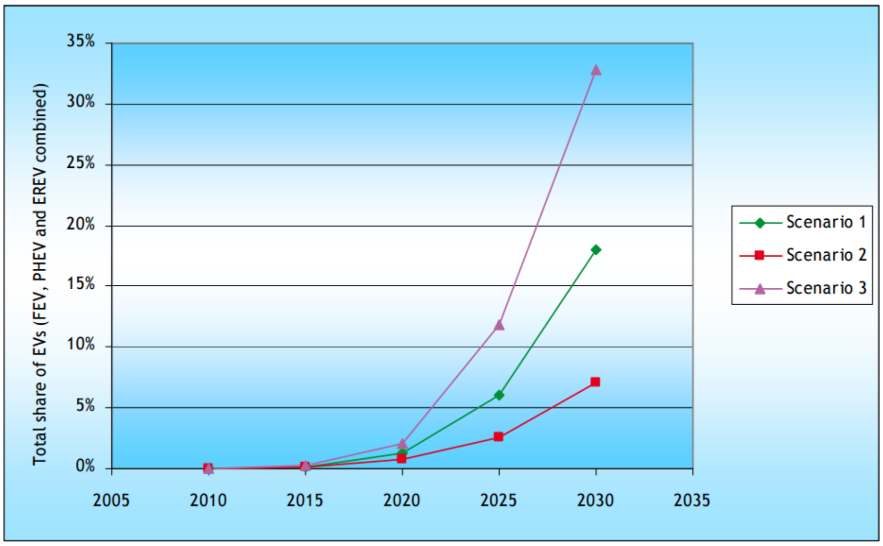
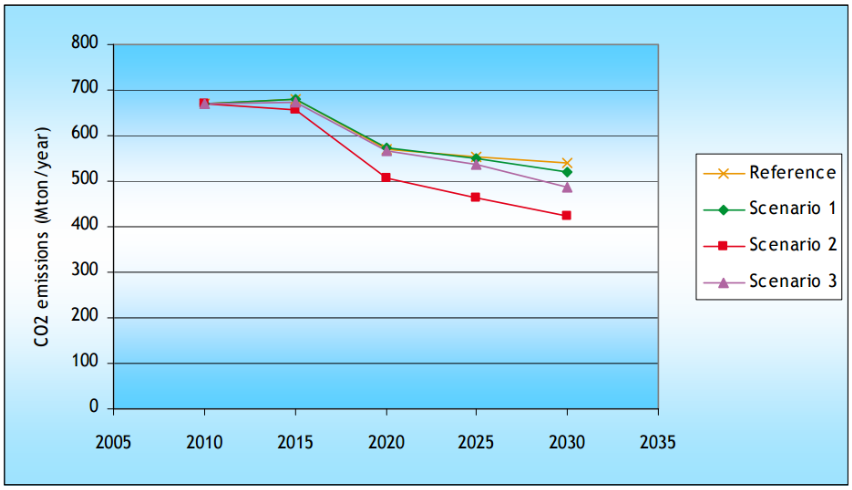


Figure 6 - Total share of EVs in the EU car fleet, BEVs, PHEVs and EREVs [26]

All scenarios point to an increase of EV share on the European car fleet, with Scenario 3 being the one where the EV penetration is higher. Figure 7 shows the net impact on CO_2 emissions in all three scenarios, as well as a Reference scenario. All scenarios lead to the conclusion that CO_2 emissions will decrease on a long term due to an increasing EV penetration, as seen in Figure 6, and due to tighter emissions regulations.



NB. Emissions from petrol and diesel are well-to-wheel, emissions from electricity include power production emissions only (not emissions due to e.g. coal mining or gas production).

Figure 7 - Net impact on CO_2 emissions from passenger cars in the EU (excl. effects of the EU ETS) [26]

A different study conducted life cycle emissions (LCE) for different kinds of vehicles [11] in Germany. The main results concern not only an electric shift in mobility, but also in energy production, by considering a realistic assessment of electric vehicle energy consumption, analysing electricity generation for charging of electric vehicles and finally presenting life cycle results. Electric vehicles charged with additional renewable energies were found to lead to significant improvement in the GHG balance, whereas other electricity sources led to no substantial improvements or even higher life cycle emissions. Figure 8 shows the estimated LCE for the different situations considered.

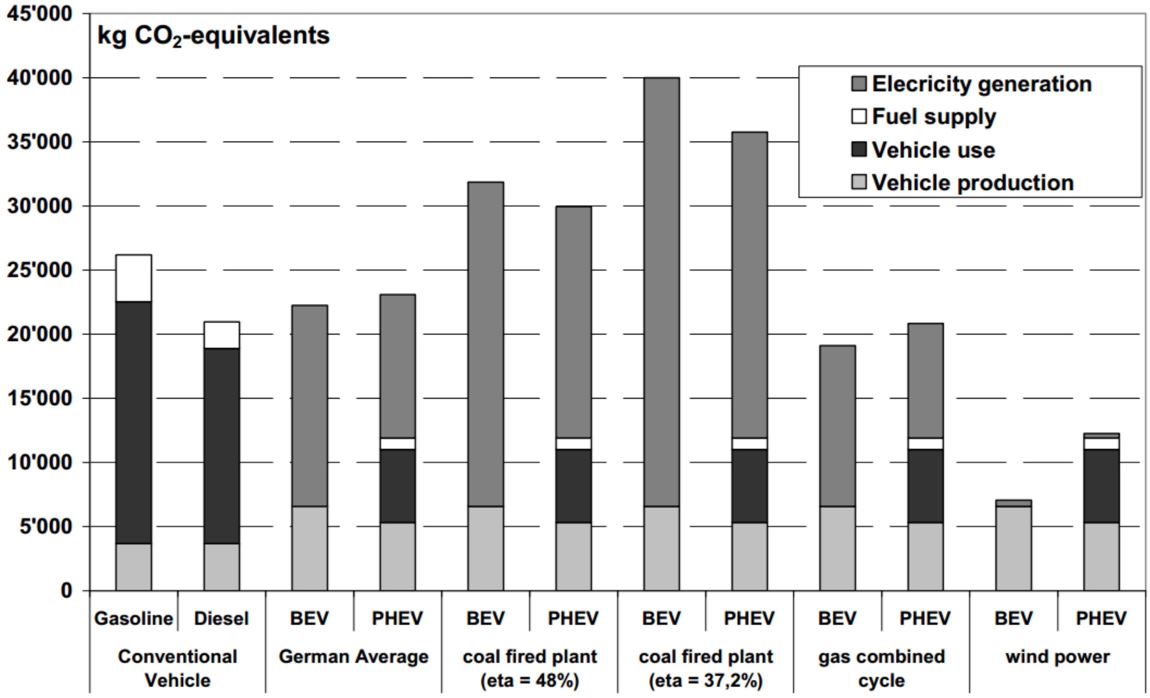


Figure 8 - Life cycle greenhouse gas emissions of a compact car with different drive trains (120.000km; 70% urban driving) [11]

Figure 8 suggests that the electric shift in the transport sector should be accompanied by a higher preponderance of renewable energy sources on electricity production in order to guarantee a decrease in CO_2 emissions. Naturally, the utilization of coal fired plants to produce electricity which will fuel BEVs and PHEVs will lead to an increase of the equivalent CO_2 emissions.

2.4. Regional analysis of electric mobility

The majority of the studies found in the literature focus on the general adoption of electric mobility, based on average distance per day, but do not consider the specific commute patterns and consequent impacts of electric vehicle use. Some authors have already examined regional differences in commute-energy performances, such as a study performed for Belgium [27] which divided the entire territory into three areas: Wallonia, Flanders and Brussels. The comparison between these areas is interesting to analyse due to differences in settlement density and economic characteristics. The results show that proximity to job markets is higher in Flanders and Brussels compared to Wallonia when comparing total energy consumed in commutes. Comparing Wallonia and Flanders, the last region shows lower values of energy consumption for home-to-work commuting. Differences within and between areas is explained by socio-economic factors such as population density, proximity to employment areas and access to public transportation. Between 1991 and 2001, urban centres show a decrease in commute-energy efficiency, while adjacent areas to big cities increased their commute-energy efficiency. These factors are explained by a decentralization of business outside the main urban agglomerations leading to shorter commutes in peripheral areas and thus less energy consumption.

Figure 9 shows the commute-energy performance index calculated for all census parishes in Belgium. This index evaluates the energy consumed in home-to-work commute in kWh per person per trip, and the figure shows that the average energy consumption is lower for Flanders when compared to Wallonia. In particular, the area of Brussels was found to be much more efficient than the others.

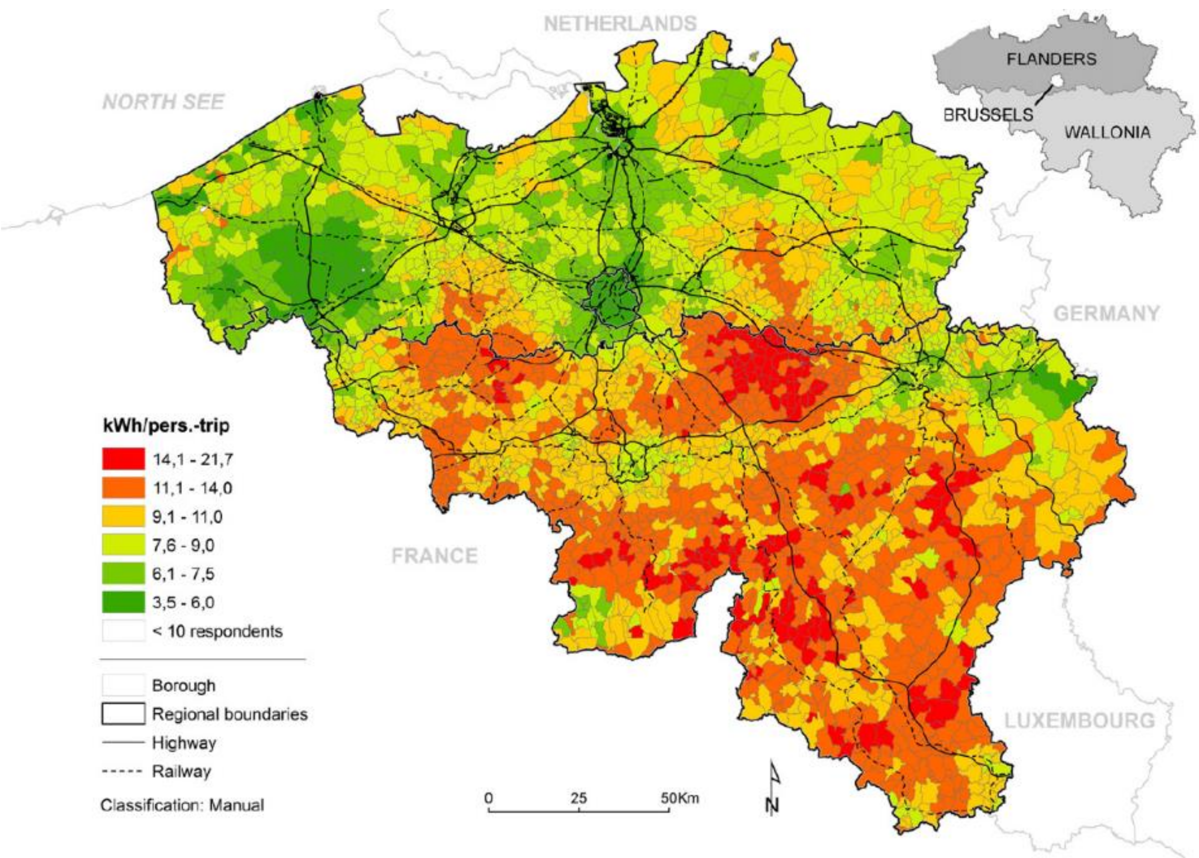


Figure 9 - Energy efficiency of home-to-work commuting in Belgium in 2001 [27]

Another study focuses on the electric mobility regional plan for the city Lombardia in Italy [28]. This study used the Systematica GIS platform and database by Deloitte S.p.a. to perform a feasibility analysis on the use of electric and hybrid vehicles in the region. Data concerning public transport accessibility and transport demand was taken into account. While the entire study is not available, some results are available which show that more peripheral areas consume more energy on day-to-day commutes and that better road networks decrease the energy consumption.

When analysing the shift to electric mobility, two main factors have great important: the reduced availability of vehicles in the market and lack of infrastructure. A first glance of the Portuguese fleet shows a quite small fraction of electric vehicles, representing less than 1% in 2015 [29]. According to data from the European Environment Agency [15], in 2015 179225 vehicles were sold in Portugal from which only 672 are electric (0.37% of total sales). The combination of hybrids and electric only accounts for 0,7% of the total vehicles sold in Portugal in 2015. According to information by ACAP [29] only in 2010 was the first lightweight passenger electric vehicle sold in Portugal and, by the end of 2013, only 441 electric cars had been sold nationally. In the first semester of 2016, following ACAP's information, 338 electric vehicles were sold, accounting for a 43% increase in sales when compared to the same period of 2015. Despite the increase, EVs only account for 1.45% of the total light-weight cars market.

When analysing EV infrastructure in Portugal, several efforts have been done in order to extend the charging stations network. Currently, according to MOBI.E's website [30], the responsible for the stations network in Portugal, there are 1173 standard charging stations and 15 fast charging stations. Other companies such as EDP MOP and Galp Energia own other charging stations. According to data retrieved from MOBI.E [31], there are in total 1173 standard charging stations spread along 39 cities, as shown in Figure 10. Lisboa and adjacent cities account for the highest number of stations, due to the potential of the region not only in terms of the number of people but also on the short distances of commute in the district. In total, these 1173 charging stations correspond to 3741 charging spots.

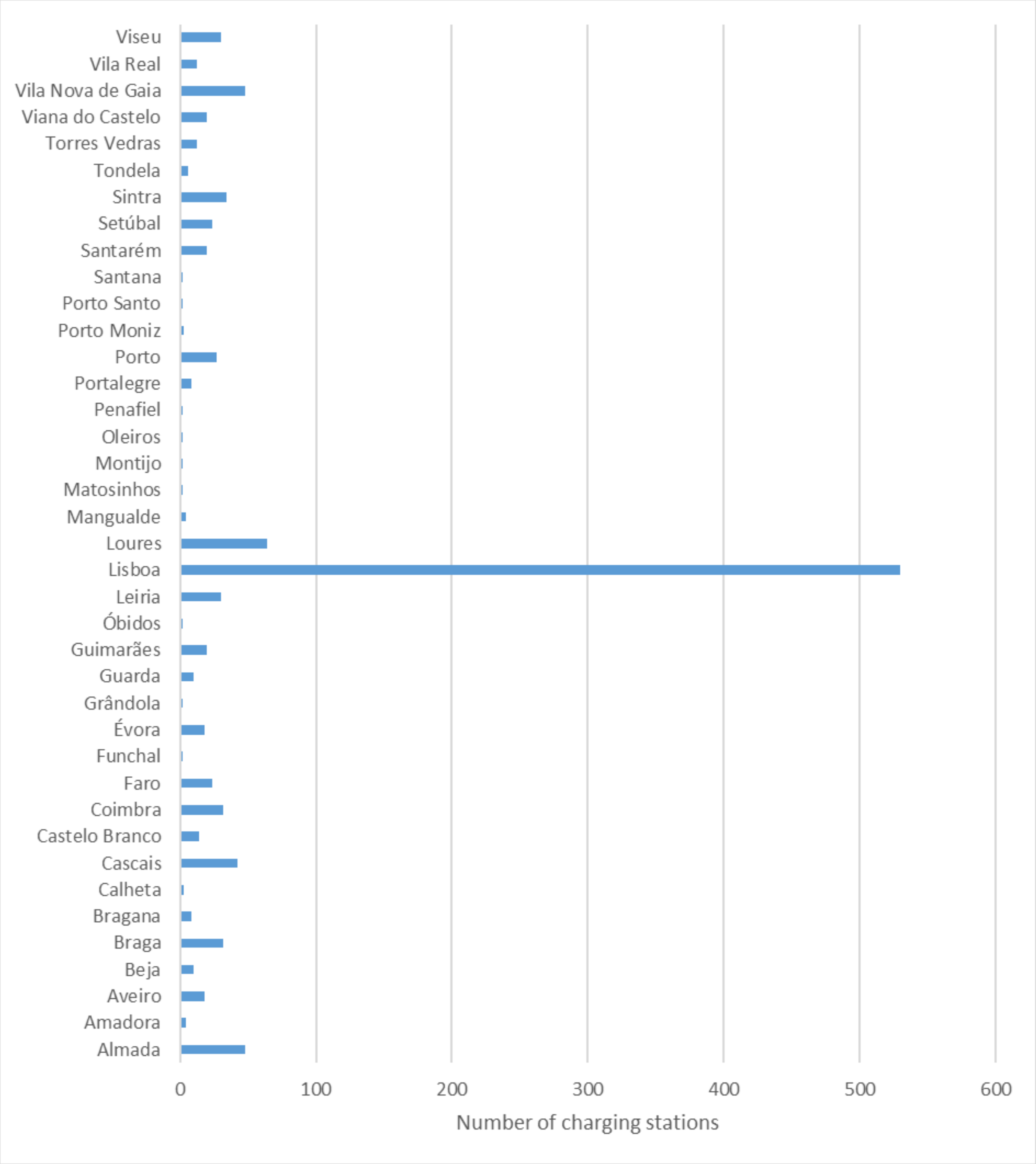


Figure 10 - Number of charging stations in Portugal

In addition to the 1173 normal charging stations, there are 15 fast charging stations spread through only three different cities: Azambuja (6), Oeiras (3) and Pombal (6). The number of charging spots from these 15 fast charging stations are 45. The number of fast charging stations is much lower than the standard ones, due to technical lateness and higher price.

The distribution of the existing charging stations in Portugal is shown in Figure 11. This figure shows the parish division in 2011, year of the last Census [32], and road infrastructure all over the country. The concentration of charging stations is higher in big metropolis and adjacent areas, such as Lisboa and Porto (as already discussed), but some cities such as Braga, Viana do Castelo and Coimbra also have a significant number of charging stations.

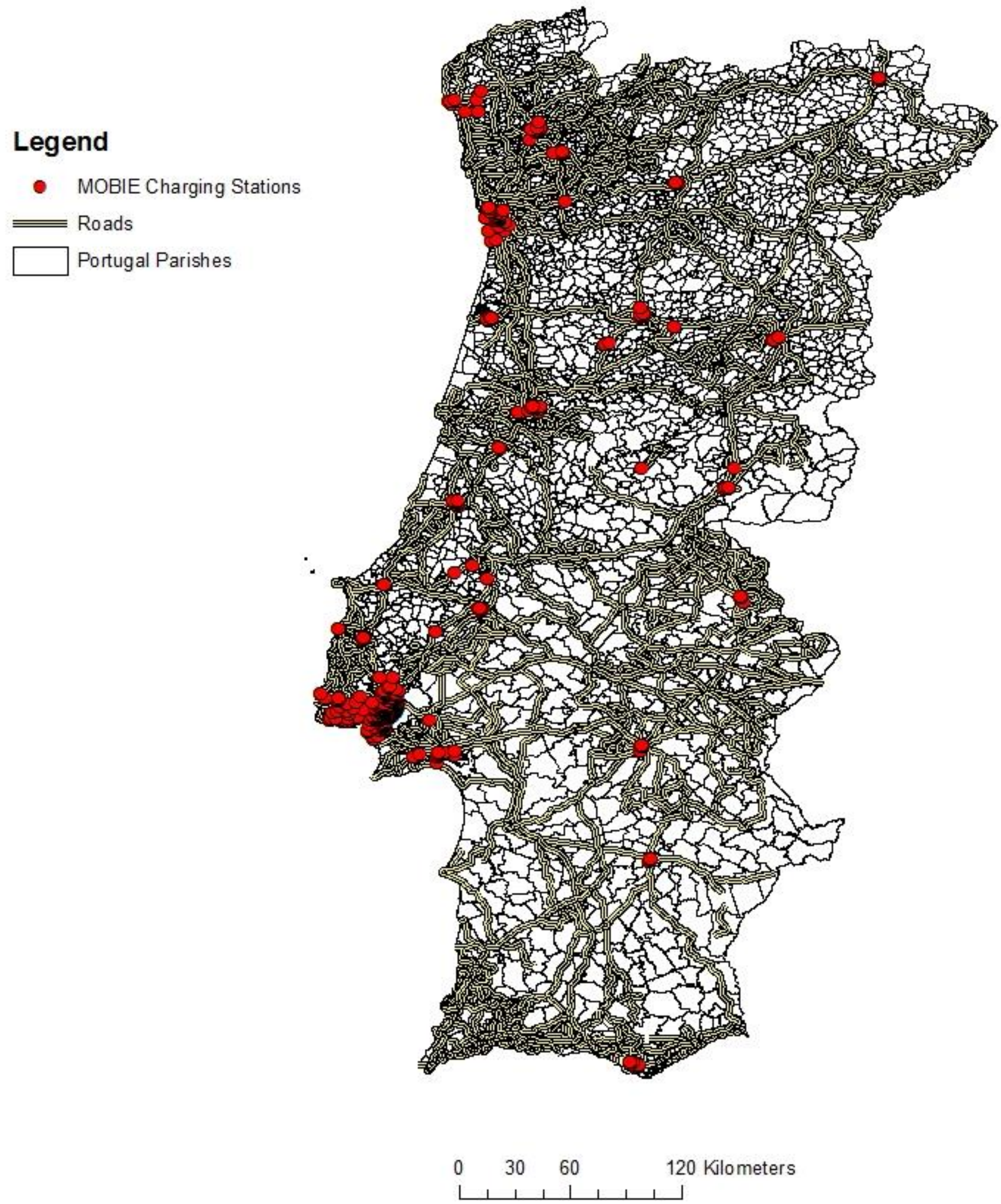


Figure 11 - Current MOBI.E charging stations network

3. Methods, key assumptions and data

3.1. Methodology

The main goals of the developed methodology is 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 (as shown in Figure 12): 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.

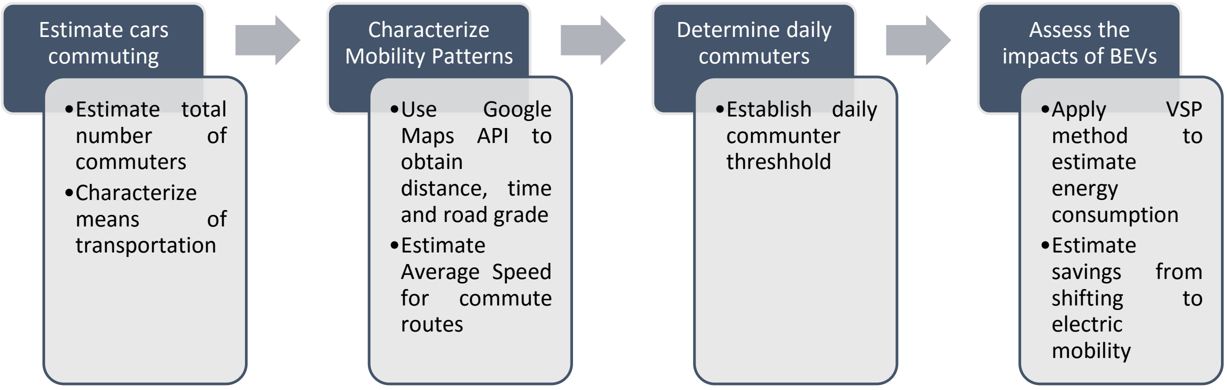


Figure 12 – Brief description of the developed methodology

3.1.1. 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 [32], 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 [32], 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.

$$\%cars = \frac{number\ of\ drivers\ commuting}{Total\ number\ of\ commuters} \tag{1}$$

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.

3.1.2.Characterization of mobility patterns

The second step consisted in the characterization of mobility patterns, by developing specific Matlab [33] code connected to the Google Maps API System [34] to obtain distance, time and road grade for each entry of the O/D matrix. 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 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 [35], to obtain the elevation in 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.

$$Road\ Grade = \frac{Elevation\ Difference}{Travelled\ Distance} \tag{2}$$

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.

The following example shows an xml type file presented by Google Maps API [34] directions system. The "leg" defines the path, in this example the travel from Lisboa to Porto, and each of the "steps" represents a segment of a trip. As seen in Figure 13, data about time, distance, start and end geographic coordinates and used street is presented.

```
▼<DirectionsResponse>
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 ▼<route>
    <summary>A1</summary>
  ▼<leg>
   ▶<step>...</step>
   ▶<step>...</step>
   ▼<step>
      <travel_mode>DRIVING</travel_mode>
    ▼<start_location>
        <lat>38.7233098</lat>
        <lng>-9.1396239</lng>
      </start_location>
    ▼<end_location>
        <lat>38.7257545</lat>
        <lng>-9.1407235</lng>
      </end_location>
    ▼<polyline>
        <points>ucjkFraxv@OF[HeBh@kA^oAf@kAb@w@\[JYH</points>
      </polyline>
    ▼<duration>
        <value>42</value>
        <text>1 min.</text>
      </duration>
      <html_instructions>Continue em frente para <b>R. Gomes Freire</b></html_instructions>
    ▼<distance>
        <value>288</value>
        <text>0,3 km</text>
      </distance>
      <maneuver>straight</maneuver>
    </step>
   ▶<step>...</step>
   ▶<step>...</step>
```


Figure 13 - Google Maps API directions [36]

The Geographic coordinates are then used in the API elevation [35] system as represented in Figure 14.


```
▼<ElevationResponse>
   <status>OK</status>
 ▼<result>
   ▼<location>
      <lat>38.7233098</lat>
      <lng>-9.1396239</lng>
    </location>
    <elevation>66.3699570</elevation>
    <resolution>1.1929940</resolution>
  </result>
 ▼<result>
   ▼<location>
      <lat>38.7257545</lat>
      <lng>-9.1407235</lng>
    </location>
    <elevation>71.5314865</elevation>
    <resolution>1.1929940</resolution>
  </result>
</ElevationResponse>
```


Figure 14 - Google Maps API elevation [35]

3.1.3.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.

3.1.4.Assess the impacts of BEVs

To evaluate the impacts of shifting to electric mobility, the energy consumption associated to the baseline fleet was first 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 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 is defined as "the instantaneous power per unit mas of the vehicle" used to overcome exterior forces such as drag and rolling resistance [37]. A simplified VSP equation in W/kg is presented in equation 3, in which a is the acceleration (m^2/s), $grade(\%)$ is the road grade (%), V is the vehicle speed (m/s) and V_w is the headwind into the vehicle (m/s).

$$VSP = V \times (1.1 \times a + 9.81 \times grade(\%) + 0.132) + 3.02 \times 10^{-4} \times (V + V_w)^2 \times V \quad (3)$$

Due to the limited data available from the evaluation of mobility patterns previously presented, only speed and road grade were available. As such, equation 3 was further simplified to obtain equation 4, with V in km/h. With this equation, it was possible to calculate the VSP in W/kg for each segment of a commute.

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

With this equation, a VSP mode can be attributed to each segment, as shown in Table 1. Furthermore, a correspondence between VSP modes and the energy consumption for different vehicle technologies (SI – spark ignition, CI – compressed ignition, BEV – battery electric vehicle) can be established based on literature data [38], as also presented in Table 1. This data is derived from experimental data [38] and is representative of Euro 5 vehicles. Since no data on this VSP approach was available for Euro 6 vehicle technologies, 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 [39]. Table 1 includes different regimes for BEVs, including regenerative braking which, for low VSP modes, lead to recharging of batteries, as presented by negative values for energy consumption 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

For a specific fleet, the average energy consumption factor ($Fleet\ FC$) can be calculated using equation 5.

$$Fleet\ FC\left(\frac{MJ}{s}\right) = \frac{SI\ FC\left(\frac{g}{s}\right) \times Petrol\ LHV\left(\frac{MJ}{l}\right) \times \%of\ Petrol\ cars}{Petrol\ density\ \left(\frac{g}{l}\right)} + \frac{CI\ FC\left(\frac{g}{s}\right) \times Diesel\ LHV\left(\frac{MJ}{l}\right) \times \%of\ Diesel\ cars}{Diesel\ density\ \left(\frac{g}{l}\right)} + BEV\ FC\left(\frac{Wh}{s}\right) \times 0.0036 \times \%of\ BEV\ cars \tag{5}$$

Where SI FC, CI FC and BEV FC are the fuel consumptions of a SI, CI and BEV engine, $\%of\ Petrol\ cars$, $\%of\ Diesel\ cars$ and $\%of\ BEV\ cars$ are the shares of the SI, CI and BEV vehicles in the considered fleet, 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 5 with the time spent on the segment, obtained in section 3.1.2. Equation 6 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 3.1.3). This allowed estimating the total daily energy consumption (in MJ) for different fleet compositions.

$$Total\ FC\ (MJ) = \sum_i \left[\sum_j \left(Fleet\ FC_j \times time_j \right)_{go} + \sum_j \left(Fleet\ FC_j \times time_j \right)_{return} \right] \times number\ of\ cars\ commuting_i \quad (6)$$

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

3.2. 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 [32]. 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 15. Also, in Figure 15, the percentage of people commuting from outside the municipality per total number of inhabitants per municipality is shown.

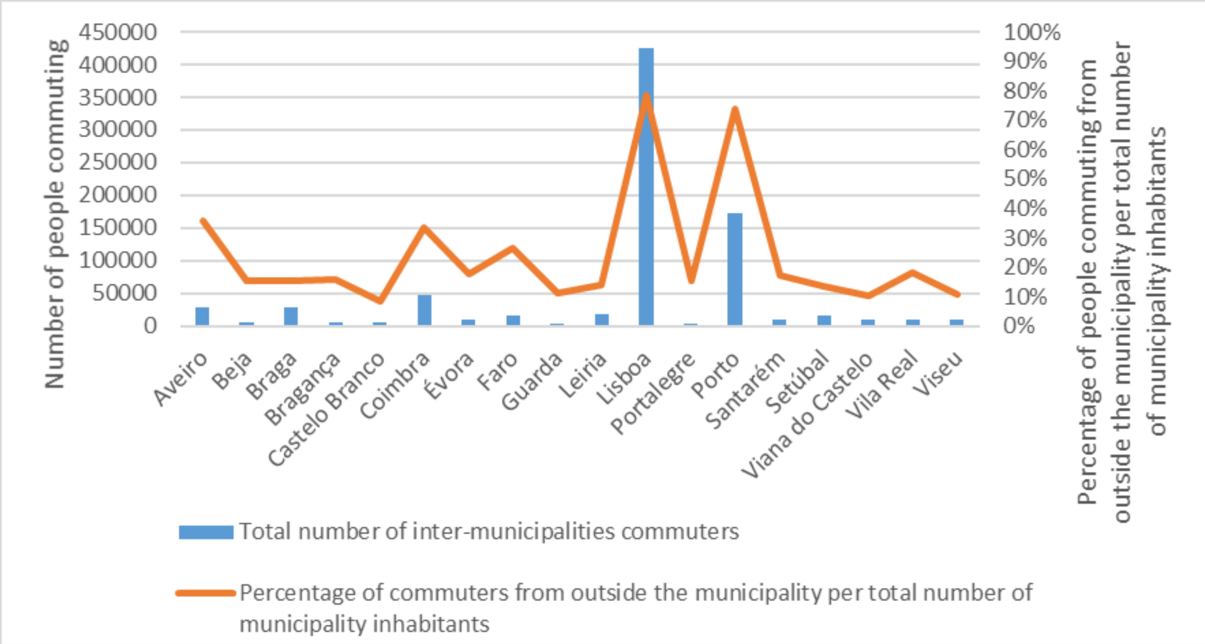

Figure 15 - Total initial number of people commuting and Percentage of people commuting from outside the municipality per total number of municipality inhabitants

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 [32]. 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 16 shows the distribution of both parameters for all parishes in Portugal.

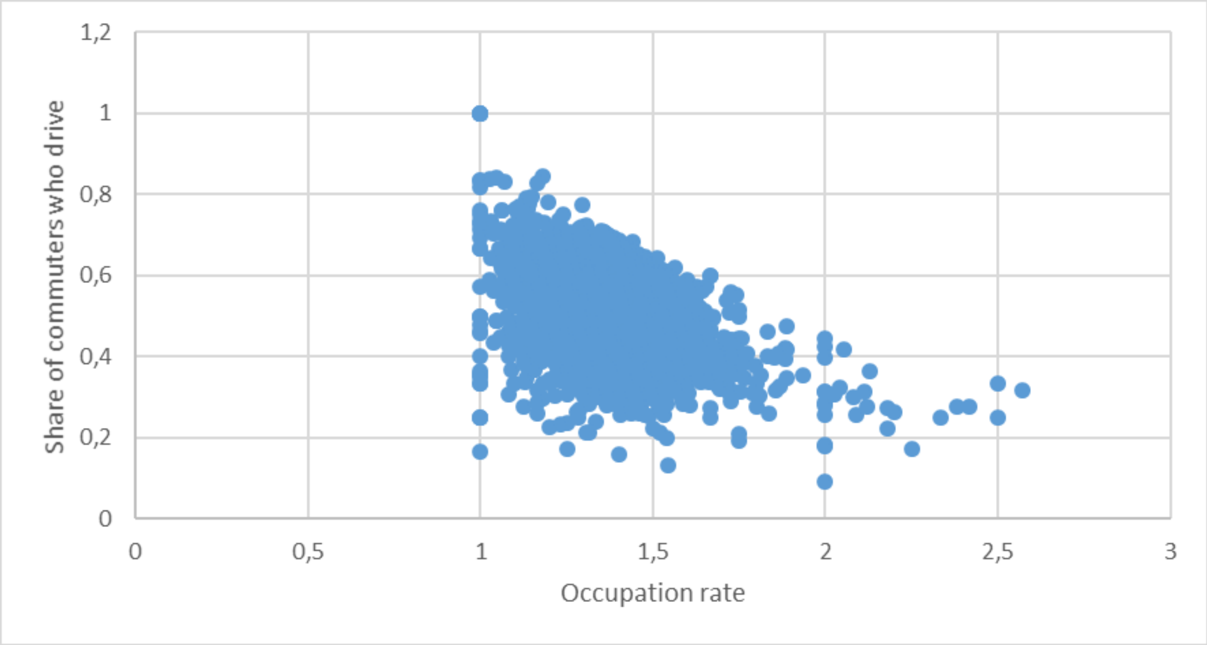

Figure 16 - Scatter graph "Occupation rate" VS "Percentage of cars commuting"

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 [15]. 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 [39]. 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 consumed (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 [29]. 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.

3.3. 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.

4. 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.

4.1. 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.

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

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.

Concerning distance, Figure 17 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.

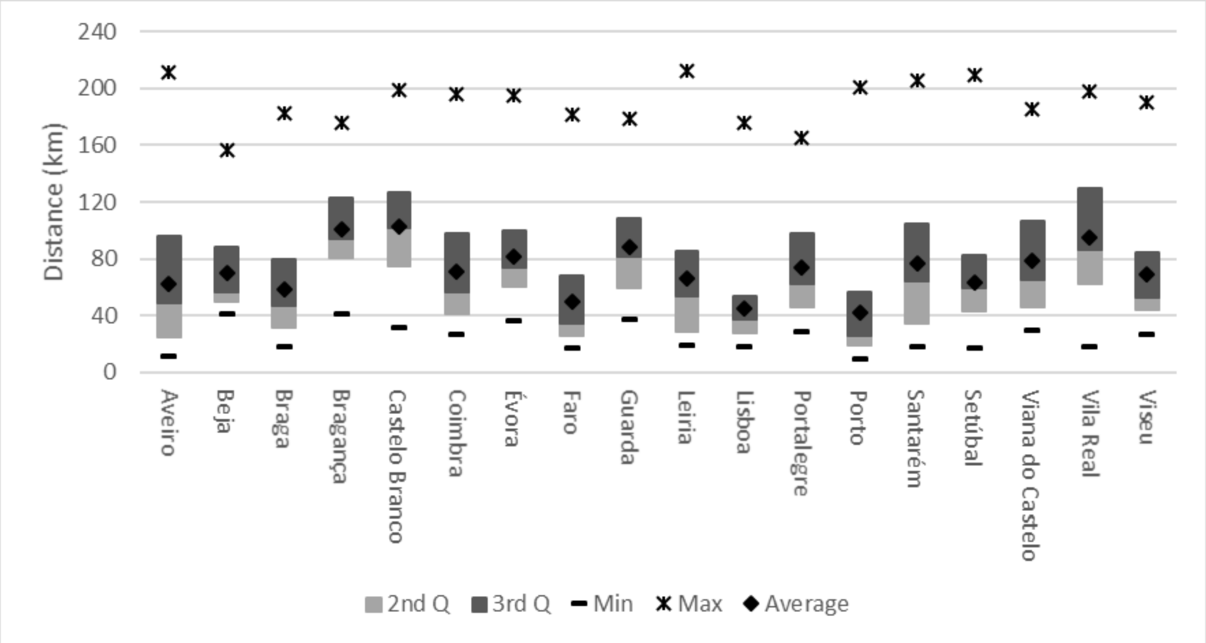

Figure 17 - Quartile distribution of distance

The quartile distribution of travel time for each municipality is shown in Figure 18. 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.

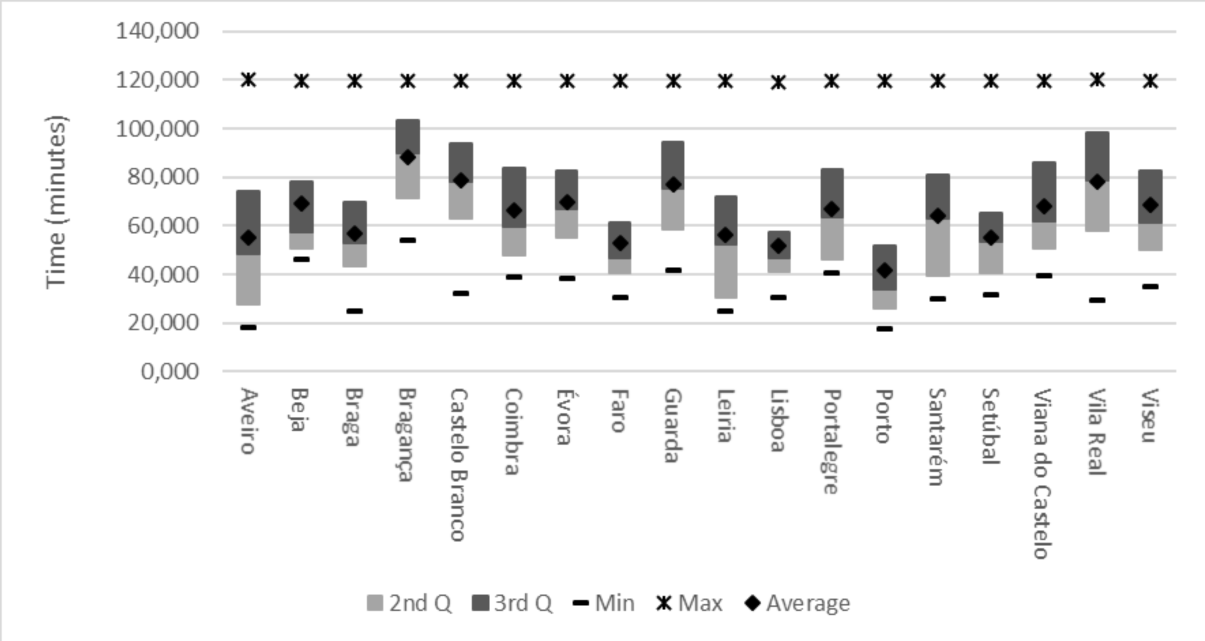

Figure 18 - Quartile distribution of time

Additionally, Figure 19 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.

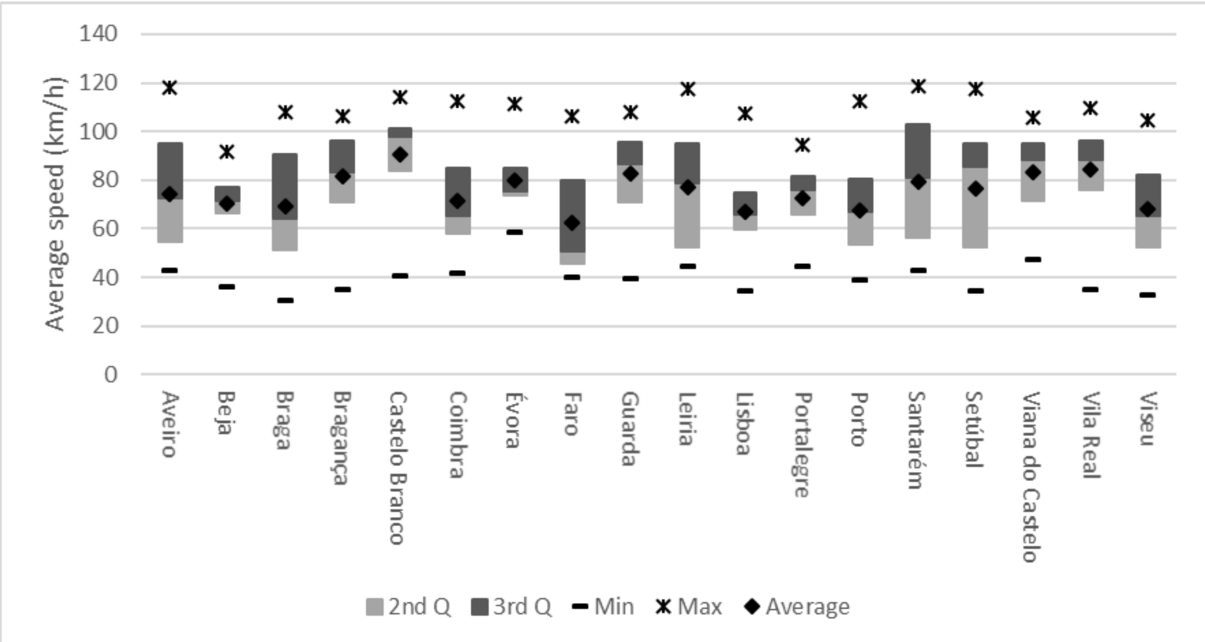

Figure 19 – Quartile distribution of speed

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 [39], 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 benefits regions with intense traffic, such as Lisboa and Porto. In these regions, the travel times in peak hours would significantly increase while the average speed would decrease. Another less expected impact

could be the change in optimal routes to perform the commute, in order to avoid traffic.

4.2. 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.

4.2.1. **Geographic distribution of energy demand**

Figure 20 to Figure 37 represent the energy consumed due to the commutes from each parish to the 18 municipalities. All images have the same distance scale and in the location of the municipality within the country being represented is shown in the centre of each figure.

Two figures are shown for each municipality, both with the same colour scale representing energy demand. The figure on the left represents the estimated energy consumption in the Baseline Scenario. The figure on the right shows the estimated energy demand for each parish if all commutes from that parish are made with electric mobility. The coloured parishes delimit the parishes that are considered to use electric mobility in Scenario 2, while the black line delimits the parishes using electric mobility in Scenario 1.

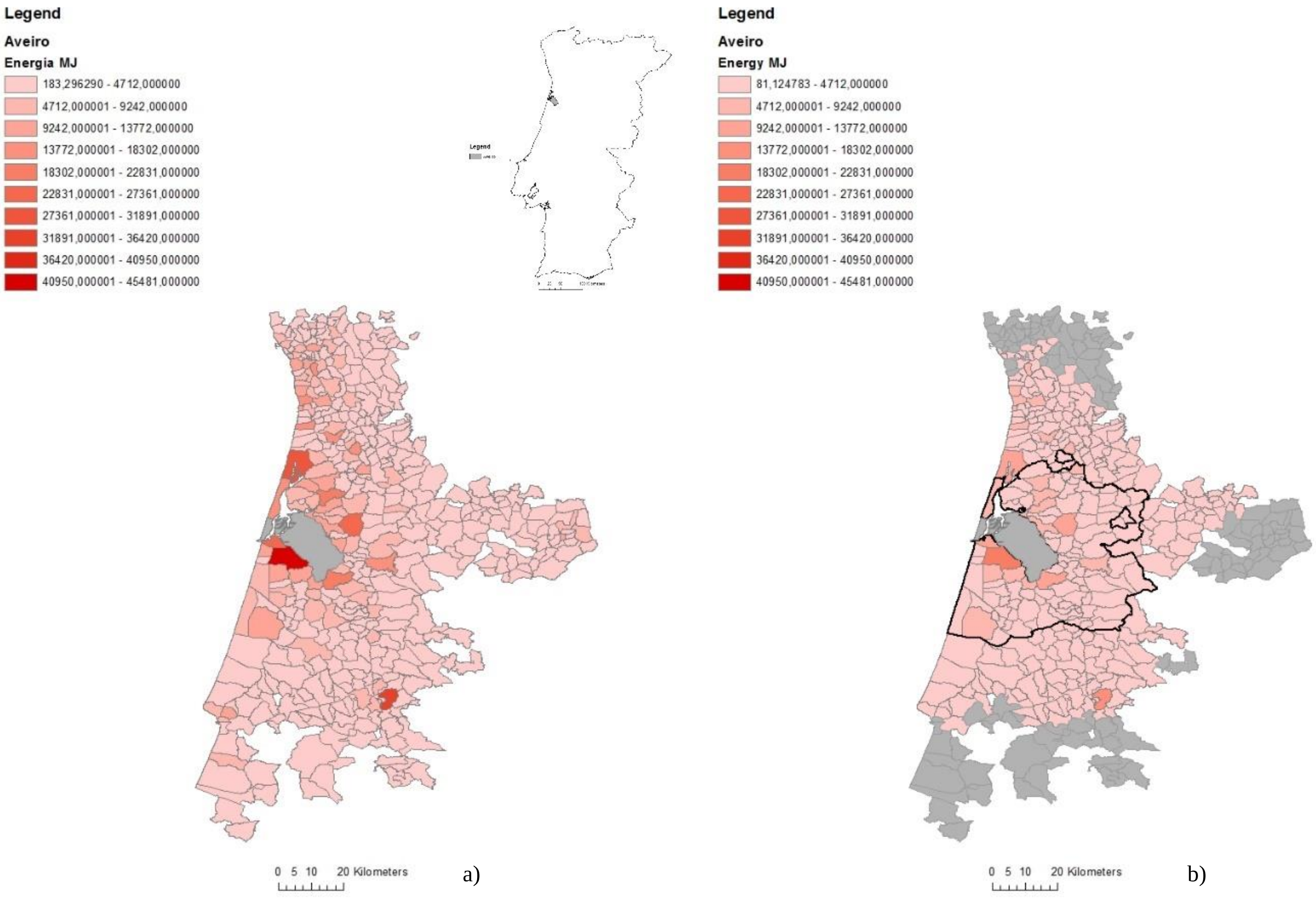

Figure 20 – Aveiro a) BAU and b) Scenario 1 and 2

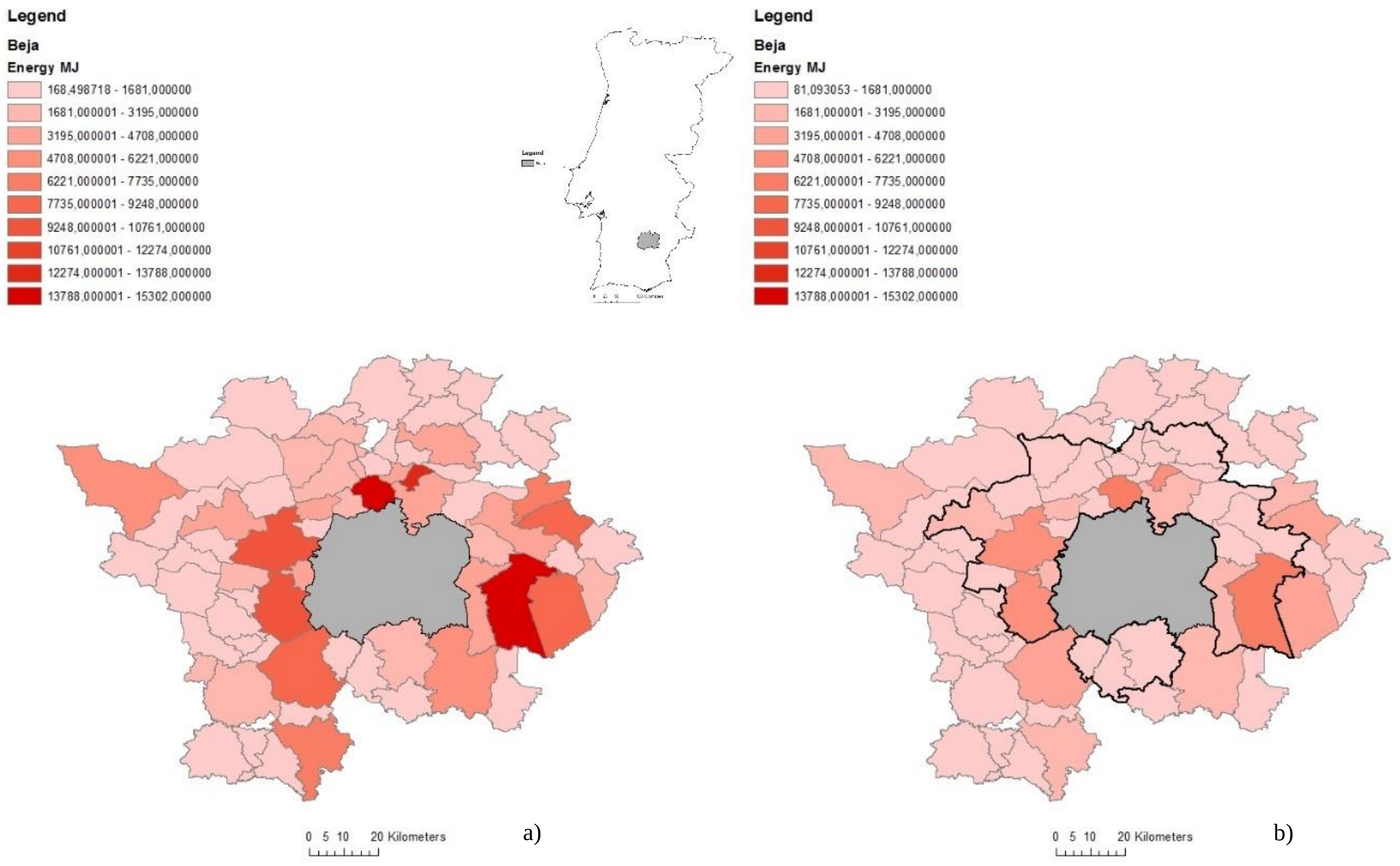

Figure 21 - Beja a) BAU and b) Scenario 1 and 2

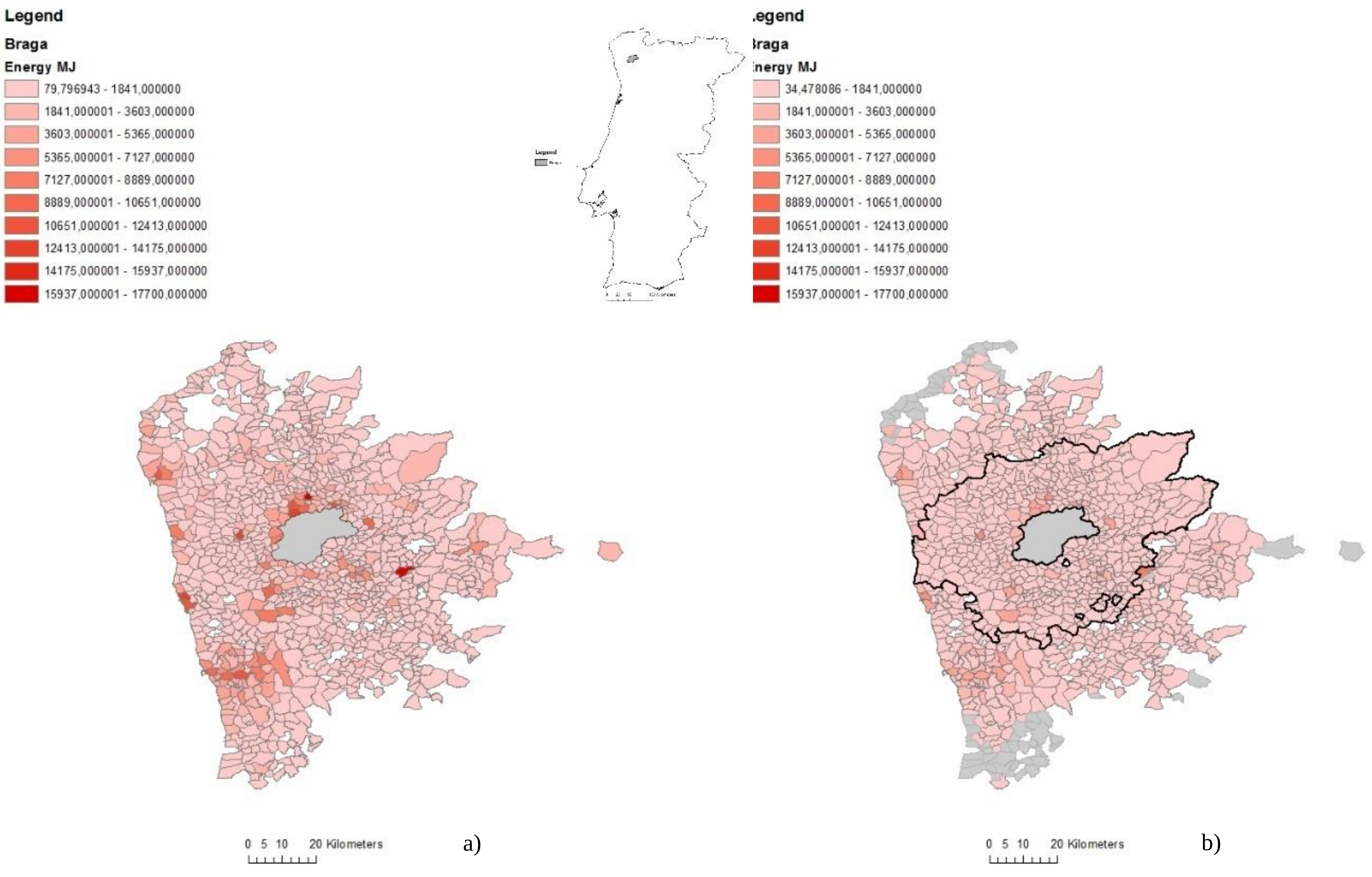

Figure 22 - Braga a) BAU and b) Scenario 1 and 2

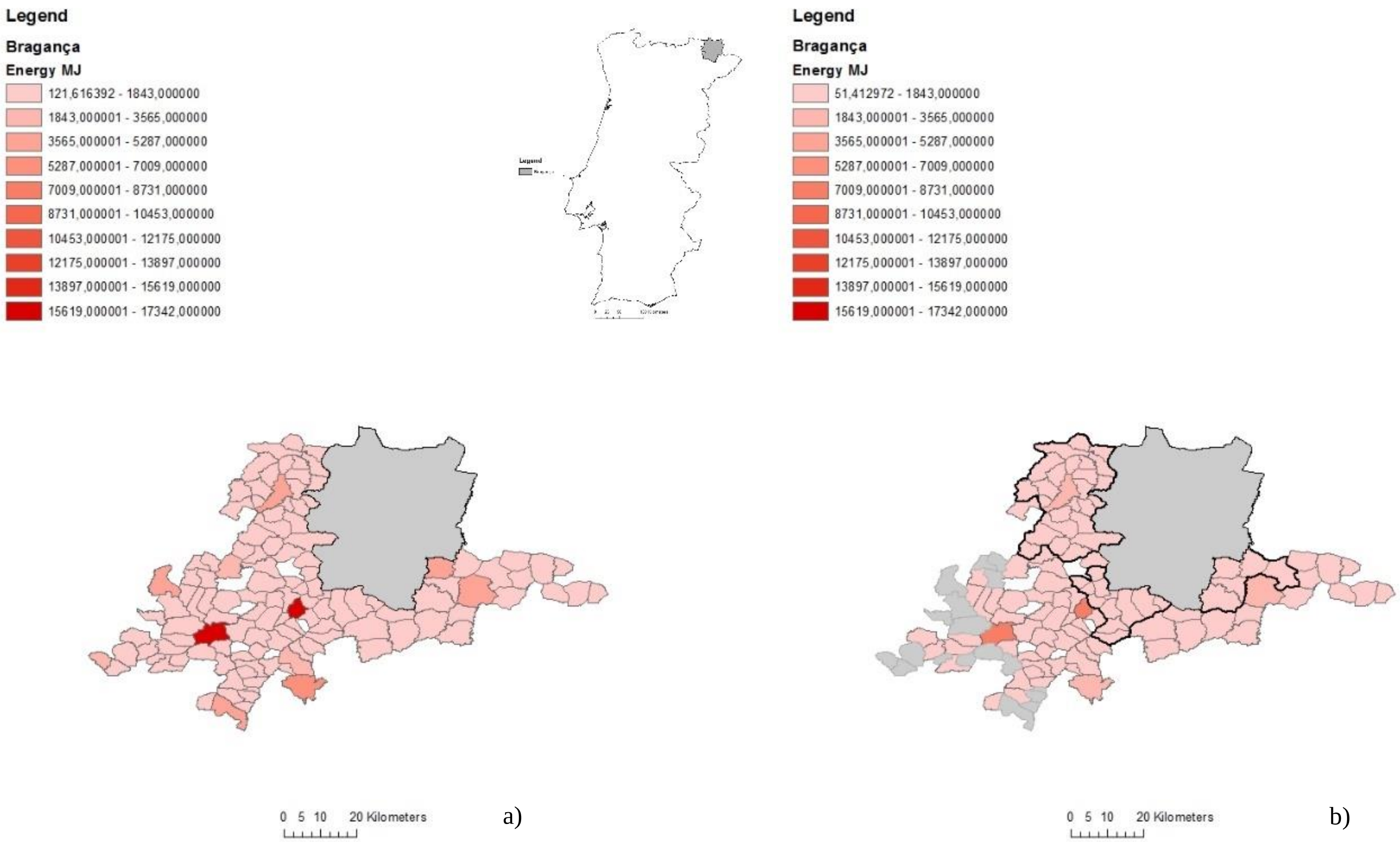

Figure 23 - Bragança a) BAU and b) Scenario 1 and 2

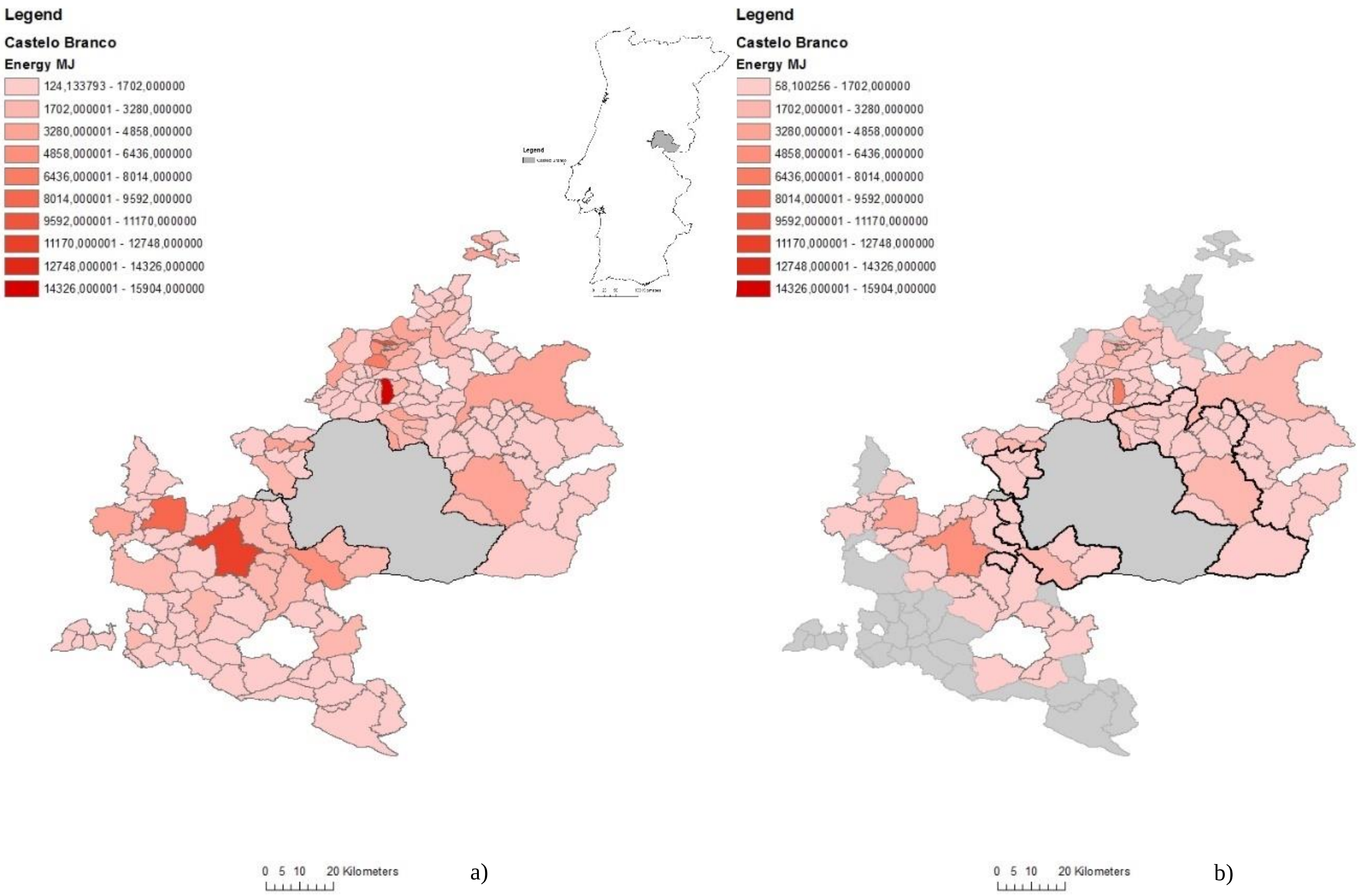

Figure 24 – Castelo Branco a) BAU and b) Scenario 1 and 2

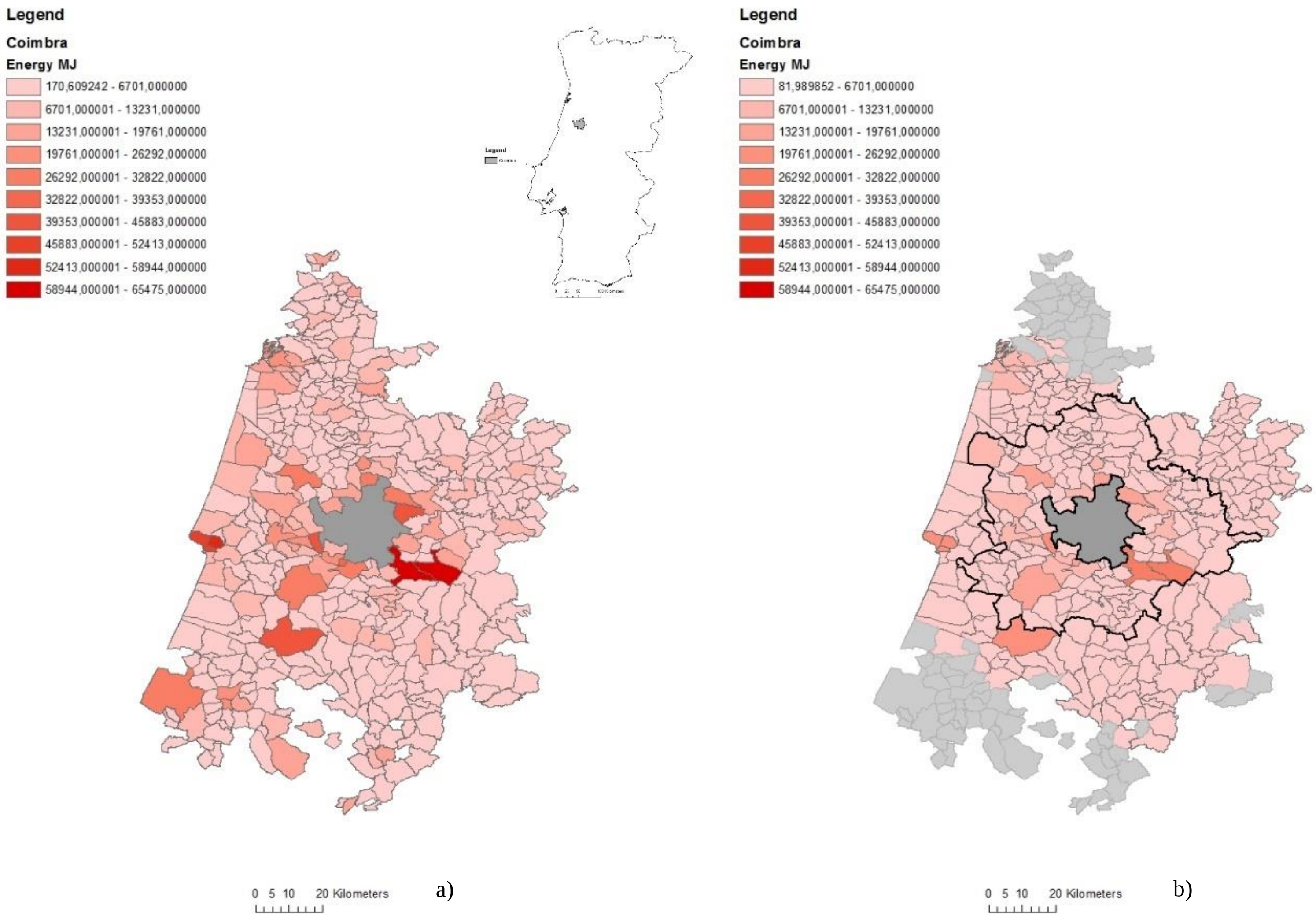

Figure 25 - Coimbra a) BAU and b) Scenario 1 and 2

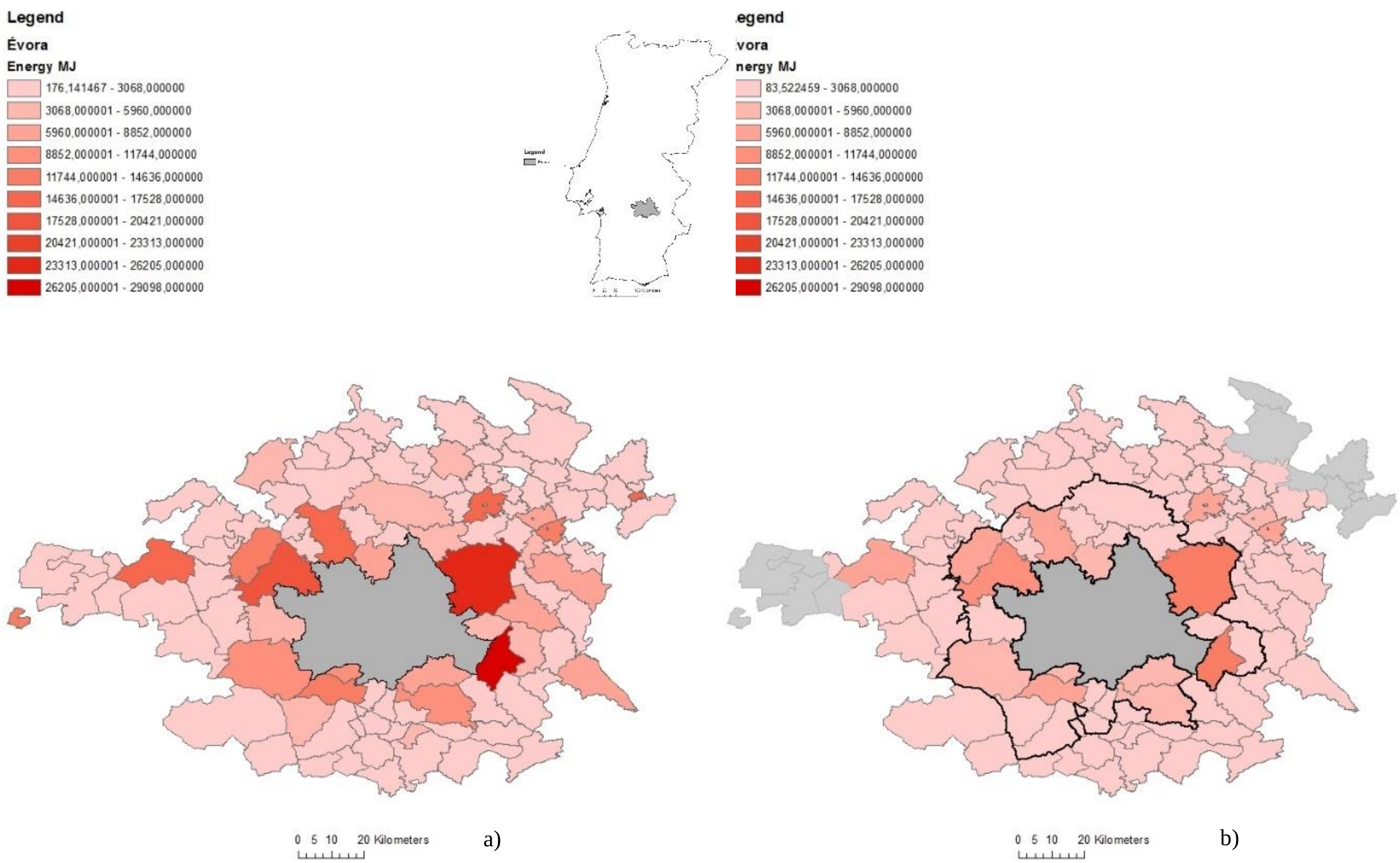

Figure 26 - Évora a) BAU and b) Scenario 1 and 2

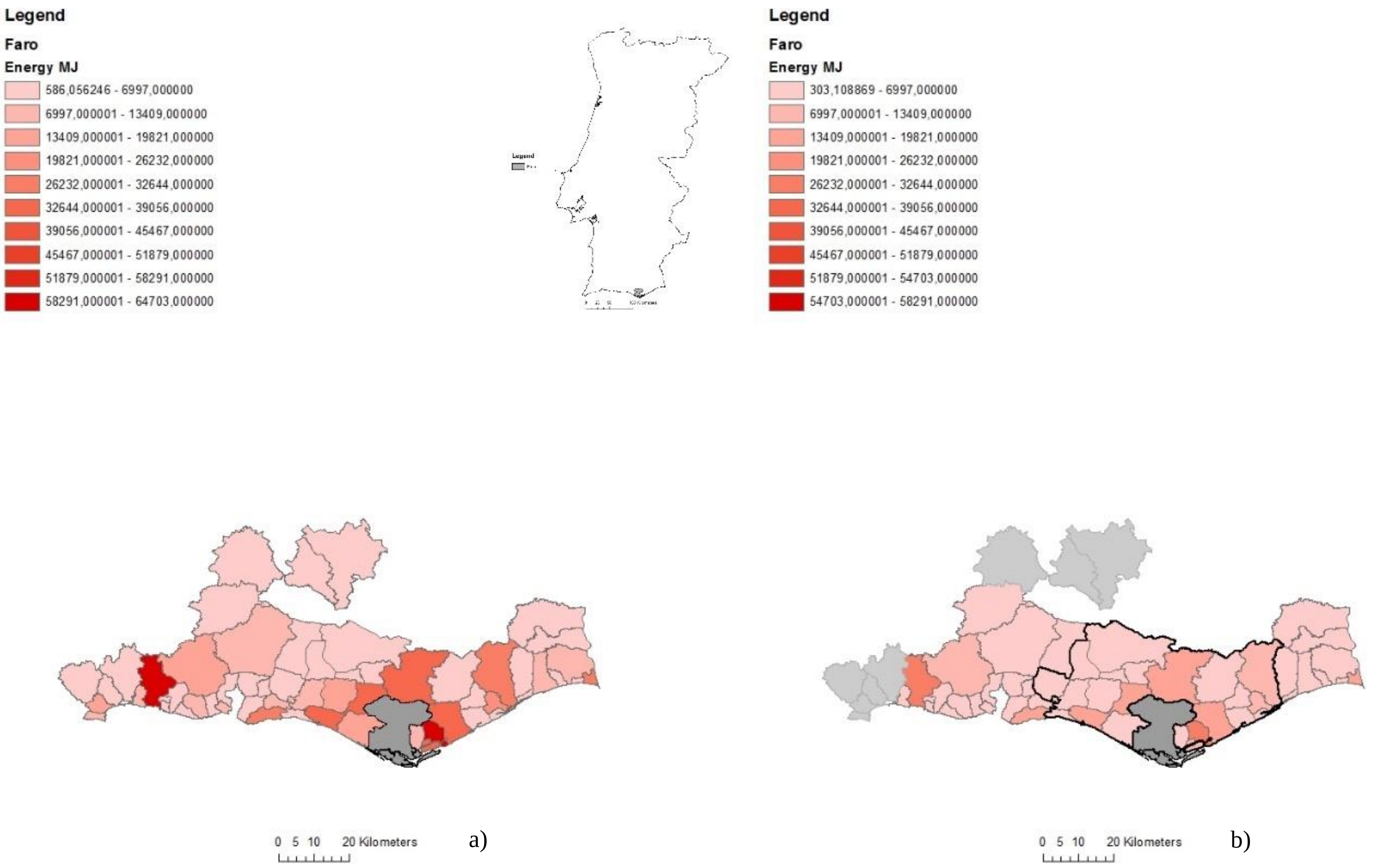

Figure 27 - Faro a) BAU and b) Scenario 1 and 2

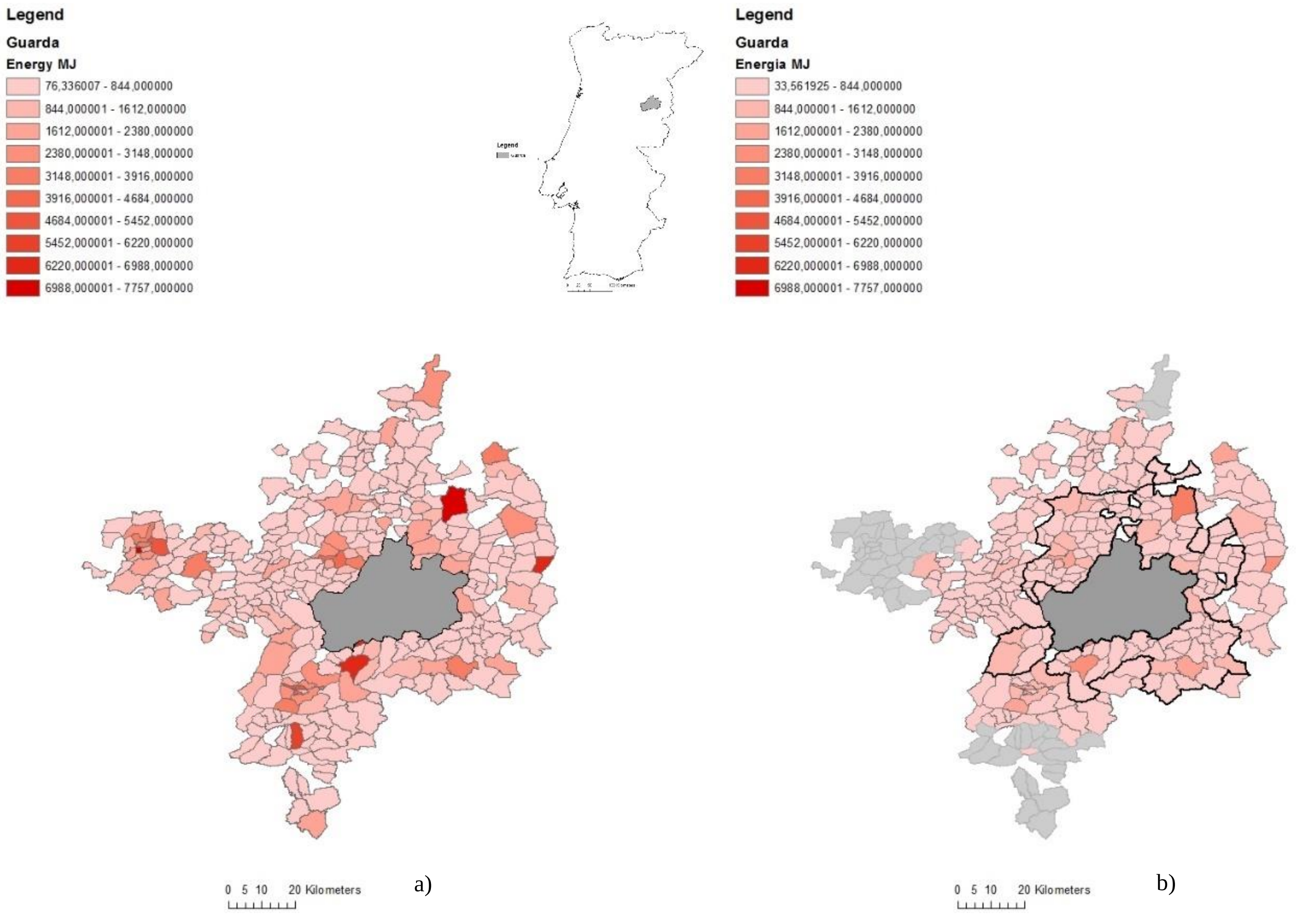

Figure 28 - Guarda a) BAU and b) Scenario 1 and 2

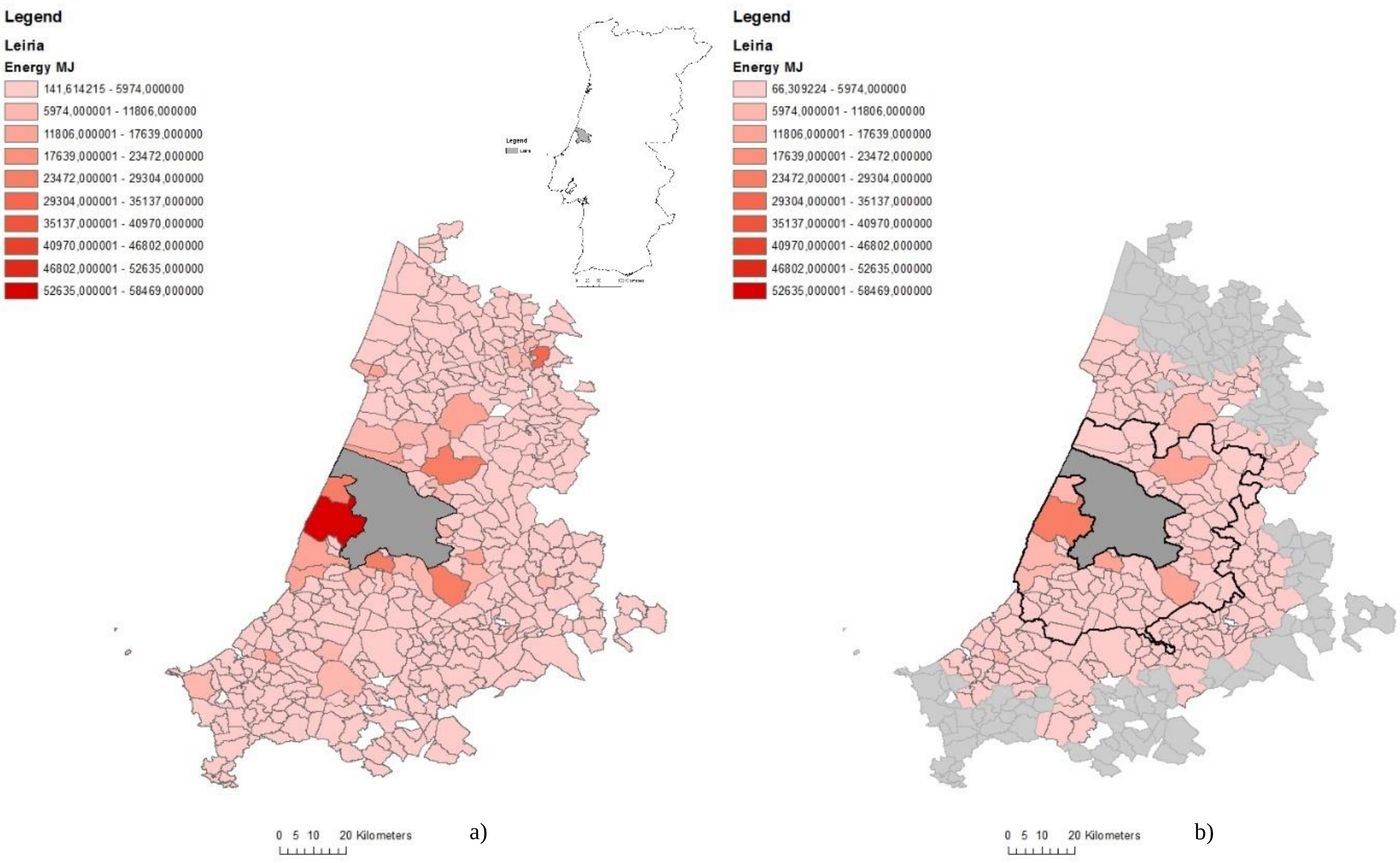

Figure 29 - Leiria a) BAU and b) Scenario 1 and 2

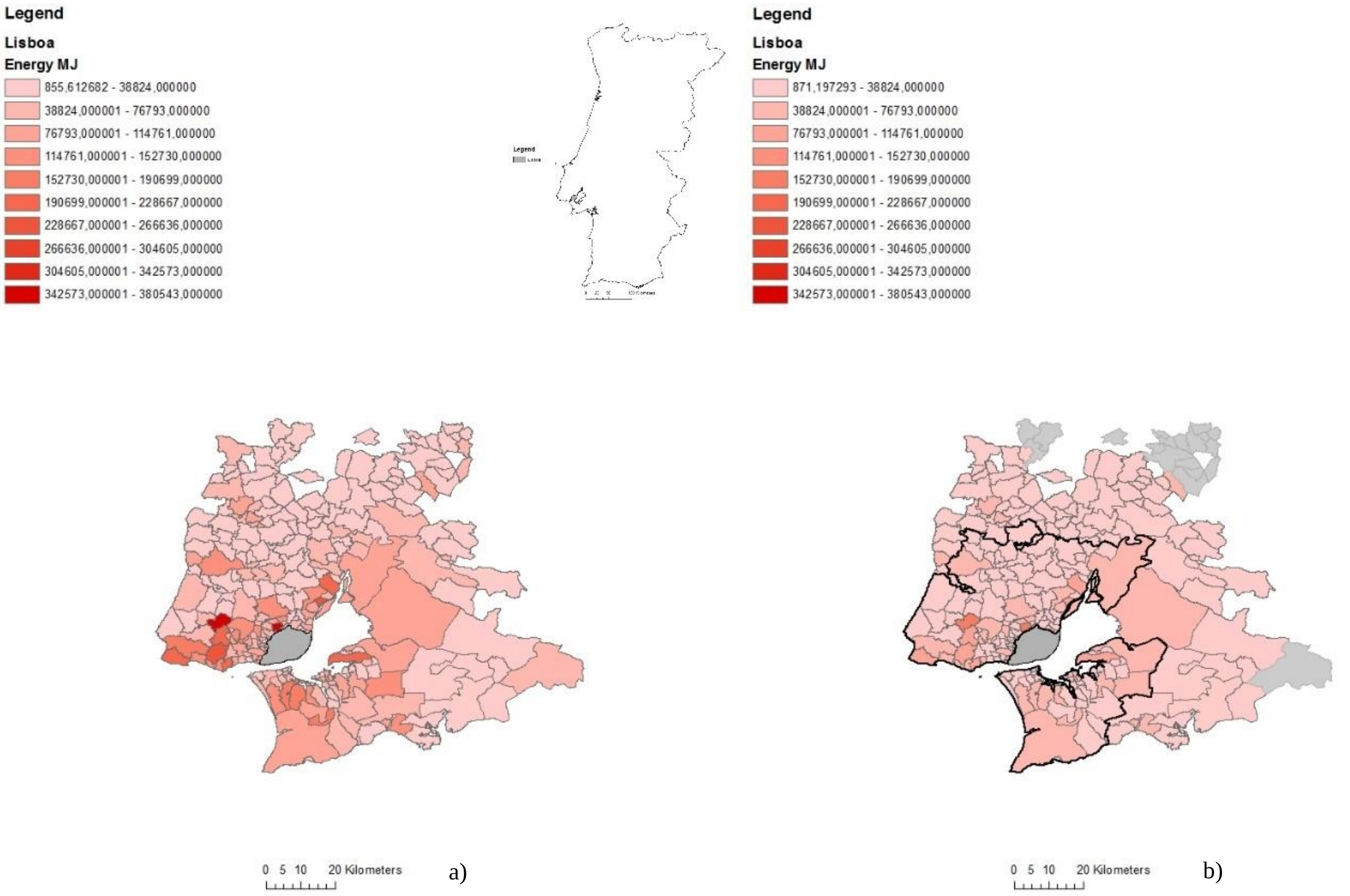

Figure 30 - Lisboa a) BAU and b) Scenario 1 and 2

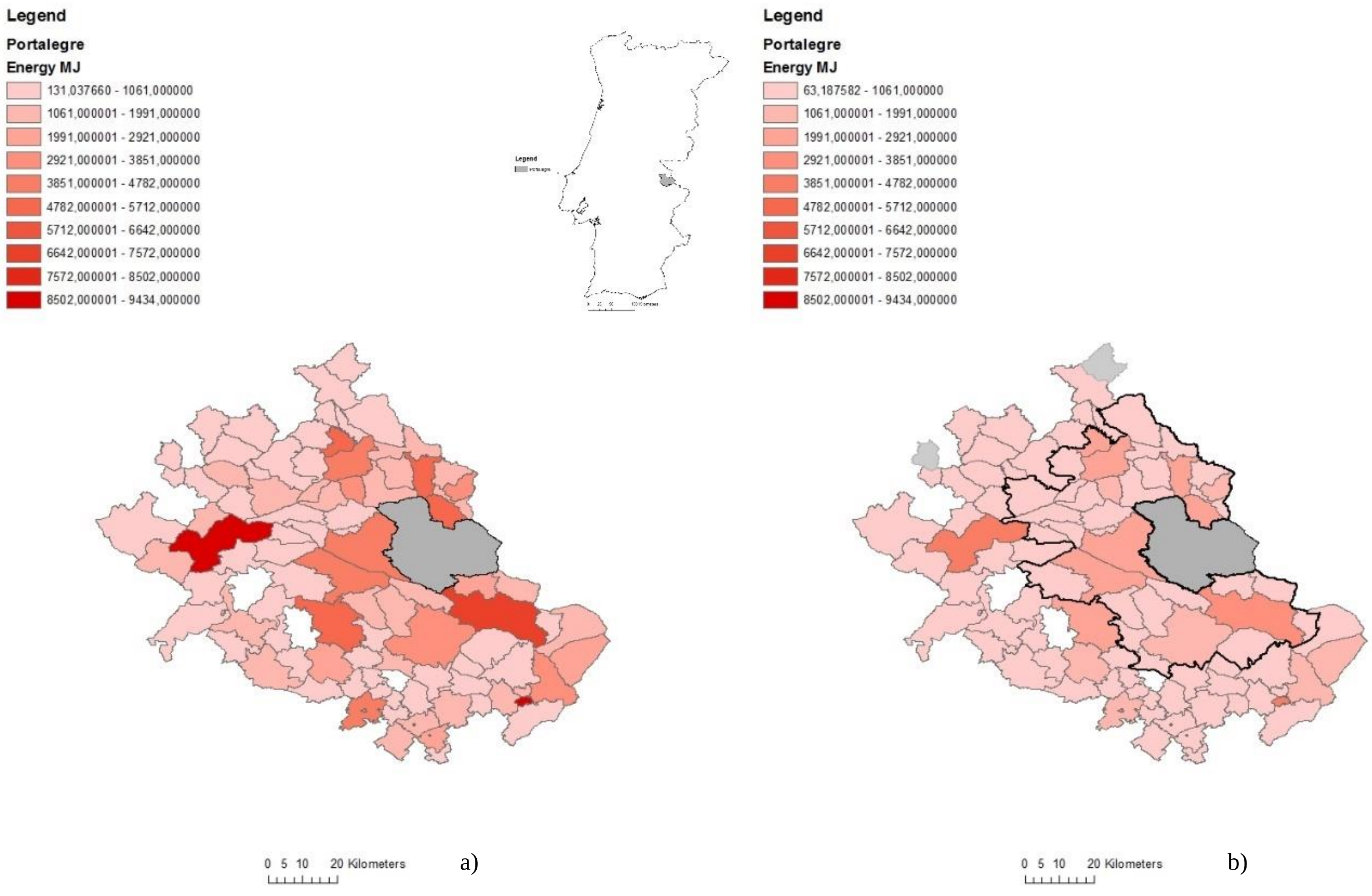

Figure 31 - Portalegre a) BAU and b) Scenario 1 and 2

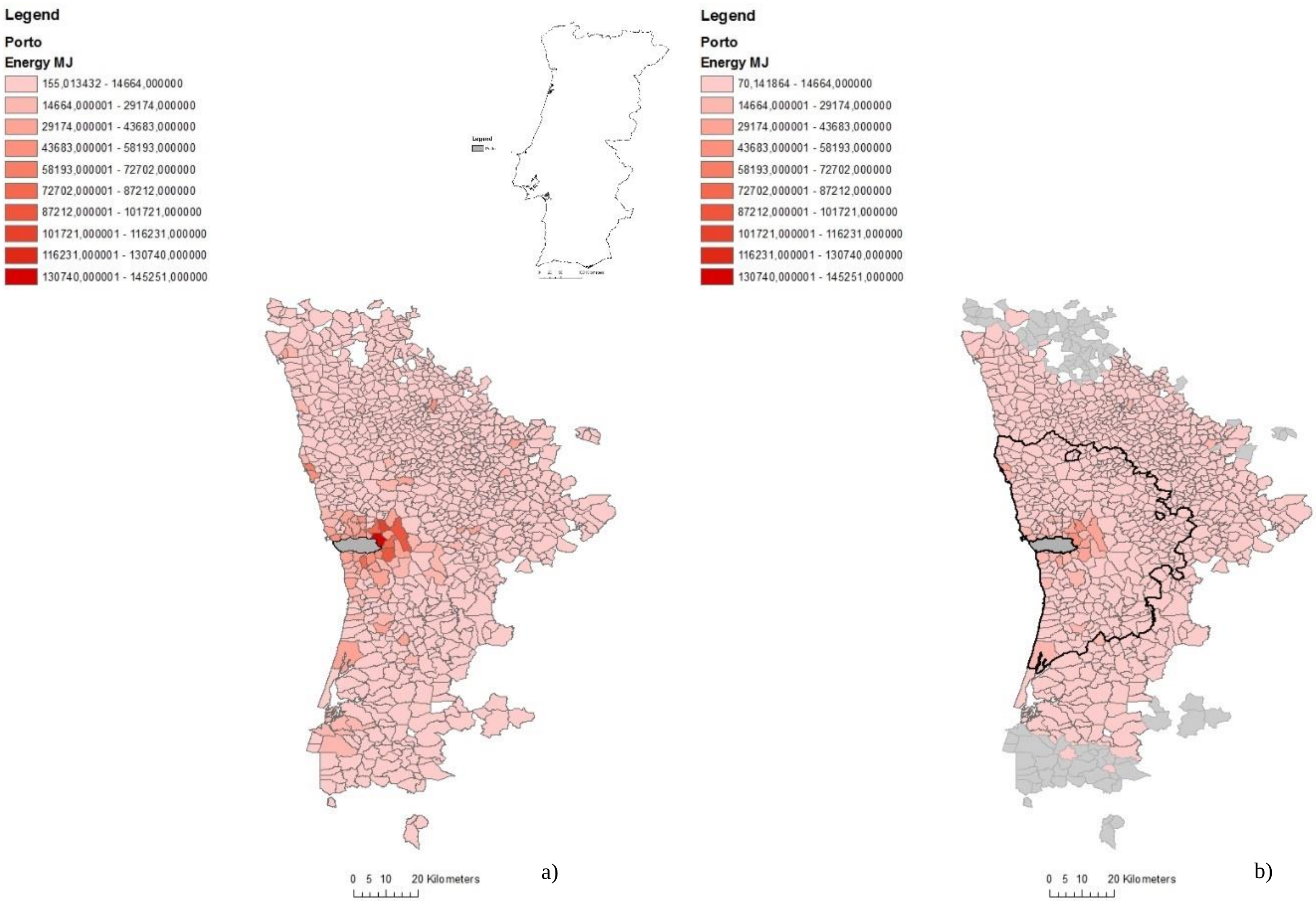

Figure 32 - Porto a) BAU and b) Scenario 1 and 2

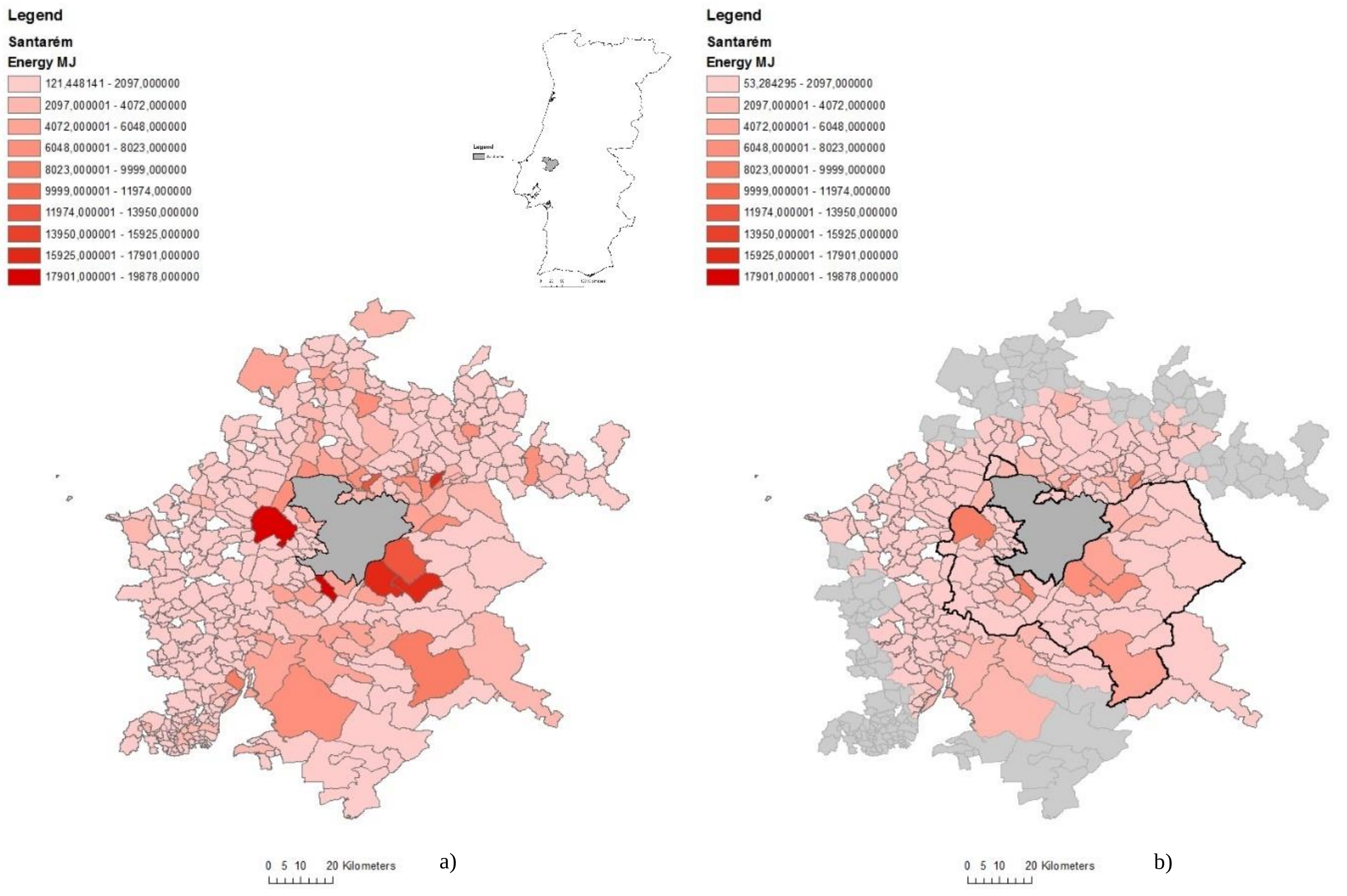

Figure 33 - Santarém a) BAU and b) Scenario 1 and 2

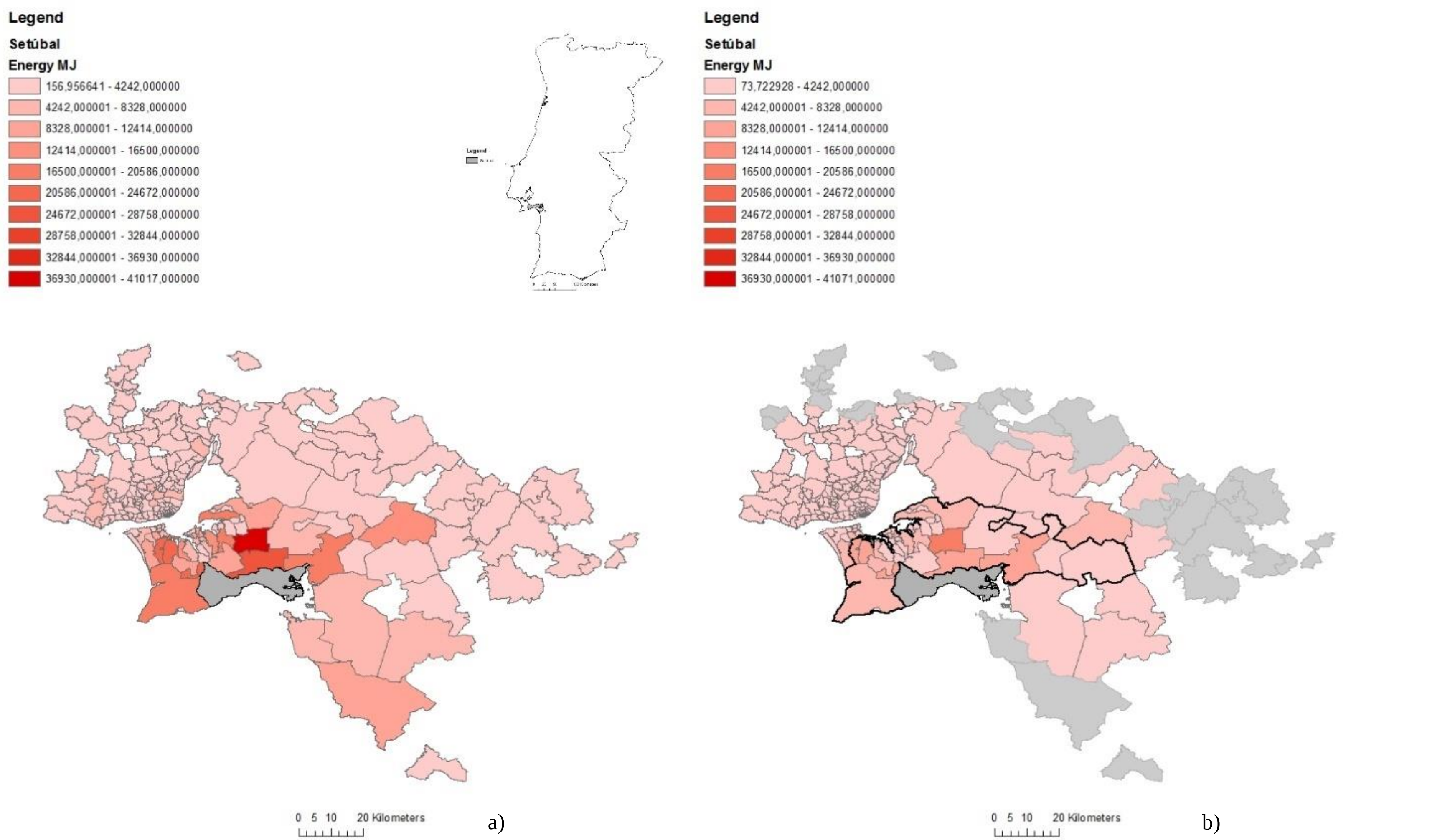

Figure 34 - Setúbal a) BAU and b) Scenario 1 and 2

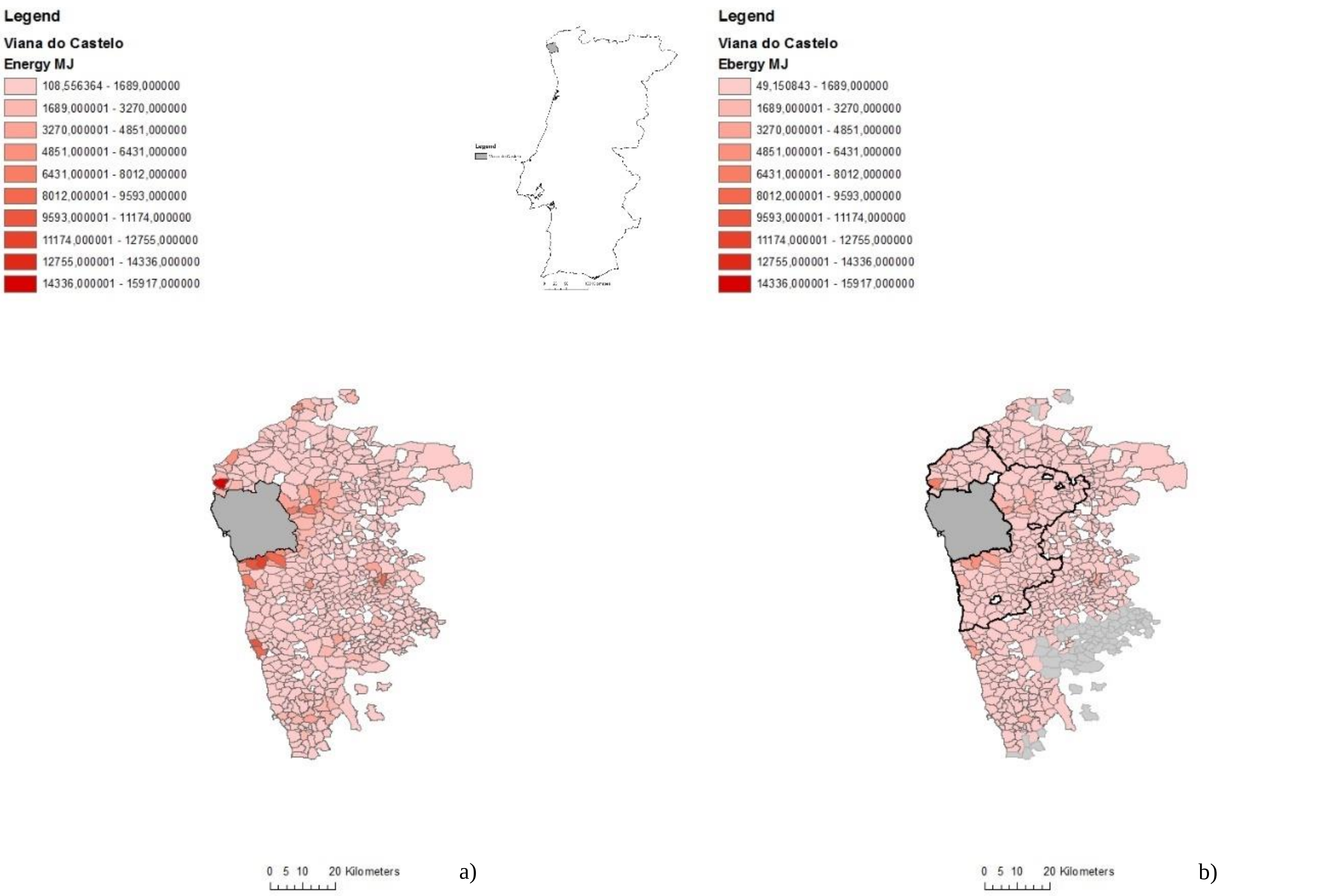

Figure 35 – Viana do Castelo a) BAU and b) Scenario 1 and 2

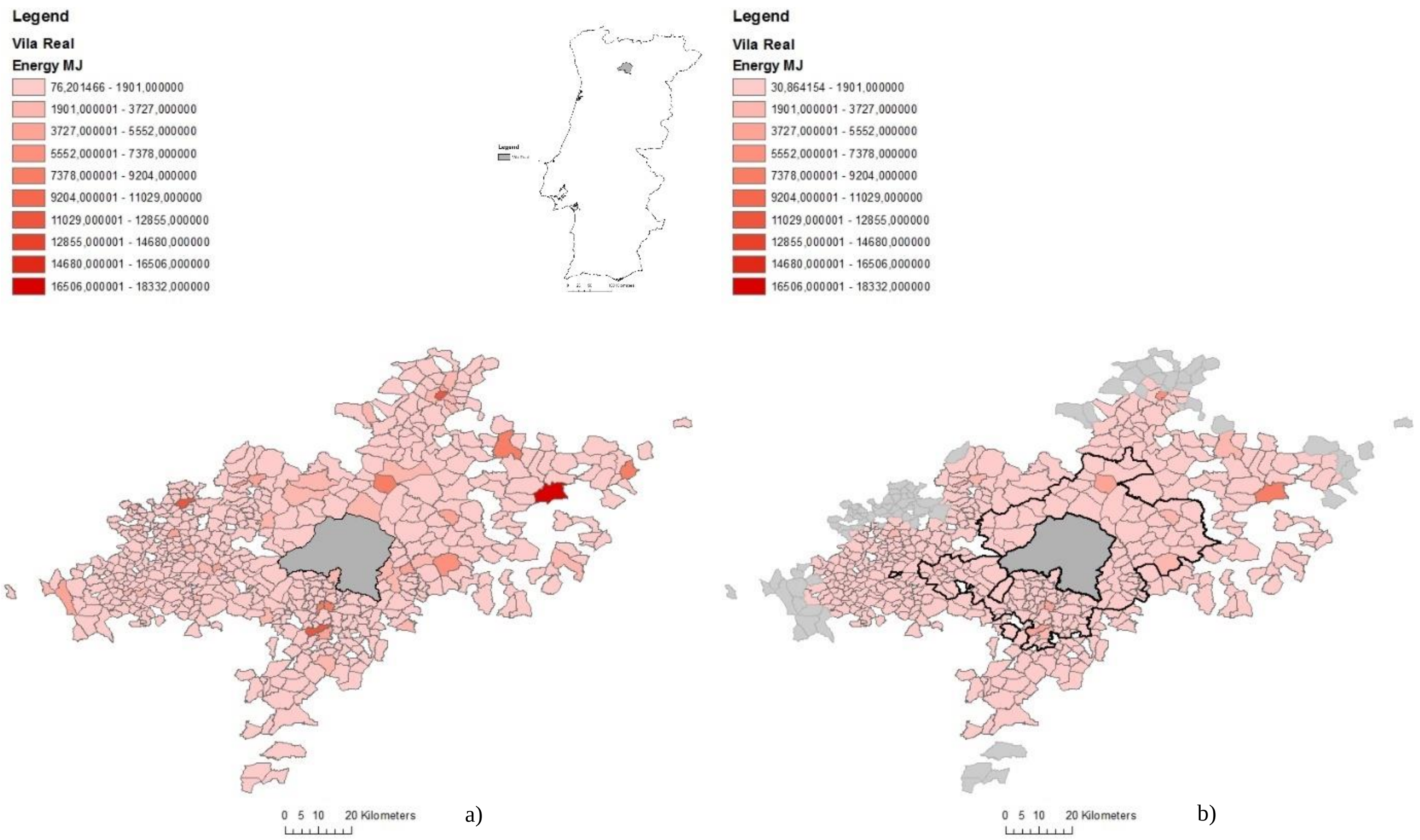

Figure 36 – Vila Real a) BAU and b) Scenario 1 and 2

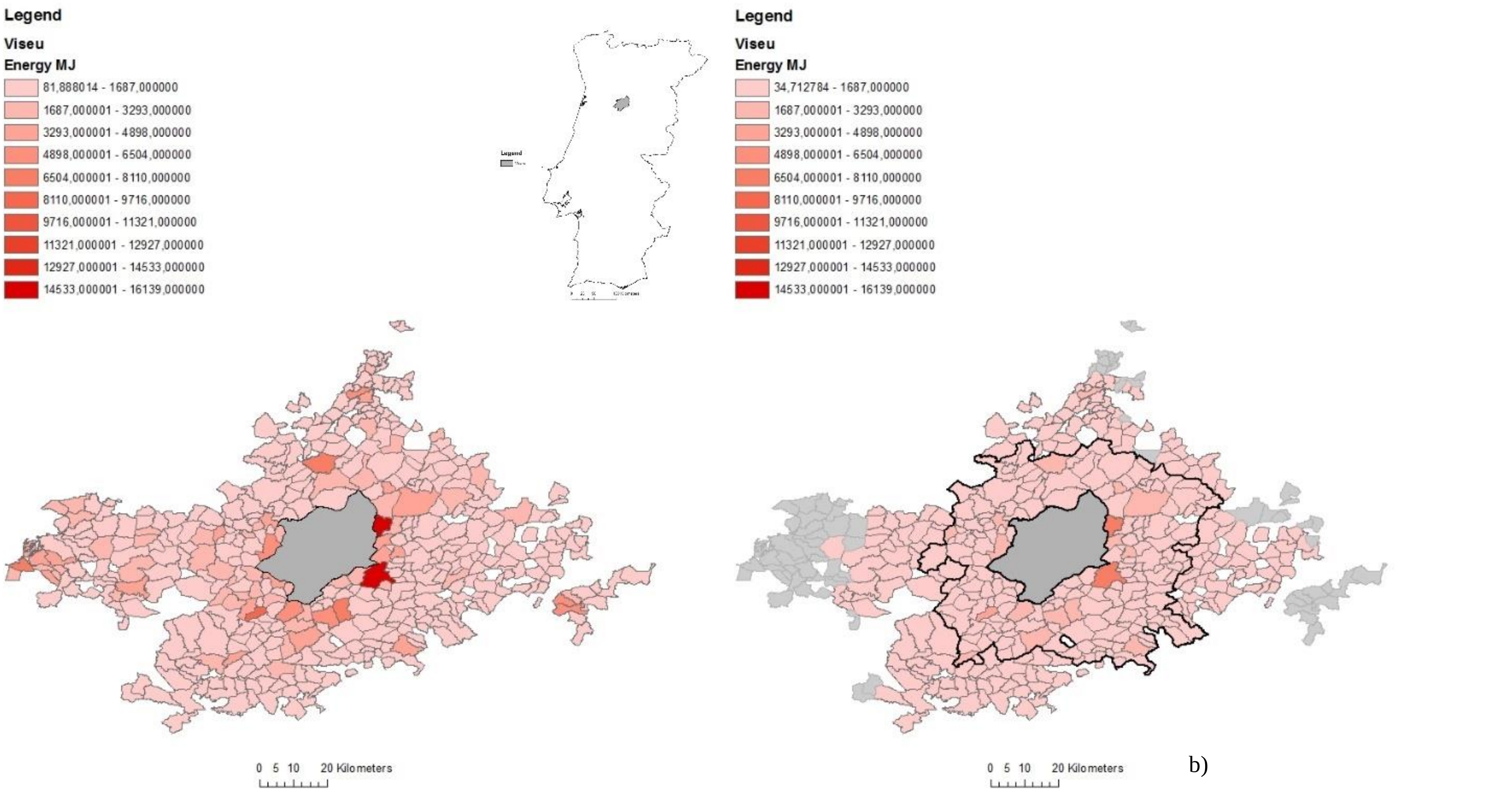

Figure 37 - Viseu a) BAU and b) Scenario 1 and 2

The impact of road infrastructure is noticeable in some municipalities, such as Aveiro (Figure 20), Faro (Figure 27) and Porto (Figure 32), in which the existence of main highways nearby allows a higher distance reach within the 2 hours threshold. The results also clearly show that electric mobility allows the reduction of energy consumption from the parishes which may use that technology, as can be seen through comparison of the figures on the left and on the right.

The following figures present the quartile distribution of energy consumption (in MJ) for the three considered scenarios. Figure 38 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).

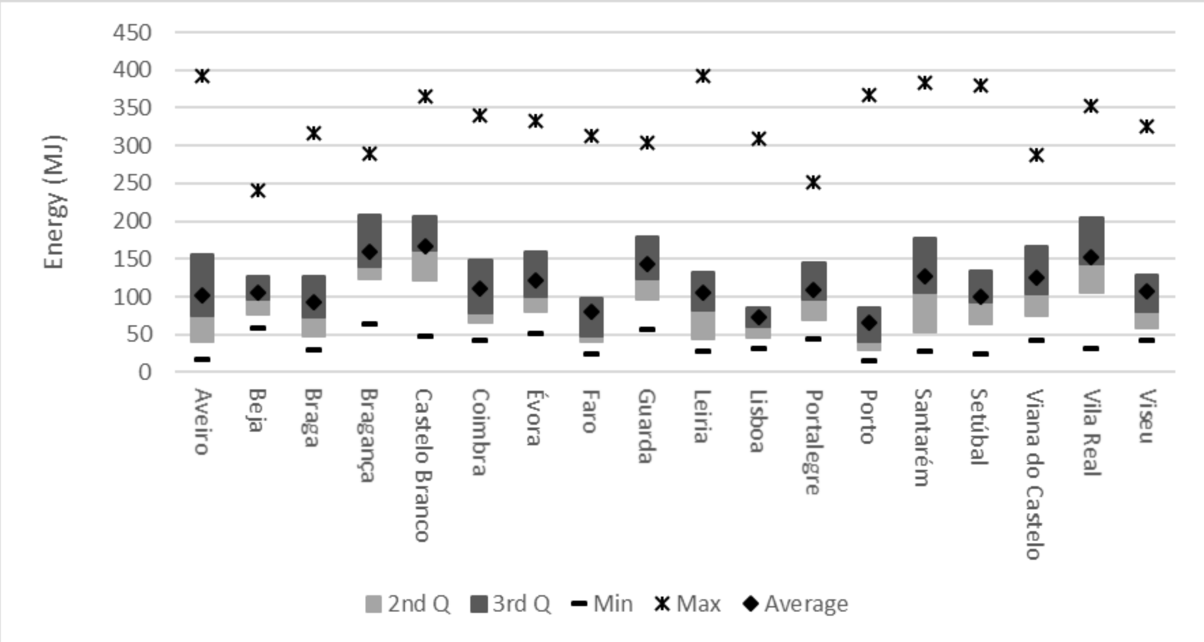

Figure 38 - Quartile distribution of energy consumption in the Baseline Scenario

Figure 39 and Figure 40 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 39) to the Baseline Scenario (Figure 38), 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.

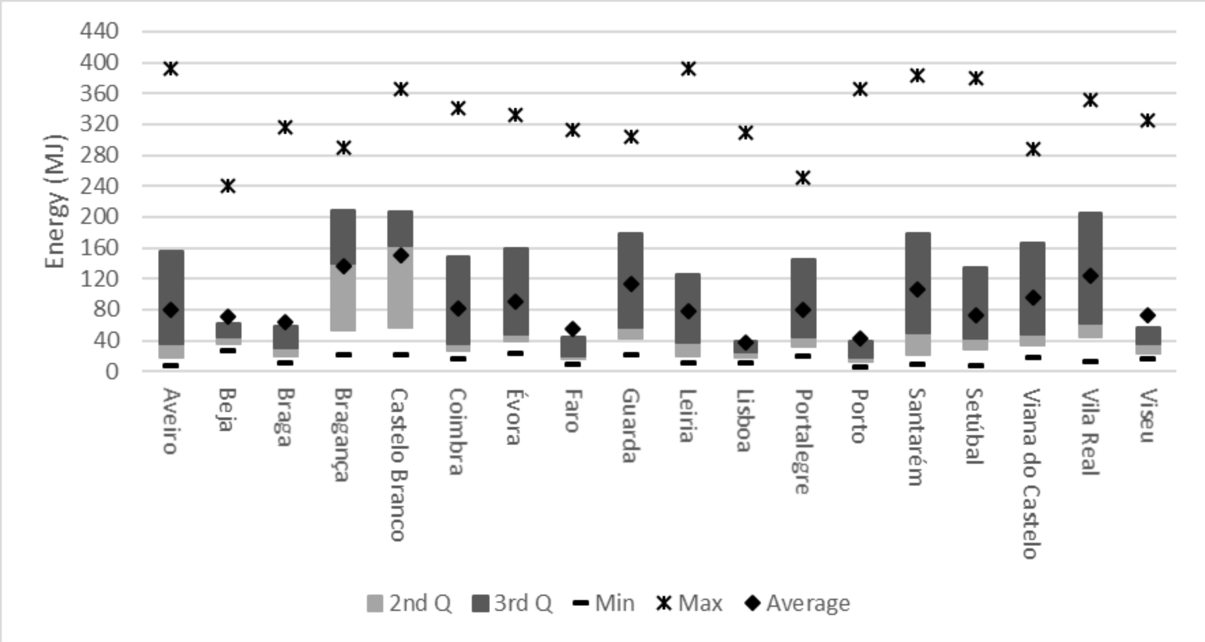

Figure 39 - Quartile distribution of fuel consumption for scenario 1

As expected, a further reduction of the average energy consumption values is observed (on average 23% lower) for Scenario 2 (Figure 40). 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.

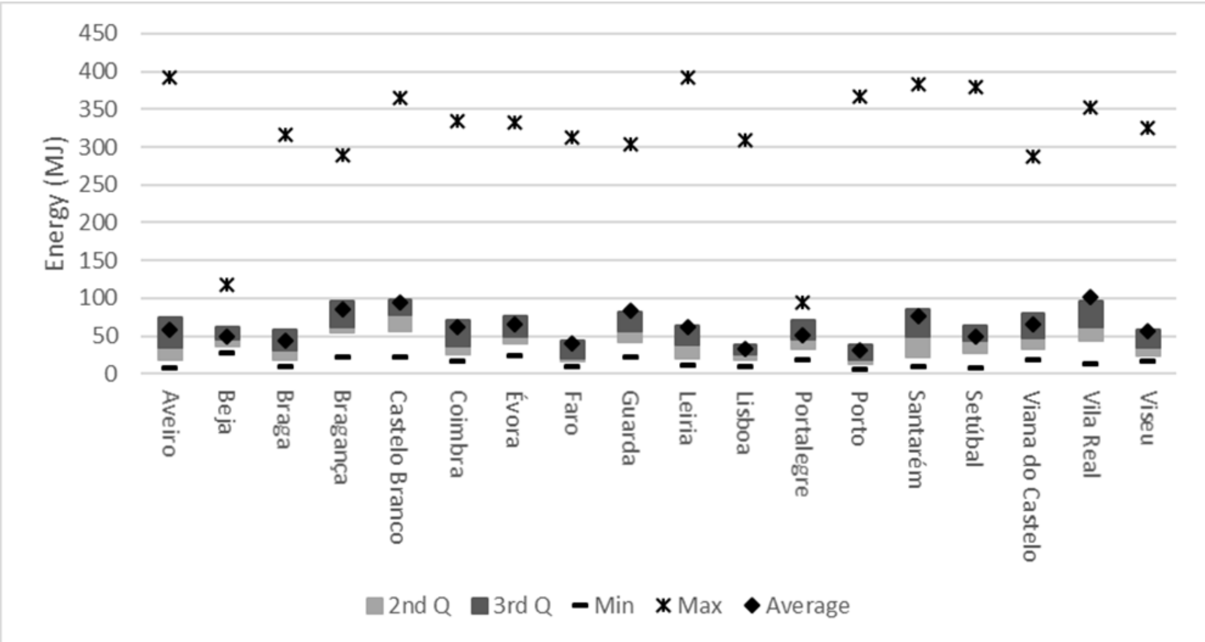

Figure 40 - Quartile distribution of fuel consumption for scenario 2

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.

4.2.2. **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 41 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.

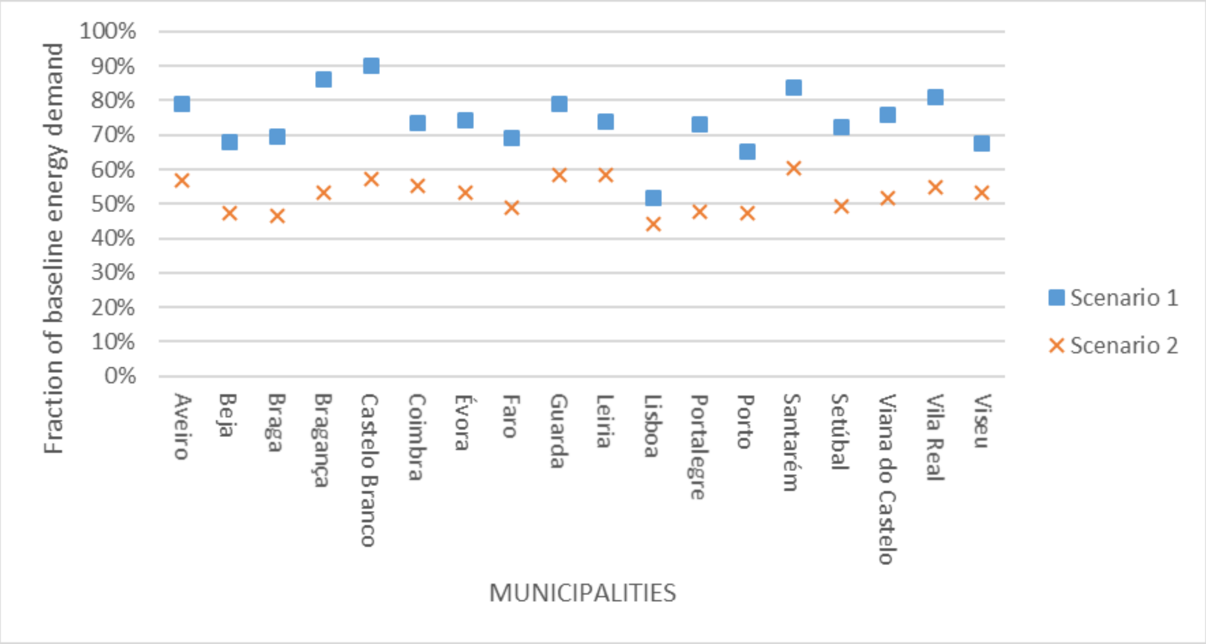

Figure 41 - Fraction of baseline total energy demand per municipality for scenarios 1 and 2

Overall, the total savings for the analysed Scenarios are of 37% of total Baseline Scenario energy demand for Scenario 1 and 52% for Scenario 2, which correspond to absolute savings of 10790 GJ for Scenario 1 and 15022 GJ for Scenario 2. The following Table 5 resumes the total savings for each municipality for both scenarios.

Table 5 - Total savings per municipality for Scenario 1 and Scenario 2

Municipalities	Scenario 1 Savings (GJ)	Scenario 2 Savings (GJ)
Aveiro	299	619
Beja	64	104
Braga	410	716
Bragança	18	60
Castelo Branco	25	109
Coimbra	604	1010
Évora	107	194
Faro	211	348
Guarda	56	110
Leiria	255	407
Lisboa	6101	7041
Portalegre	39	77
Porto	1899	2867
Santarém	113	276
Setúbal	202	369
Viana do Castelo	139	280
Vila Real	91	218
Viseu	156	224
Total	10790	15028

As expected, Scenario 2 account for higher energy savings, representing a 39% increase in savings when compared to Scenario 1. It is also important to point out the preponderance of Lisboa, which accounts for 56.6% of total energy savings for Scenario 1 and 47% of total savings for Scenario 2. If Scenario 2 is considered, Castelo Branco would increase its savings by 336%, being the municipality which would account for the highest percentage of savings increase. However, while Lisboa would only increase its savings by 15% from Scenario 1 to Scenario 2, it would still be the municipality with the second highest increase of savings in absolute values (940GJ), after Porto (968GJ).

4.2.3. **Share of energy demand consumed by BEVs**

The share of energy demand consumed accountable to BEVs was also assessed, as is presented in Figure 42. For the Baseline Scenario, BEV are not accounted for, therefore its energy consumption is not presented.

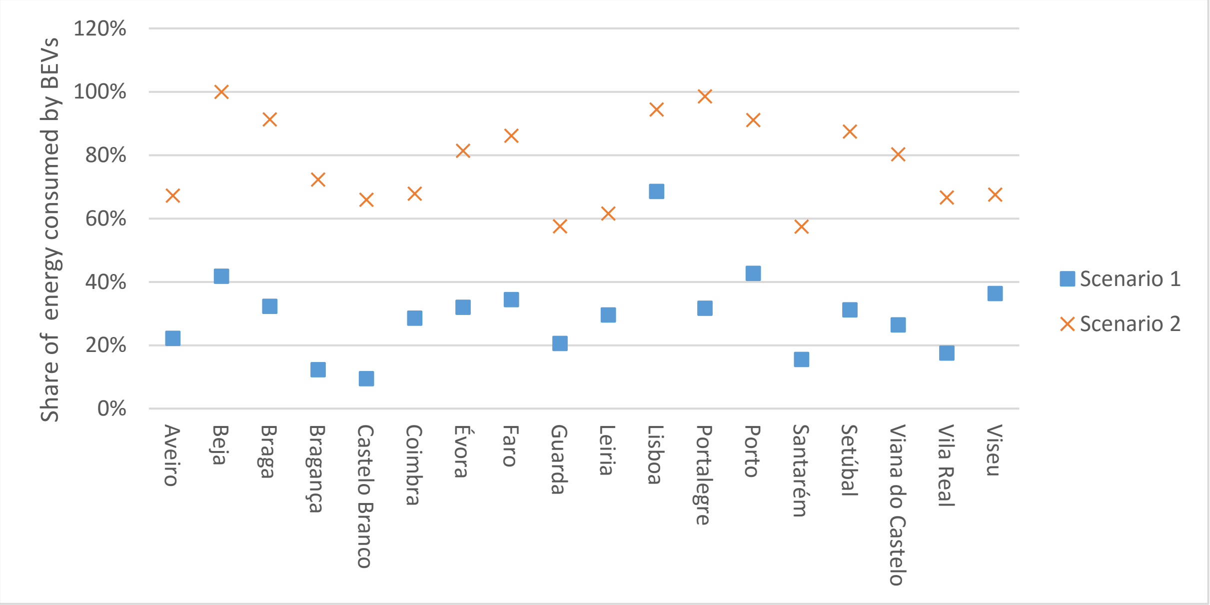

Figure 42 - Share of energy consumed by BEVs per scenario

For Scenario 1, Lisboa is the municipality that accounts for the highest share of energy consumed by BEVs (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 a BEV because their energy needs would be 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. Analysing 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. The following Table 6 shows the absolute values of savings for every studied scenario and the total values.

Table 6 - Energy demand by BEVs for Scenario 1 and Scenario 2

Municipalities	Scenario 1	Scenario 2
	Energy demand by BEVs (GJ)	Energy demand by BEVs (GJ)
Aveiro	250.3	544.2
Beja	56.0	93.7
Braga	300.6	570.8
Bragança	13.6	49.2
Castelo Branco	21.7	96.6
Coimbra	472.8	847.3
Évora	98.6	180.6
Faro	162.8	289.3
Guarda	43.0	89.0
Leiria	214.7	354.7
Lisboa	4475.5	5278.9
Portalegre	34.0	69.2
Porto	1516.3	2358.4
Santarém	90.1	240.0
Setúbal	164.8	316.1
Viana do Castelo	115.6	238.9
Vila Real	68.5	176.4
Viseu	117.5	173.4
Total	8216.5	11966.7

Naturally, scenario 2 represents higher values for energy demand by BEVs than Scenario 1 due to higher use, representing an increase of 3750198MJ (46% increase). When analysing absolute values, the preponderance of Lisboa and Porto become visible. In the Scenario 1, Lisboa accounts for 54% of total energy demand by BEVs and in Scenario 2 it accounts for 44% of total energy demand. Also, Porto accounts for significant values representing 18% in Scenario 1 and 20% in Scenario 2 of total energy demand by BEVs.

4.2.4.Municipalities and parishes charging needs

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. Table 7 summarizes the charging needs at the origin and destination for each municipality under analysis and for both scenarios. 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.

Table 7 - Total charging needs (kWh) at parish and municipality level for Scenario 1 and Scenario 2

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

4.2.5. **Share of commuters using BEVs**

The share of cars commuting that could switch to BEVs in each scenario is shown in Figure 43, with Table 8 indicating the absolute values. 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 42. 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 42. 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.

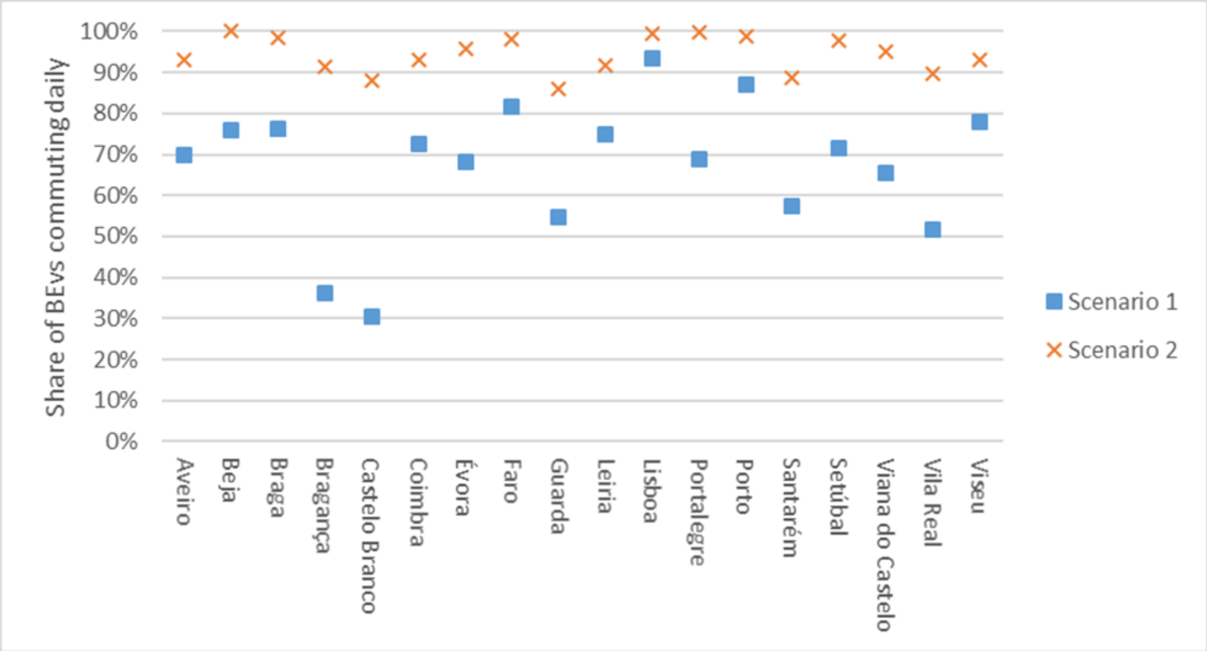

Figure 43 - Share of BEVs commuting daily per scenario

Table 8 - Number of BEVs commuting for Scenario 1 and Scenario 2

Municipalities	Scenario 1	Scenario 2
Aveiro	9775	13054
Beja	1419	1871
Braga	10988	14188
Bragança	291	735
Castelo Branco	467	1356
Coimbra	14732	18875
Évora	2319	3271
Faro	6979	8377
Guarda	1011	1593
Leiria	6927	8497
Lisboa	162787	173027
Portalegre	930	1349
Porto	71526	81332
Santarém	3132	4843
Setúbal	5208	7107
Viana do Castelo	3008	4380
Vila Real	1635	2836
Viseu	3504	4192
Total	306638	350883

4.3. 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 44 (Scenario 1) and Figure 45 (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.

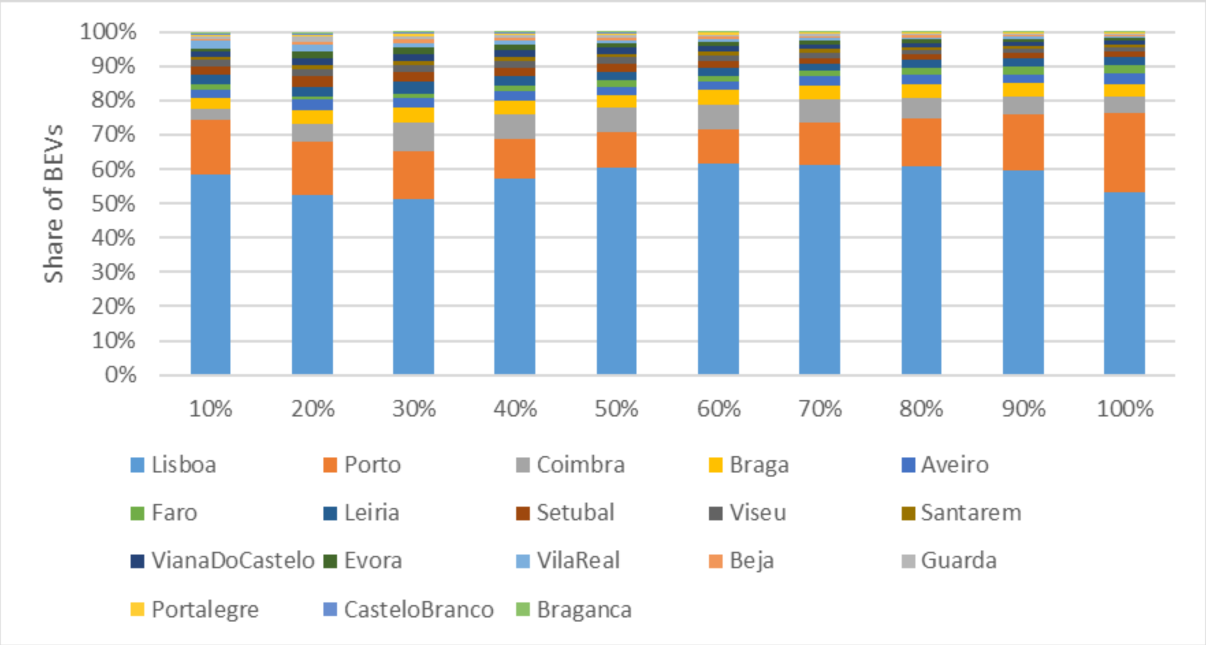

Figure 44 - Distribution of BEVs per municipality for Scenario 1 according to fraction of BEVs replaced

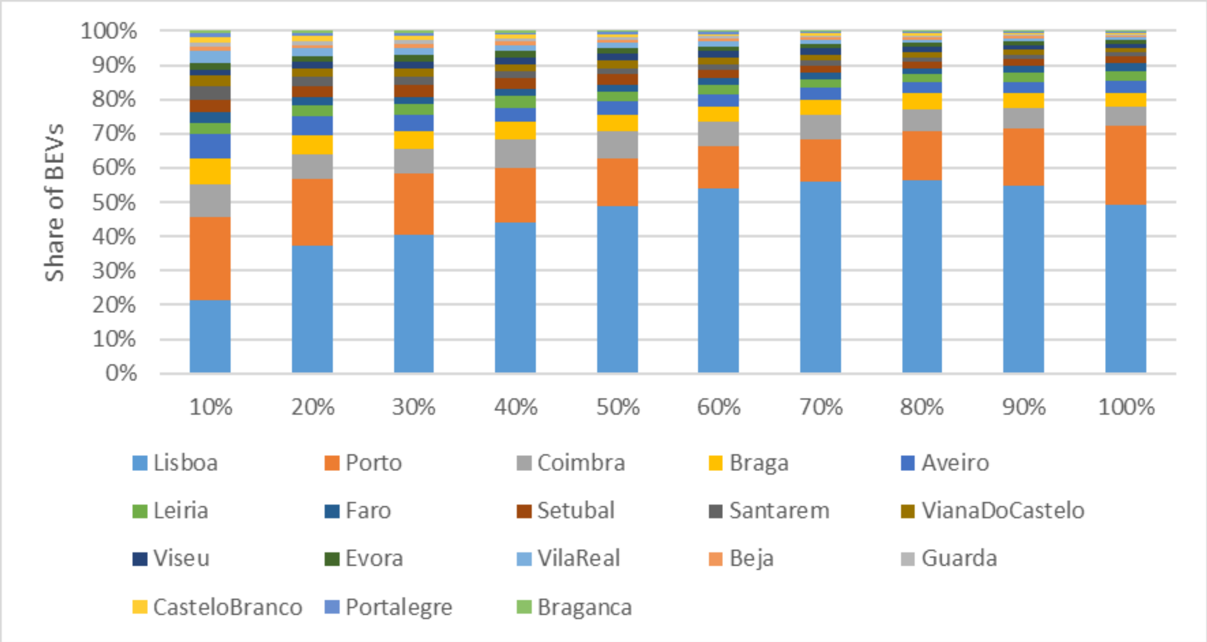

Figure 45 - Distribution of BEVs per municipality for Scenario 2 according to fraction of BEVs replaced

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 in Figure 45, 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 46 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.

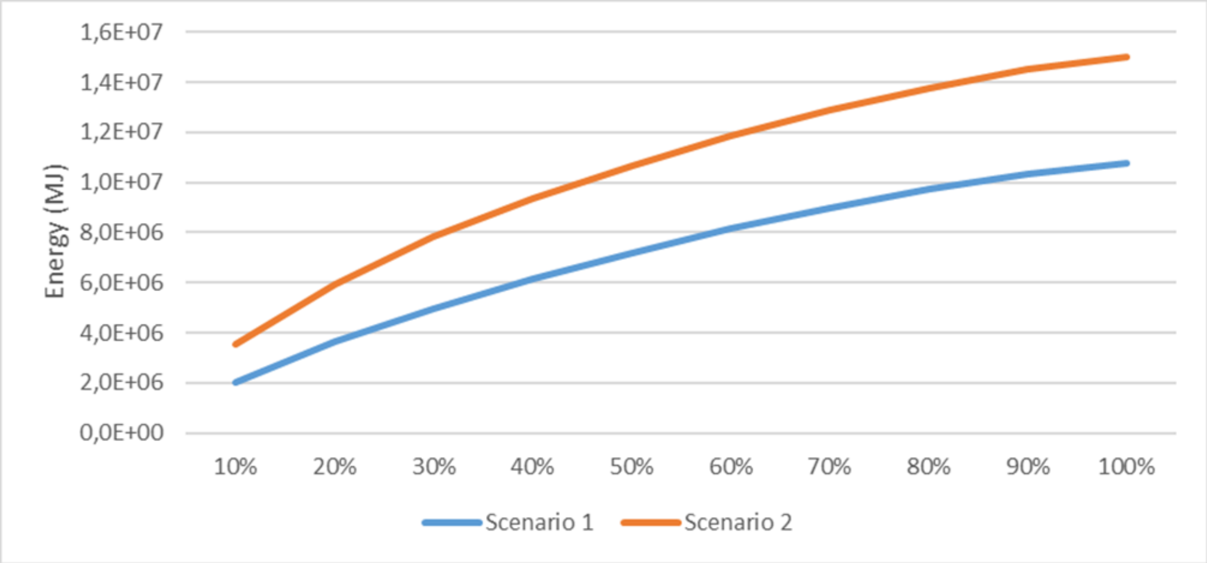

Figure 46 - Energy savings for different fraction of BEVs replaced for Scenarios 1 and 2

Table 9 shows the fraction of savings when compared to the total energy demand of the Baseline Scenario for the different fractions of BEVs replaced. Ultimately, if policy makers are able to guarantee that the vehicles with highest savings are replaced first, it would only be necessary to replace close to 30% of the total potential BEVs to achieve around 50% of the total potential energy savings in both scenarios.

Table 9 - Fraction of energy savings for both Scenario 1 and Scenario 2, when compared to the Baseline Scenario, for different fractions of BEVs replaced

%BEVs	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Scenario1	6.9%	12.4%	17.0%	21.0%	24.7%	27.9%	30.8%	33.3%	35.5%	37.0%
Scenario2	12.1%	20.4%	26.9%	32.1%	36.6%	40.6%	44.1%	47.2%	49.8%	51.5%

4.4. 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 47.

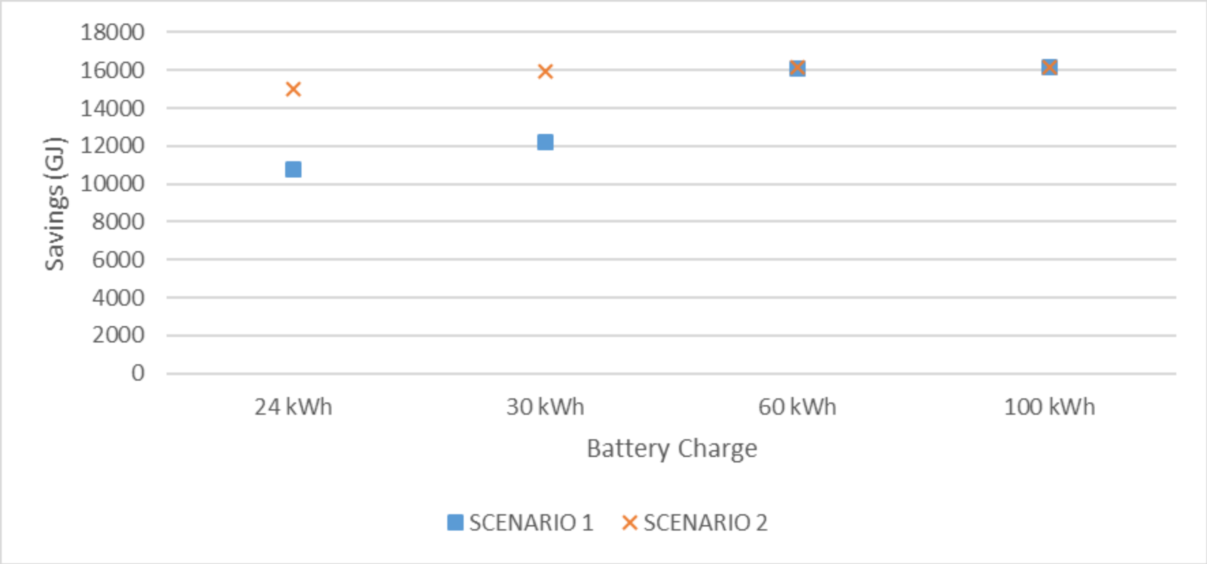

Figure 47 - Total savings per battery charge and per scenario

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 48. Table 10 summarizes the fraction of savings for each of the studied batteries for both scenarios. Both the increases in share of BEVs commuting and savings are very significant for Scenario 1 when evaluating the growth of 30 kWh battery to a 60 kWh battery. The implications of these results is that, if battery capacity increases to high values (60 kWh), the need for commuters using BEVs to charge in the destination of their commutes will reduce very significantly.

Table 10 - Fraction of savings when compared to the Baseline Scenario for different battery capacities

Battery (kWh)	SCENARIO 1	SCENARIO 2
24	37,0%	51,5%
30	41,9%	54,7%
60	55,1%	55,4%
100	55,3%	55,4%

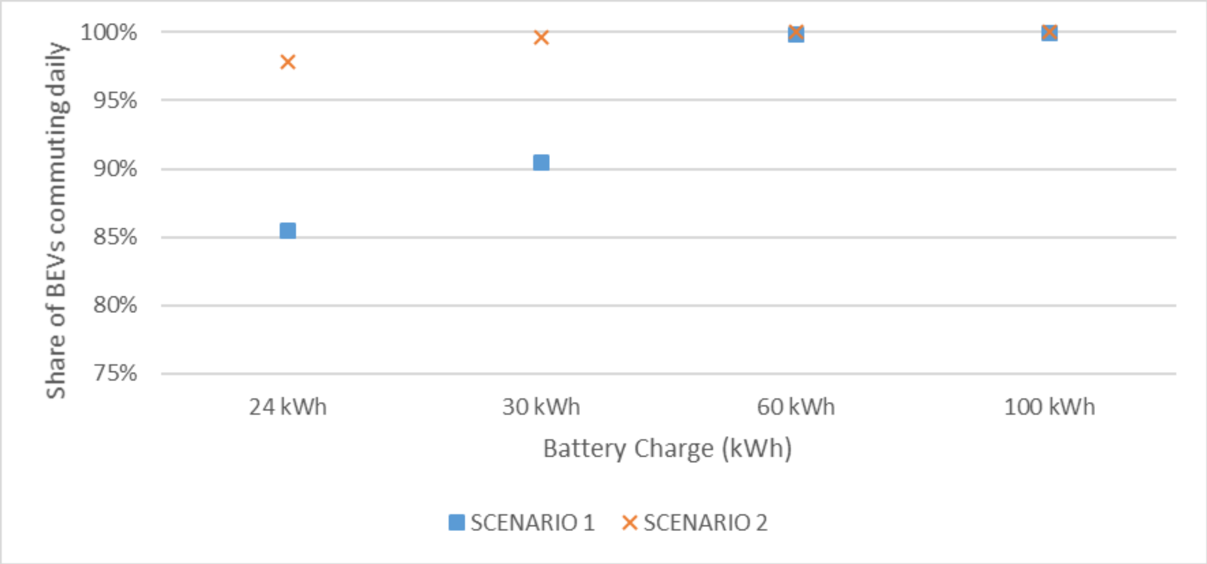

Figure 48 - Share of BEVs commuting daily following the sensitivity analysis

5. Conclusions and Future Work

5.1. 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.

5.2. Future Work

The developed methodology is applicable to any case study, however, as an improvement, the methodology should be applied to all municipalities in Portugal. Also, the application of the methodology to other counties would provide more insights into the impacts of variables such as topography, commuting patterns, usage of other transport modes, etc. Inner municipality mobility patterns could also be included. However, due to a lack of available information concerning living and working locations inside a municipality, this study would currently be very difficult.

During the data collection stage, geographical coordinates were retrieved to determine the entry and exit locations in every trip segment. Using this information, it should be possible to estimate appropriate locations for fast charging stations between destinations, by identifying the most relevant roads used for commutes.

The developed methodology could also be improved. First, different vehicle technologies could be included, such as PHEVs and different Euro standards. Second, when defining origin and destination, the available information does not define accurately the location (Google always attributes the parish or city centre as default), making the commute quite imprecise. A better characterization of the O/D matrices or even an address-to-address O/D matrix would improve the study accuracy.

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