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The Impacts of Battery Electric Vehicles on the Power Grid: A Monte Carlo Method Approach

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Abstract: Balancing energy demand and supply will become an even greater challenge considering the ongoing transition from traditional fuel to electric vehicles (EV). The management of this task will heavily depend on the pace of the adoption of light-duty EVs. Electric vehicles have seen their market share increase worldwide; the same is happening in Portugal, partly because the government has kept incentives for consumers to purchase EVs, despite the COVID-19 pandemic. The consequent shift to EVs entails various challenges for the distribution network, including coping with the expected growing demand for power. This article addresses this concern by presenting a case study of an area comprising 20 municipalities in Northern Portugal, for which battery electric vehicles (BEV) sales and their impact on distribution networks are estimated within the 2030 horizon. The power required from the grid is estimated under three BEV sales growth deterministic scenarios based on a daily consumption rate resulting from the combination of long- and short-distance routes. A Monte Carlo computational simulation is run to account for uncertainty under severe EV sales growth. The analysis is carried out considering three popular BEV models in Portugal, namely the Nissan Leaf, Tesla Model 3, and Renault Zoe. Their impacts on the available power of the distribution network are calculated for peak and off-peak hours. The results suggest that the current power grid capacity will not cope with demand increases as early as 2026. The modeling approach could be replicated in other regions with adjusted parameters.

Keywords: BEV; PHEV; electric vehicles; EV sales; energy demand; distribution grid; power impact

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1. Introduction

EU legislation targets are to cut CO_2 emissions from cars by 37.5% by 2030 [1]. Currently, the transport sector is a significant contributor to greenhouse gas emissions. An increase in the uptake of electric vehicles could contribute to the EU's policy objective of reducing greenhouse gas emissions from transports. Globally, low-carbon and sustainable energy actions are already underway, including electric mobility (e-mobility) initiatives, aiming to boost the transition to low (and zero)-emission vehicles. Electric vehicles represent a promising solution that meets the environmental goals for global sustainable development in terms of reducing local air pollution and addressing climate change.

Stricter emission regulations, lower battery costs, widely available charging stations, and increasing consumer acceptance will create new and strong momentum for market penetration of electrified vehicles in the coming years. Without exception, the present technical and economic studies predict a progressive replacement of internal combustion engine vehicles with EVs in the years to come.

Today the market offers several types of EVs that may be classified according to their propulsion systems and energy sources, including battery electric vehicles (BEVs), hybrid electric vehicles (PHEVs), plug-in hybrid electric vehicles, and extended-range electric vehicles [2,3]. In the future, other solutions may be available, including adding a fuel cell range extender to electric vehicles [4]; among other impacts, this approach might reduce the so-called range anxiety and affect vehicles owners' behavior. EVs rely on plug-in electricity, requiring a home charging point. They take electricity from the distribution grid and store it in rechargeable batteries that power the electric motor. Therefore, an affordable charge infrastructure is essential for the widespread adoption of EVs [5].

Several scientific works have been published, disseminating strategies and methodologies for analyzing and assessing the batteries' behaviors [6,7]. The studies' focus ranges from the maximization of the battery operation itself to the minimization of environmental impacts. They present significant results to minimize load peaks, flatten the load profile, and maximize the integration of renewables [8,9].

Several researchers have explored EV charging activities and their impacts on residential and distribution networks [10,11]. In addition, the impact of EV charging was validated in downtown Manhattan by assessing the effect on the distribution grid [12].

At the regional level, the charging of EVs can significantly increase electricity loads, causing possible negative impacts on distribution networks (e.g., cables and distribution transformers), especially for high-power charging [13]. The charging of residential EVs results in a significant increase in household electricity consumption that may exceed the maximum power supported by the distribution system itself. The situation can be worsened during times of high electricity utilization, such as peak hours or extreme days.

The distribution grid will have to carry out interventions and upgrades to manage the new and progressively increasing heavy energy load. To solve the technical constraints and understand how the network will withstand the increasing penetration of EVs, Mancini [14] developed urban and rural grid models to highlight the differences between the impacts on high- and low-density networks.

Although the transition to EVs is inevitable, their massive penetration will undoubtedly impact energy system management. Forecasting energy consumption helps to prepare for appropriate supply. In the literature, one can find forecasting models [15] that use five-year energy consumption data from a specific region and use the grey fractional model to analyze the next six years. Other forecasting methods have been studied, showing different requirements for raw data [16,17].

From technical and cybersecurity concerns to economic and social impacts, many issues have been addressed by several researchers, such as Ceballos Delgado [18], Das [19], and Jiang [20]. Other studies have already considered the consequences of a high EV penetration into the electricity market [21,22] in terms of the additional electrical load and surges in demand during peak hours. Anastasiadis [23] addressed the security of the distribution grids, while Khalid [24] analyzed problems related to power quality and reliability. Some authors have presented methodologies to limit the maximum power extracted from the grid to recharge EVs [25,26]. However, in the future, the integration of vehicle-to-grid (V2G) technology and smart grid charging may help address grid congestion and maintain the reliability and security of the power supply [27,28].

EV sales growth is a reality all over the world [29], driven by macroeconomic factors on which the development of battery technology and charging accessibility depend. At present, the purchase of an EV is not yet within everyone's financial reach, due to factors such as the high initial cost, battery degradation, and inadequate charge infrastructure [30]. Therefore, the evolution of EVs will largely depend on social and macroeconomic factors (including the rise of the global consumer middle class) and new mobility services such as car-sharing and e-hailing [31]. Currently, public financial incentives, such as reduced road and vehicle acquisition taxes, still directly impact BEV sales [32]. Norway is an example of the use of incentives aiming at massive electric vehicle adoption; the country has exempted BEVs from registration taxes since 1991 and from value-added tax since 2001; has waived tolls and ferry and parking fees for BEV owners since the late 1990s; and BEV drivers are allowed to use bus lanes and pay reduced company car taxes [33]. In 2020, BEVs accounted for 51.6% and PHEVs for 22.9% of Norway's passenger car sales [34]. Despite incentives, Norway had excellent conditions to adopt electric vehicles—a wealthy population, cheap hydroelectric energy, and high home charging availability, which are prerequisites that are unlikely present in most countries [33]. Today, Norway is dealing with more investment in public charging capacity, namely in regions with low EV density (raising charger placement issues).

Nevertheless, price reductions in further electric vehicles and business models such as car leases may enable people with no available capital to purchase electric vehicles. Additionally, the smart charging concept is worth mentioning, which refers to all intelligent technologies enabling a car to be charged at the best possible moment, thereby reducing the local grid congestion. In addition, residential smart charging could also smooth the integration of BEVs in the grid and could provide financial benefits to drivers, thereby reducing ownership costs [32].

E-mobility has reached a point of no return. As more models become available and prices decrease, EV purchases will increase, reaching a broader range of the vehicle-owning population, which should encompass more than 10% of sales by 2025 and 20–30% of sales by 2030 [35]. The current production forecast [36] reveals that car producers are expected to manufacture more EVs in the EU than necessary to comply with the minimum requirements of the EU CO_2 emission reduction standards. The share of EVs in car production in 2025 will be around 22% if carmakers follow the current vehicle production forecast, which is higher than the average 15% EV sales share needed.

The EV market in Portugal is also evolving at a fast pace. In 2020, the total number of BEV passenger cars circulating was 36,882, while PHEVs reached 27,710 units; combined, PEV and BEV cars represented a little over 1% of the national car fleet [37–39], which was over 5.5 million cars in 2020 (Table 1). Figure 1 displays the total number of BEV and PHEV passenger cars registered between 2015 and 2020 and their respective percentages relative to the total national fleet (including all types of cars).

Table 1. Portugal's total passenger car sales and fleet between 2015 and 2020 [37].

Year	Total National Passenger Car Sales		Total National Fleet	
	Number of Cars	**Growth Rate**	**Number of Cars**	**Growth Rate**
2015	178,503		4,850,000	
2016	207,330	16.15%	4,714,000	−2.80%
2017	222,134	7.14%	4,936,667	4.72%
2018	228,290	2.77%	5,232,500	5.99%
2019	223,799	−1.97%	5,376,481	2.75%
2020	145,417	−35.02%	5,504,776	2.39%
Average growth rate		8.69% *		2.61%

* Average of sales from 2016 to 2018 (excluding the short-term effects of the COVID-19 pandemic).

Despite the short-term impacts of the COVID-19 pandemic, resulting in a severe decline in national total passenger car sales because of economic uncertainty and changing consumer priorities, BEV and PHEV sales kept increasing, reaching a combined 13.5% of total passenger sales in 2020 [37], as seen in Figure 2. Moreover, continued growth is expected to be sustained throughout the 2020s [40].

There must be a huge investment in charging infrastructure, without which the decarbonization of transportation via electrification will be at stake. Additionally, distribution grids must be strengthened to cope with the expected energy demands from EV owners, especially considering the ambitious goal of achieving 20% e-mobility in 2030 established by the Portuguese government [41].

As mentioned by Awadallah and colleagues [42], every grid is a special case requiring an autonomous study to explore the issues and limits of EV charging loads. This paper aims to forecast the *BEV* segment development toward the 2030 horizon and its effect on the distribution power grid for an area comprising 20 municipalities in Northern Portugal.

The case describes three scenarios that consider different goals and energy consumption levels, relying on three popular EV models in the country, namely the Nissan Leaf, Tesla Model 3, and Renault Zoe. The impacts of the growing EV fleet on the distribution network are assessed, namely the extent to which the available grid power for charging copes with the load demand increases during peak and off-peak hours. The distribution network in this case study is analyzed according to its technical characteristics, constitution, and substation building type. The results are discussed to identify possible measures to address the impacts mentioned above and conclude if and when the local power grid operator should invest in the coming years to be prepared for such impacts.

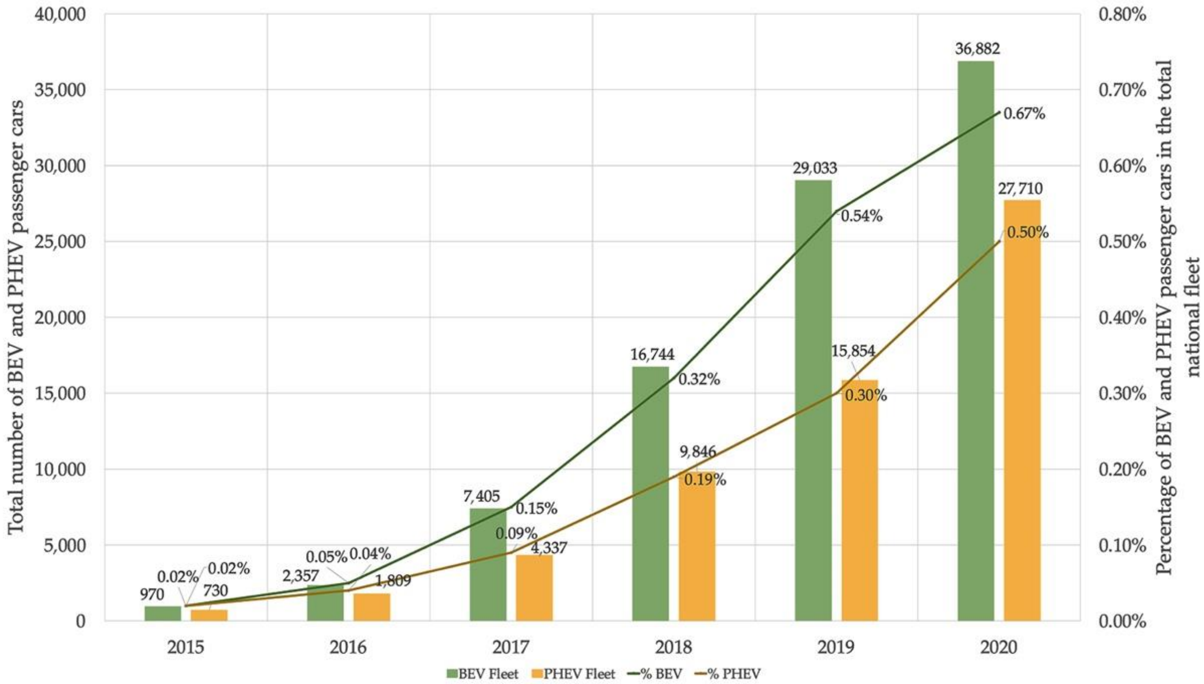

Figure 1. BEV and PHEV passenger car fleet and percentage of the total fleet, 2015–2020. Adapted from [37].

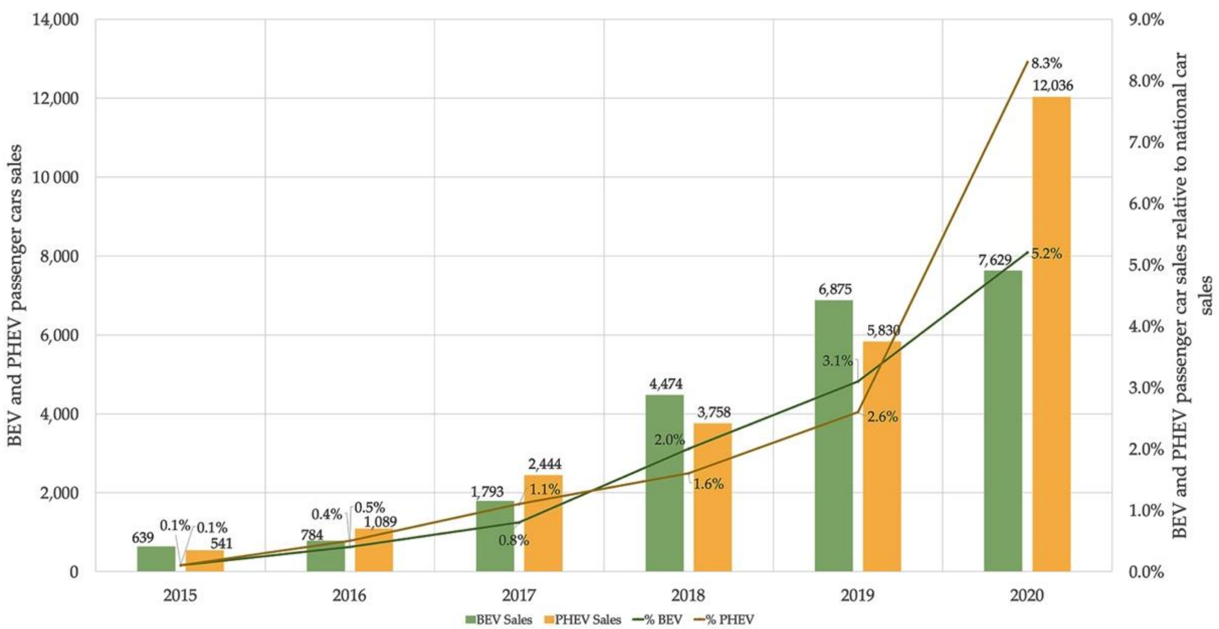

Figure 2. BEV and PHEV passenger car sales and percentage of the total national sales, 2015–2020 [37].

2. Case Study

2.1. Demographics

The study focuses on 20 municipalities in the regions of Ave, Tâmega, and Sousa, occupying an area of 3439.64 km^2 in Northern Portugal (Figure 3). As of July 2021, there were 911,878 residents in that area [43].

Figure 3. The 20 municipalities in Northern Portugal under study.

The population slightly decreased in the 2001–2019 period (−3.7%) [44]. The population per municipality was estimated for the period of 2021 to 2030, assuming it will follow the respective growth rate from the previous time span. In 2030, the projected population for the region totals 859,002 residents, or 8.9% of the national projected total, according to [43]. The residents per municipality, given as the percentage of the national total until 2030, will be used in this study as the basis for estimating the numbers of BEVs from national total sales and fleet.

2.2. BEV Consumption

The energy demanded from the grid to power BEVs depends on the vehicle owner's travel habits and automobile features. According to Sanguesa [45], the vehicle's mass is crucial for energy consumption in urban areas, while other coefficients play a critical role in highway environments. An energy consumption minimization framework for the routing optimization of BEVs is proposed in [46], yielding lower energy requirements to reaching destinations than Google's map original routes. Another study [47] proposes a real-time multi-objective prediction energy management strategy to optimize the fuel, electric, and battery degradation costs simultaneously for the energy management of a plug-in range-extended electric vehicle.

To determine the expected BEVs' energy consumption, this study considers two pattern routes: a long-distance route (intercity) and a short one (city route). In addition, the calculations involve three popular BEV models in Portugal [48], namely the Nissan Leaf, Tesla Model 3, and Renault Zoe.

2.2.1. Long-Distance Route

The route between Amarante (AM) and Águas Santas (AS), which is just outside the region's southwest borderline, was chosen to characterize the long-distance pathway. This is a 48 km long intercity highway with significant daily movement of passenger light-duty vehicles and with altitudes varying between 120 and 370 m. Considering the different slopes across the entire route, the power required for a one-way trip is different from that required on the way back.

The amount of mechanical energy output generated by the BEV motor impacts the car's acceleration and traction capacity; that is, the weight that it can move. The mechanical energy power output refers to the product of rotation speed and torque. The energy consumption of a BEV depends on the model, its technical characteristics, and its driving speed. The consumption calculation assumes an average speed of 100 km/h (kilometers per hour). In addition, when estimating EV consumption, other factors matter, such as the battery capacity and torque (the motor's pulling power in Nm).

Table 2 calculates the energy required for each BEV model to travel the mentioned long-distance route.

Table 2. Energy consumption for the long-distance route.

BEV Model	BEV Technical Characteristics			Energy Consumption		
	Weight (kg)	**Torque (Nm)**	**Capacity (kWh)**	**AM-AS (Wh)**	**AS-AM (Wh)**	**Round trip (Wh)**
Nissan Leaf	1520	320	40	7577	7397	14,974
Tesla Model 3	1847	350	74	8154	7934	16,088
Renault Zoe	1480	220	41	7042	6867	13,909

AM—Amarante; AS—Águas Santas.

As shown in Table 1, the energy required for each BEV model is below the battery capacity, at 37% for the Nissan Leaf, 22% for the Tesla, and 34% for the Renault Zoe. In order to extend a battery's life span, it should not discharge below 20% or charge above 80%; therefore, a BEV should be completely charged only for long-distance trips [49]. Herein, the battery net capacity will be considered as 60% of the total capacity. According to the actual daily route and the BEV's features, some vehicles may or may not need a charge once a day.

2.2.2. Short-Distance Route

Many electric vehicle drivers travel relatively short distances within the municipalities, moving from home to office throughout urban areas. A random route of 15 km was chosen to characterize a short-distance route, considering an average speed of 50 km/h. The ground slope of this route was not considered.

The power required to bring a BEV to the speed of 50 km/h is obtained by the sum of the resistive forces to the movement times the target speed. The resultant of these forces, the total drag force, can be estimated through the vehicle's mass, frontal surface area, and the rolling and drag coefficients. The power output requirement is determined from the drag force times the speed.

According to the specific characteristics of each BEV model, Table 3 presents the power output for the short-distance route and the daily energy consumption for the round trip (30 km), which is carried out in 36 min (0.6 h). As seen in Table 3, the energy required from the three BEVs for a short journey represents only about 6% of the battery capacity for the Nissan Leaf, 6.5% for the Tesla, and 5.7% for the Renault Zoe.

Table 3. Energy consumption for the short-distance route.

BEV Model	Battery Capacity (kWh)	Power (W)	Energy Consumption (Wh)
Nissan Leaf	40	3960	2376
Tesla Model 3	74	4325	2595
Renault Zoe	41	3769	2261

This study considers the representative energy consumption as the average consumption for the short- and long-distance routes, weighted by each BEV's relative market share, coming to a total of 8776 Wh required energy per day (Table 4).

Table 4. Daily average energy consumption.

BEV Model	Long Route (Wh)	Short Route (Wh)	Average Journey (Wh)	Weighting Factor (%)	Weighted Energy (Wh)
Nissan Leaf	14,974	2376	8675	42.2	3661
Tesla Model 3	16,088	2595	9342	35.2	3288
Renault Zoe	13,909	2261	8085	22.6	1827
				100.0	8776

Once the BEV's weighted energy value is known, it is possible to estimate the time needed for charging and the necessary power supply. As such, a single-phase station will be considered here, namely the Wallbox 7.4 kW (32 A), a semi-fast charging system that can withstand the power needs for this case. This equipment requires a home contracted (installed) power of 10.35 kVA (45 A), which is the standard rating to meet the required current for the battery.

2.3. Installed Power and Available Energy during Peak and Off-Peak Hours

The consumer substations installed in the municipalities involved in the study are of different types based on locality and design, such as pole-mounted substations (PMSs), high cabin station (HCSs), and low cabin station (LCSs), totaling 121, 77, and 83, respectively. Altogether, the power installed in the municipalities equals 1,443,943 kVA, as shown in Table A1 (Appendix A). This table also exhibits the power consumed in each municipality and calculates the available power during peak and off-peak hours. The aggregate available power is 13% higher than consumption during peak hours and 104% higher during off-peak hours. Naturally, the growth of BEVs over the years should boost the demand for power. To a certain extent, the distribution grid may cope with demand if consumer behavior changes and drivers are encouraged to recharge their BEVs during off-peak hours.

2.4. BEV Development from 2021 to 2030: Three Scenarios

Looking at the current state of the EV market worldwide, there is no doubt that it will increase over the next decade. However, the significant growth of EVs leading up to 2030 will present significant challenges for the distribution grid, notably in the available power supply from utilities [50,51]. As can be noted in Figure 2, in 2020 PHEV sales peaked, overcoming BEV sales. The preference for PHEV may be related to high prices for BEVs and the lack of sufficient charging stations in Portugal, totaling 2471 in 2020, of which 494 were fast charge (>22 kW) and 1976 were normal charge (<22 kW) points, whereas the number of EVs per public recharging point was 26, which is far above the European Union (EU) average of 9 [37]. As recharging stations evolve and BEV prices fall, BEV sales should increase substantially in relation to PHEVs.

The following sections describe three scenarios for the BEV market in Portugal and how they will impact the power grid of this case study's locations until the end of the decade. In all scenarios, the number of BEVs considered is determined as the proportion of the case study location's population to the national population times the national fleet. The energy required by projected BEVs is obtained by multiplying the number of vehicles by the installed recharging capacity of 10.35 kVA and is then compared to the available energy during peak and off-peak hours, thereby determining the impact of the BEV fleet on the distribution grid.

2.4.1. Scenario 1

The first scenario assumes that BEV passenger car sales will increase to one-third of the total national sales in 2030, a milestone conveyed by the Portuguese minister for the environment and climate action [52]. The BEV sales in the first nine months of 2021 reached 7984 cars; this figure was extended to 10,645 car sales in 2021. The projection starts with this total, evolving at a constant yearly pace to reach one-third of the total BEV sales in 2030. The total national passenger car sales in 2021, 2022, and 2023 are estimated to grow at 11%, 20%, and 15%, respectively, reflecting the expected short-term higher growth following the COVID-19 pandemic; from 2024 to 2030, grow is estimated at 8.69%/year, assuming national sales will stabilize at the pre-pandemic growth rate (as determined in Table 1). The BEV sales volume for the 20 municipalities of the case study is calculated as a percentage of total national sales; that percentage increases by the year to reach one-third of the total national sales in 2030. Accordingly, in that year the BEV fleet will reach 654,451 cars (Table 5).

Table 5. Calculation of the BEV fleet for scenario 1.

Year	Total National Passenger Car Sales	Percent of BEV Sales	Number of BEV Sales	BEV Fleet
2020	145,417	5.2%	7629	36,882
2021	161,413	6.6%	10,645	47,527
2022	193,695	9.6%	18,529	66,056
2023	222,750	12.5%	27,926	93,982
2024	242,100	15.5%	37,544	131,527
2025	263,131	18.5%	48,623	180,150
2026	285,989	21.4%	61,344	241,494
2027	310,833	24.4%	75,907	317,401
2028	337,835	27.4%	92,538	409,939
2029	367,183	30.4%	111,486	521,425
2030	399,080	33.3%	133,027	654,451

2.4.2. Scenario 2

In the second scenario, the authors assume constant BEV passenger car sales growth that equals the rate registered from 2020 to 2021, or 39.5%, starting with 10,645 car sales in 2021, as in the previous scenario. Thus, in 2030, the BEV fleet will equal 763,424 cars across the 20 municipalities (Table 6).

Table 6. Impacts of the BEV fleet on the grid during peak hours under scenario 1 (values in kVA).

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Number of BEV sales	7629	10,645	14,854	20,727	28,922	40,358	56,314	78,579	109,648	153,000	213,493
BEV fleet	36,882	47,527	62,382	83,109	112,031	152,389	208,703	287,283	396,931	549,931	763,424

2.4.3. Scenario 3

The third scenario forecasts the BEV fleet, aiming to meet the 'National Energy and Climate Plan' document [41], i.e., reaching 20 percent electric mobility. In the case study, this means that the BEV fleet will also reach that percentage of the circulating passenger fleet in 20 municipalities. Table 7 shows the forecasted national fleet, where the percentage of BEVs is set to 0.67% in 2020 and 2021 to align the fleet number with known estimates for those years. The BEV fleet is then determined as a percentage of the total national fleet, ensuring a steady pace and reaching 20% in 2030 (Table 7).

2.4.4. Scenario Comparison

All scenarios forecast a notable growth in the BEV fleet for the entire country and consequently for the 20 municipalities at stake until 2030 (obtained as a proportion of the population against the total national); the required energy increase follows the same rate (obtained from multiplying the number of BEVs by 10.35 kVA), as seen in Figure 4.

Table 7. Calculation of the BEV fleet in scenario 1.

Year	National Fleet	Percent of BEV Sales	BEV Fleet
2020	5,504,776	0.67%	36,882
2021	5,543,580	0.67%	47,527
2022	5,633,276	2.82%	158,733
2023	5,724,424	4.97%	284,249
2024	5,817,046	7.11%	413,786
2025	5,911,167	9.26%	547,440
2026	6,006,811	11.41%	685,310
2027	6,104,002	13.56%	827,499
2028	6,202,766	15.70%	974,110
2029	6,303,128	17.85%	1,125,248
2030	6,405,114	20.00%	1,281,023

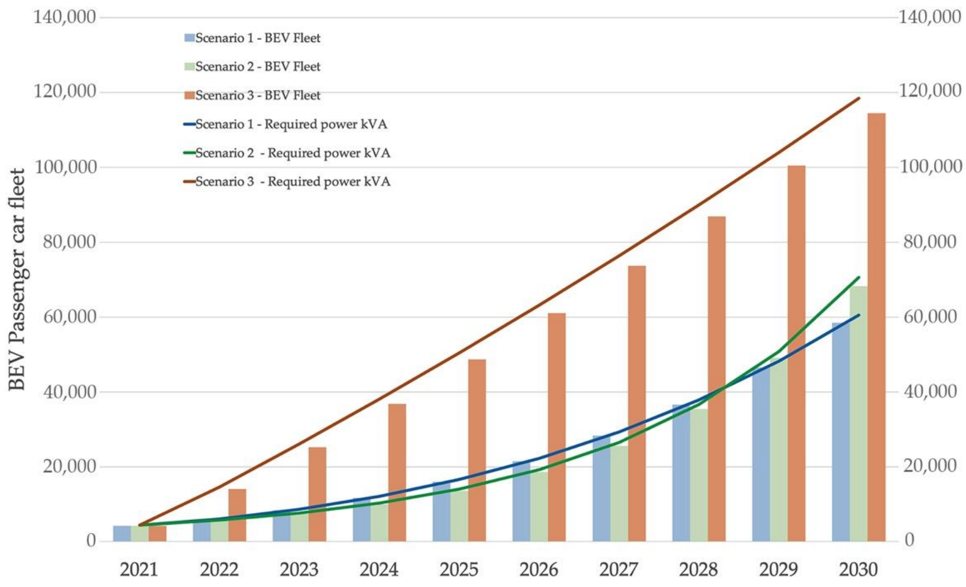

Figure 4. BEV passenger car fleets under the three scenarios, 2021–2030.

Scenarios 2 and 3 generate very close curves, achieving total national fleets in 2030 of comparable magnitude (58,477 and 68,214, respectively), whereas scenario 3 takes off very quickly, reaching a total of 114,463 units within the same year. In 2030, the required power from the grid for recharging the BEV fleet is 605,240 kVA in scenario 1,706,018 kVA in scenario 2, and 1,184,696 kVA in scenario 3. The available power during peak and off-peak hours, calculated in Table A1 (Appendix A), must be enough to satisfy this demand in each municipality. Table A2 (Appendix B), Table A4 (Appendix C), and Table A6 (Appendix D) show the impacts of BEV recharging during peak hours for scenarios 1, 2, and 3, respectively, calculated as the differences between available power during peak hours and the required power. Similarly, Table A3 (Appendix B), Table A5 (Appendix C), and Table A7 (Appendix D) show the impacts of BEV recharging during off-peak hours for scenarios 1, 2, and 3, respectively, calculated as the differences between available power during off-peak hours and the required power.

The local grid can satisfy demand in scenarios 1 and 2, except for very few critical situations that occur only in 2030 during peak hours in a limited number of municipalities (three in scenario 1 and nine in scenario 2, enhanced in bold in Table A2, Appendix B, and Table A4, Appendix C). In the 20 municipalities, the aggregate impact is positive; that is, the region is globally able to cope with power requirements for BEV recharging. During off-peak hours, there is no criticality in scenarios 1 and 2 (Figure 5).

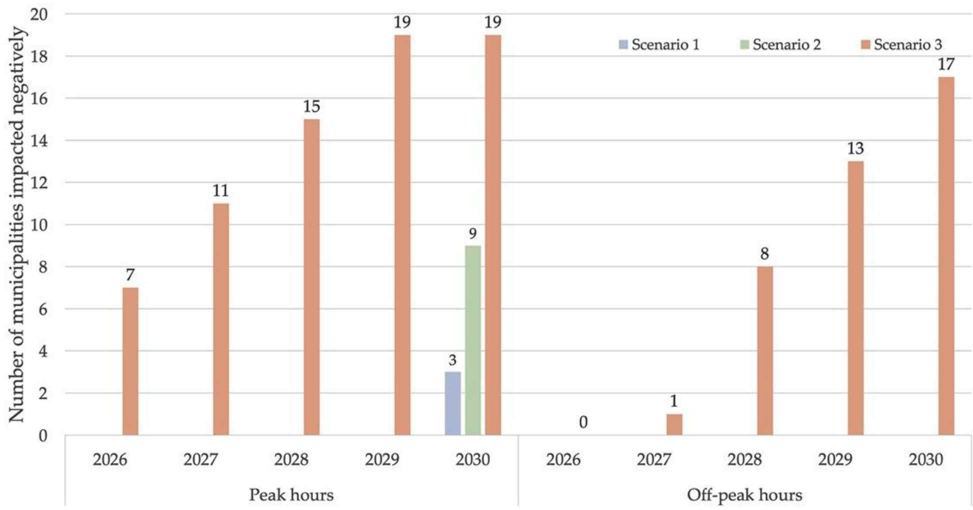

Figure 5. Number of municipalities impacted negatively during peak and off-peak hours, 2026–2030.

In contrast, scenario 3 is quite critical (Figure 6). Several municipalities cannot cope with the power required by BEVs during peak hours, starting at 7 in 2026 and ending at 19 out of 20 in 2030 (enhanced in bold in Table A6, Appendix D). The situation is also critical for off-peak hours from 2027 to 2030; in 2030, 17 out of 20 municipalities do not satisfy demand (enhanced in bold in Table A7, Appendix D). In aggregate terms, however, the impacts are negative during peak and off-peak hours in 2028 and 2029, respectively.

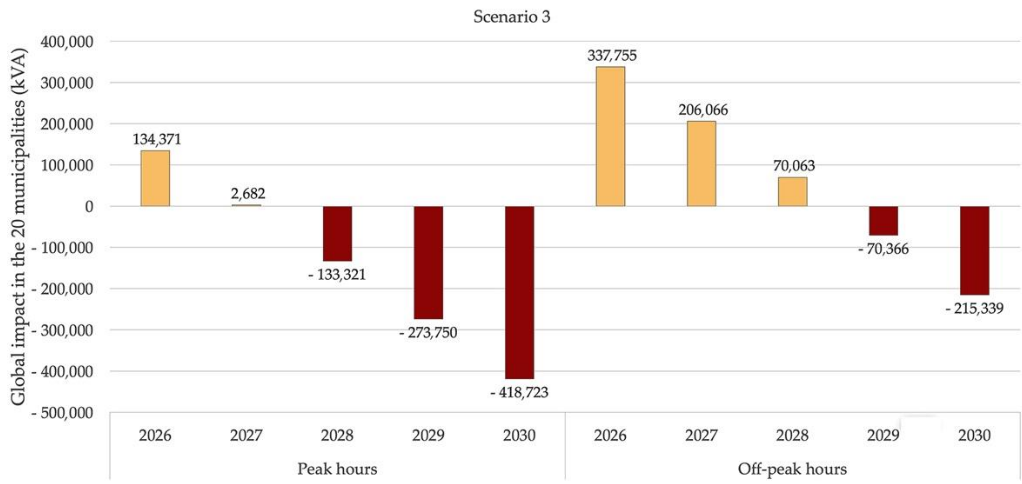

Figure 6. Global impacts for the municipalities during peak and off-peak hours, 2026–2030.

3. Monte Carlo Computational Simulation

At this point, one could question the likelihood of the occurrence of the three scenarios. The national goals set for the 2030 horizon in [41], which led to scenario 3, result from the government commitment towards achieving carbon neutrality in 2050, in line with EU targets. Therefore, one could expect the government to create measures to encourage grid operators to invest in increasing the power infrastructure capacity and consumers to shift their preferences to EVs. As such, EV sales will probably rise, and as more recharging stations become available, BEVs sales will be boosted. Accordingly, scenario 3 may be the most likely; it would be prudent to take it seriously because it points to dramatic impacts. Moreover, power demands due to EV sales could increase even further. As mentioned previously [36], carmakers are already planning for sales beyond the EU's regulatory CO_2 compliance for 2025 and 2030, as they foresee a real market-driven demand for electric cars. As such, the national electric vehicle fleet should experience growth beyond the forecast in scenario 3 if the Portuguese market follows that trend. In the absence of known estimates concerning more severe scenarios, one can only acknowledge the likely acceleration in EV adoption compared to scenario 3 and consider the BEV sales as a probabilistic variable; then, one can use Monte Carlo computational numerical methods to forecast the impact of BEVs on the power grid, incorporating stochastic variability in the deterministic base case in scenario 3.

As mentioned in [36], EV production may reach 22% of total passenger car production in 2025, higher than the 15% of sales needed to comply with the EU targets, which means sales could be around 46% higher than expected. We will start from a three estimated points approach, defining the sales under scenario 3 as the most likely, the sales under scenario 2 as optimistic, and a new sequence of yearly sales 46% higher than in scenario 3 sales as pessimistic. To perform the Monte Carlo simulation analysis, the BEV sales from 2022 to 2030 will be modeled as a beta-Pert distribution, using the pessimistic, most likely, and pessimistic sales as parameters (sales in 2021 will remain the same as before). A 10,000 trial simulation shows that the aggregate impact means for the peak and off-peak hours are not very different from the base case scenario 3. However, it now reveals the probability of that impact being negative, which is valuable information (Table 8, in bold).

Table 8. Monte Carlo simulation, showing impacts during peak and off-peak hours (2022–2030) and the probability of negative impacts.

Year:	2022	2023	2024	2025	2026	2027	2028	2029	2030
Peak hours									
Base Case (kVA)	620,156	504,645	385,246	261,856	134,371	2682	−133,321	−273,750	−418,723
Mean (kVA)	626,432	516,887	402,318	282,409	156,679	25,014	−112,737	−257,563	−410,095
Standard Deviation (kVA)	24,652	36,118	44,241	51,070	56,886	61,600	65,504	68,118	69,883
Minimum (kVA)	573,920	414,971	266,044	127,354	−40,433	−199,774	−337,943	−499,078	−666,851
Maximum (kVA)	698,954	647,472	562,702	465,303	344,411	234,067	118,196	−18,459	−163,785
Probability that impact < 0 kVA	0.0%	0.0%	0.0%	0.0%	**0.3%**	**34.7%**	**95.9%**	**100.0%**	**100.0%**
Off-peak hours									
Base Case (kVA)	823,540	708,029	588,630	465,240	337,755	206,066	70,063	−70,366	−215,339
Mean (kVA)	829,816	720,271	605,702	485,793	360,063	228,398	90,647	−54,179	−206,711
Standard Deviation (kVA)	24,652	36,118	44,241	51,070	56,886	61,600	65,504	68,118	69,883
Minimum (kVA)	777,304	618,355	469,428	330,738	162,951	3610	−134,559	−295,694	−463,467
Maximum (kVA)	902,338	850,856	766,086	668,687	547,795	437,451	321,580	184,925	39,599
Probability that impact < 0 kVA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**8.0%**	**79.1%**	**99.8%**

As an example, Figure 7 depicts the simulation for 2027 during peak hours; the red area of the curve translates into a 34.7% probability of negative impact.

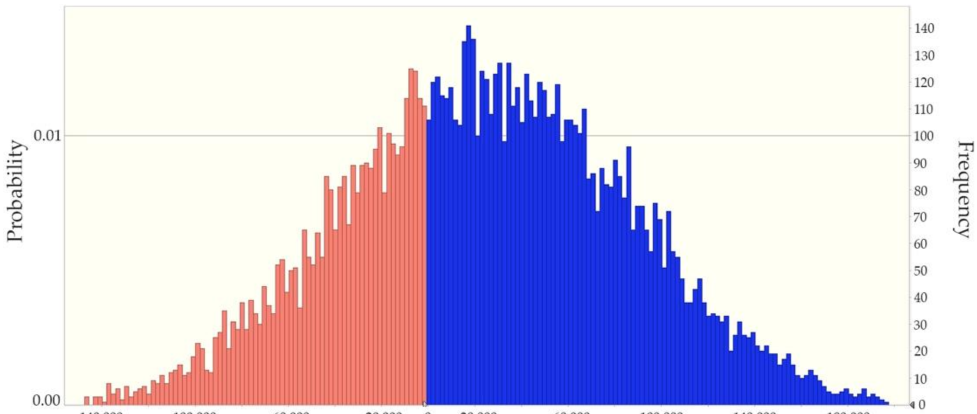

Figure 7. Monte Carlo simulation: probability/frequency chart of impact during peak hours in 2027.

In the simulation base case (scenario 3), the aggregate impacts during peak hours are negative only from 2028 to 2030; now, the simulation reveals that there is a 0.3% and

34.7% likelihood that those impacts will occur by 2026 and 2027, respectively. Similarly, the aggregate impacts during off-peak hours are negative only in 2029 and 2030; now, there is a probability that they will also happen in 2028. The simulation confirms scenario 3′s expectations and shows that there is a risk of failing to cope with demand earlier than expected.

4. Discussion and Conclusions

This case study addressed the growing BEV passenger car fleet in 20 municipalities of Northern Portugal and how the required power for recharging batteries will impact the local power distribution grid. The case was first analyzed under three scenarios. Firstly, assumptions were established concerning demographics, representative entities for a BEV, its power consumption, and daily distance covered (weighted average of long and short routes), and public information was gathered to describe the installed power grid capacity within the considered municipalities and the national EV sales and fleet. Then, each scenario was specified with further assumptions. In brief, scenario 1 assumed the goal of achieving BEV sales equaling one-third of the total national sales in 2030. In scenario 2, the goal is maintaining the recently registered sales growth from 2019 to 2020 during the 2021–2030 period. In scenario 3, the goal is for the national BEV passenger car fleet to reach 20% of the national total. The number of BEVs in the region was estimated as a percentage of the national fleet (calculated as the proportion of residents to the national population), while the required power by each BEV was 10.35 kVA. Finally, the impact of the BEV fleet on the power distribution grid was estimated as the difference between available power and the required energy for both peak and off-peak hours. In all scenarios, some municipalities were unable to cope with the demand for recharging batteries. The aggregated demand in scenarios 1 and 2 was satisfied by the installed capacity; however, in scenario 3, the grid could not satisfy the demand from 2028 to 2030 during peak hours and from 2029 to 2030 during off-peak hours. Another forecast was carried out, acknowledging the possible acceleration of EV sales at a rate 46% higher than expected (keeping in mind EU targets). In that case, the authors decided to perform a Monte Carlo computational simulation to predict the power demands, incorporating uncertainty in the deterministic base case in scenario 3, which impacted the aggregate demand, which although not far from the base case showed a significant probability of being negative earlier than expected. This information is valuable for the grid operators because it provides a measure of the risk of not meeting BEV demand and underpins the need to consider timely expansion investments of the power grid.

The study's deterministic and stochastic modeling of BEV fleet impacts on the power grid shows that the network runs out of its feeding capacity if BEV production increases until the end of the decade. This approach could be easily replicated in other regions, provided the parameters are calibrated to reflect differences in the considered variables. However, one should note several aspects of the case study assumptions that could significantly alter the model and its outputs. Firstly, the representative BEV was characterized based on three models only. The availability of new affordable BEVs will soon change the current scenario. Additionally, one can anticipate that carmakers will invest in improving all EV characteristics, including weight and efficiency. Therefore, the representative model should be adjusted accordingly. Secondly, the required power for recharging a BEV was estimated based on the daily distance covered by a vehicle and the characteristics of the routes. In this case, a representative route was defined based on long- and short-distance paths. Other routes could be considered, which might create alternative energy requirements. Thirdly, our approach estimated the BEV fleet as a proportion of the local population to the national population. This assumption could be refined, as the expected population growth for the region may be somehow evolve differently from the country's population growth. Additionally, the local residents' average purchasing power may not coincide with that of the national residents. Another important remark is that the forecasts described in the case study estimated the ability of the local power grid to attend to the BEV fleet demands as a whole; that is, the model analyzed whether the grid could cope with all demands during peak and off-peak hours. Eventually, the grid could feed all BEVs if the consumers comply with controlled recharging, splitting demand between both periods. Although operators may encourage charging during off-peak hours, it is not guaranteed that consumers will cooperate; as such, we opted for the worst-case scenario. However, should there be any reason to believe that splitting could be enforced, a new study should analyze the impacts of controlled consumer behavior. Finally, other BEV sales and fleet forecasting assumptions do not take into consideration the idea that possibly alternative technologies may make an impact soon (e.g., hydrogen cars), while PHEVs could still have opportunity for growth if carmakers decide to improve their technology and weight, which would change assumptions about sales and market shares.

The replication of the case study approach in other regional networks may highlight congestion issues. To tackle such situations, distribution operators must strengthen their infrastructure. In addition, there are various additional technical interventions to consider: the current conductors' replacement with a larger cross-section to withstand the thermal limits; the insertion of more conductors in parallel to decongest the overloaded cables; and the transformer power reinforcement, which is the most crucial upstream action. Additionally, the distribution grid considered in this study comprises consumer substations of different building types (PMS, HCS, and LCS). The BEV fleet growth will cause impacts in terms of voltage drops; some are better prepared to meet increased demand than others. In this regard, major physical interventions may be necessary, as is the case with building restructuring. Another approach is to explore the dynamic line rating (DLR) approach, whereby the power system has thermally sensitive assets such as lines and transformers, and there is a growing trend to use the capacity of those assets dynamically under varying operating conditions [53]. A good solution to lighten the consequences of BEV demand increases is micro-production. The self-production of photovoltaic electricity is becoming crucial. Charging a BEV with electricity generated by photovoltaic systems should become a worthwhile option. The energy from a building's own roof is cost-effective and has net-zero emissions. Providing easy home and workplace charging should be a priority. Although not within the scope of this study, one should mention the negative impact that the integration on the grid of other electric vehicles may cause, namely trucks and bus fleets [28]. This perspective calls for the adoption of smart charging to address the expected grid congestion and maintain the reliability and security of the power supply. Finally, storage systems based on the second use of discarded electric vehicle batteries have been identified as cost-efficient and sustainable alternatives to first-use battery storage systems [54]. In addition, EV second-life battery storage systems may prove responsive, efficient, and scalable [55]; they could contribute to additional buffer capacity for the electrical grids.

There is little doubt that EVs are here to stay. Consumers are increasingly more inclined to consider EVs. As prices decrease and governments offer financial incentives such as tax reductions and exemptions for electric vehicles, the shift towards electric mobility will increase. Power grid operators must be aware of this process, anticipate infrastructure investments, and manage BEV recharging to cope with this growing demand. Charging infrastructure needs to be effectively deployed in line with the growing EV uptake at all levels. This study intended to provide an original and feasible approach to analyze the impacts of BEV passenger fleet growth on the power grid until 2030. It could be adjusted to reflect improved assumptions and contextual changes and could helpful in studying other grids beyond the one considered in the case study.

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Appendix A

Table A1. Installed power and available energy during peak and off-peak hours by municipality [56].

Municipality	Power Installed (kVA)	Power: Peak Hours (kVA)		Power: Off-Peak Hours (kVA)	
		Required	Available	Required	Available
Castelo de Paiva	24,100	10,055	14,045	7038	17,062
Cabeceiras de Basto	26,103	10,968	15,135	7679	18,424
Celorico de Basto	29,975	12,605	17,370	8825	21,150
Fafe	88,711	40,022	48,689	28,015	60,696
Guimarães	280,295	115,396	164,899	80,778	199,517
Póvoa de Lanhoso	35,118	16,296	18,822	11,407	23,711
Vieira do Minho	23,243	9138	14,105	6397	16,846
Vila Nova de Famalicão	199,080	88,544	110,536	61,980	137,100
Vizela	33,435	18,031	15,404	12,621	20,814
Amarante	73,798	40,828	32,970	28,580	45,218
Baião	25,640	12,720	12,920	8904	16,736
Felgueiras	88,050	49,395	38,655	34,577	53,473
Lousada	72,835	35,516	37,319	24,862	47,973
Marco de Canaveses	83,600	40,657	42,943	28,461	55,139
Paços de Ferreira	101,375	46,845	54,530	32,792	68,583
Paredes	110,210	53,739	56,471	37,617	72,593
Penafiel	99,600	51,915	47,685	36,341	63,259
Mondim de Basto	12,485	5662	6823	3964	8521
Cinfães	23,980	12,717	11,263	8902	15,078
Resende	12,310	6921	5389	4846	7464
Total	1,443,943	677,970	765,973	474,586	969,357

Appendix B

Table A2. Scenario 1: Impacts (available power–required power) of the BEV fleet on the grid during peak hours (values in kVA).

Municipality.	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	13,474	13,312	13,029	12,605	12,036	11,303	10,381	9246	7868	6214	4250
Cabeceiras de Basto	14,558	14,394	14,110	13,683	13,111	12,374	11,449	10,311	8930	7275	5311
Celorico de Basto	16,665	16,463	16,111	15,580	14,869	13,949	12,790	11,358	9615	7519	5021
Fafe	46,908	46,394	45,501	44,154	42,345	40,003	37,049	33,395	28,943	23,581	17,186
Guimarães	159,252	157,623	154,786	150,512	144,765	137,323	127,935	116,318	102,158	85,098	64,743
Póvoa de Lanhoso	18,025	17,796	17,396	16,794	15,985	14,938	13,618	11,985	9996	7600	4743
Vieira do Minho	13,669	13,548	13,337	13,021	12,601	12,061	11,387	10,561	9564	8375	6970
Vila Nova de Famalicão	105,635	104,195	101,687	97,897	92,777	86,115	77,669	67,166	54,298	38,720	20,039
Vizela	14,513	14,250	13,791	13,097	12,158	10,934	9380	7443	5066	2184	**−1278**
Amarante	31,004	30,445	29,473	28,011	26,053	23,527	20,353	16,442	11,694	5997	**−772**
Baião	12,229	12,035	11,698	11,191	10,516	9647	8559	7223	5606	3674	1386
Felgueiras	36,560	35,952	34,894	33,297	31,148	28,359	24,836	20,469	15,137	8704	1015
Lousada	35,577	35,064	34,171	32,818	30,991	28,611	25,591	21,833	17,224	11,640	4938
Marco de Canaveses	41,031	40,476	39,509	38,051	36,087	33,539	30,319	26,327	21,453	15,570	8539
Paços de Ferreira	52,414	51,787	50,694	49,040	46,800	43,878	40,164	35,535	29,848	22,946	14,648
Paredes	53,358	52,455	50,883	48,512	45,319	41,178	35,947	29,464	21,549	12,000	588
Penafiel	45,096	44,346	43,039	41,070	38,419	34,981	30,640	25,263	18,700	10,784	1328
Mondim de Basto	6567	6496	6372	6187	5939	5622	5225	4739	4152	3452	2625
Cinfães	10,592	10,404	10,079	9591	8940	8105	7062	5782	4238	2394	215
Resende	5016	4912	4731	4459	4097	3633	3052	2340	1480	453	**−761**
Total	732,145	722,347	705,292	679,569	644,954	600,080	543,405	473,200	387,519	284,179	160,733

Table A3. Scenario 1: Impacts (available power–required power) of the BEV fleet on the grid during off-peak hours (values in kVA).

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	16,491	16,329	16,046	15,622	15,053	14,320	13,398	12,263	10,885	16,491	16,329
Cabeceiras de Basto	17,847	17,683	17,399	16,972	16,400	15,663	14,738	13,600	12,219	17,847	17,683
Celorico de Basto	20,445	20,243	19,891	19,360	18,649	17,729	16,570	15,138	13,395	20,445	20,243
Fafe	58,915	58,401	57,508	56,161	54,352	52,010	49,056	45,402	40,950	58,915	58,401
Guimarães	193,870	192,241	189,404	185,130	179,383	171,941	162,553	150,936	136,776	193,870	192,241
Póvoa de Lanhoso	22,914	22,685	22,285	21,683	20,874	19,827	18,507	16,874	14,885	22,914	22,685
Vieira do Minho	16,410	16,289	16,078	15,762	15,342	14,802	14,128	13,302	12,305	16,410	16,289
Vila Nova de Famalicão	132,199	130,759	128,251	124,461	119,341	112,679	104,233	93,730	80,862	132,199	130,759
Vizela	19,923	19,660	19,201	18,507	17,568	16,344	14,790	12,853	10,476	19,923	19,660
Amarante	43,252	42,693	41,721	40,259	38,301	35,775	32,601	28,690	23,942	43,252	42,693
Baião	16,045	15,851	15,514	15,007	14,332	13,463	12,375	11,039	9422	16,045	15,851
Felgueiras	51,378	50,770	49,712	48,115	45,966	43,177	39,654	35,287	29,955	51,378	50,770
Lousada	46,231	45,718	44,825	43,472	41,645	39,265	36,245	32,487	27,878	46,231	45,718
Marco de Canaveses	53,227	52,672	51,705	50,247	48,283	45,735	42,515	38,523	33,649	53,227	52,672
Paços de Ferreira	66,467	65,840	64,747	63,093	60,853	57,931	54,217	49,588	43,901	66,467	65,840
Paredes	69,480	68,577	67,005	64,634	61,441	57,300	52,069	45,586	37,671	69,480	68,577
Penafiel	60,670	59,920	58,613	56,644	53,993	50,555	46,214	40,837	34,274	60,670	59,920
Mondim de Basto	8265	8194	8070	7885	7637	7320	6923	6437	5850	8265	8194
Cinfães	14,407	14,219	13,894	13,406	12,755	11,920	10,877	9597	8053	14,407	14,219
Resende	7091	6987	6806	6534	6172	5708	5127	4415	3555	7091	6987
Total	935,529	925,731	908,676	882,953	848,338	803,464	746,789	676,584	590,903	935,529	925,731

Appendix C

Table A4. Scenario 2: Impacts (available power–required power) of the BEV fleet on the grid during peak hours (values in kVA).

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	13,474	13,312	13,086	12,771	12,334	11,725	10,879	9701	8064	5786	2619
Cabeceiras de Basto	14,558	14,394	14,167	13,851	13,411	12,800	11,950	10,769	9127	6846	3675
Celorico de Basto	16,665	16,463	16,181	15,788	15,240	14,476	13,412	11,928	9861	6980	2965
Fafe	46,908	46,394	45,678	44,679	43,285	41,341	38,629	34,846	29,569	22,208	11,940
Guimarães	159,252	157,623	155,349	152,176	147,750	141,573	132,954	120,928	104,149	80,735	48,066
Póvoa de Lanhoso	18,025	17,796	17,476	17,029	16,406	15,537	14,325	12,634	10,276	6987	2399
Vieira do Minho	13,669	13,548	13,380	13,147	12,824	12,376	11,756	10,897	9708	8061	5782
Vila Nova de Famalicão	105,635	104,195	102,180	99,359	95,409	89,878	82,132	71,281	56,083	34,793	4970
Vizela	14,513	14,250	13,881	13,364	12,639	11,623	10,198	8198	5395	1461	**−4056**
Amarante	31,004	30,445	29,667	28,584	27,078	24,982	22,066	18,010	12,369	4522	**−6391**
Baião	12,229	12,035	11,766	11,391	10,872	10,151	9151	7763	5838	3168	**−535**
Felgueiras	36,560	35,952	35,103	33,917	32,260	29,946	26,712	22,195	15,884	7066	**−5252**
Lousada	35,577	35,064	34,346	33,339	31,929	29,953	27,184	23,302	17,862	10,236	**−454**
Marco de Canaveses	41,031	40,476	39,700	38,617	37,103	34,988	32,033	27,904	22,135	14,074	2810
Paços de Ferreira	52,414	51,787	50,908	49,675	47,946	45,520	42,115	37,337	30,632	21,219	8008
Paredes	53,358	52,455	51,194	49,433	46,972	43,535	38,734	32,027	22,657	9568	**−8717**
Penafiel	45,096	44,346	43,298	41,835	39,792	36,939	32,955	27,391	19,620	8767	**−6391**
Mondim de Basto	6567	6496	6397	6260	6070	5807	5442	4937	4237	3268	1925
Cinfães	10,592	10,404	10,144	9784	9284	8592	7632	6302	4460	1909	**−1625**
Resende	5016	4912	4767	4567	4289	3903	3369	2629	1604	183	**−1785**
Total	732,145	722,347	708,668	689,566	662,892	625,644	573,626	500,982	399,529	257,840	59,955

Table A5. Scenario 2: Impacts (available power–required power) of the BEV fleet on the grid during off-peak hours (values in kVA).

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	16,491	16,329	16,103	15,788	15,351	14,742	13,896	12,718	11,081	8803	5636
Cabeceiras de Basto	17,847	17,683	17,456	17,140	16,700	16,089	15,239	14,058	12,416	10,135	6964
Celorico de Basto	20,445	20,243	19,961	19,568	19,020	18,256	17,192	15,708	13,641	10,760	6745
Fafe	58,915	58,401	57,685	56,686	55,292	53,348	50,636	46,853	41,576	34,215	23,947
Guimarães	193,870	192,241	189,967	186,794	182,368	176,191	167,572	155,546	138,767	115,353	82,684
Póvoa de Lanhoso	22,914	22,685	22,365	21,918	21,295	20,426	19,214	17,523	15,165	11,876	7288
Vieira do Minho	16,410	16,289	16,121	15,888	15,565	15,117	14,497	13,638	12,449	10,802	8523
Vila Nova de Famalicão	132,199	130,759	128,744	125,923	121,973	116,442	108,696	97,845	82,647	61,357	31,534
Vizela	19,923	19,660	19,291	18,774	18,049	17,033	15,608	13,608	10,805	6871	1354
Amarante	43,252	42,693	41,915	40,832	39,326	37,230	34,314	30,258	24,617	16,770	5857
Baião	16,045	15,851	15,582	15,207	14,688	13,967	12,967	11,579	9654	6984	3281
Felgueiras	51,378	50,770	49,921	48,735	47,078	44,764	41,530	37,013	30,702	21,884	9566
Lousada	46,231	45,718	45,000	43,993	42,583	40,607	37,838	33,956	28,516	20,890	10,200
Marco de Canaveses	53,227	52,672	51,896	50,813	49,299	47,184	44,229	40,100	34,331	26,270	15,006

Table A5. *Cont.*

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Paços de Ferreira	66,467	65,840	64,961	63,728	61,999	59,573	56,168	51,390	44,685	35,272	22,061
Paredes	69,480	68,577	67,316	65,555	63,094	59,657	54,856	48,149	38,779	25,690	7405
Penafiel	60,670	59,920	58,872	57,409	55,366	52,513	48,529	42,965	35,194	24,341	9183
Mondim de Basto	8265	8194	8095	7958	7768	7505	7140	6635	5935	4966	3623
Cinfães	14,407	14,219	13,959	13,599	13,099	12,407	11,447	10,117	8275	5724	2190
Resende	7091	6987	6842	6642	6364	5978	5444	4704	3679	2258	290
Total	935,529	925,731	908,676	882,953	848,338	803,464	746,789	676,584	590,903	935,529	925,731

Appendix D

Table A6. Scenario 3: Impacts (available power–required power) of the BEV fleet on the grid during peak hours (values in kVA).

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	13,474	13,312	11,604	9689	7725	5712	3648	1533	**−633**	**−2854**	**−5128**
Cabeceiras de Basto	14,558	14,394	12,672	10,743	8767	6746	4676	2558	391	**−1826**	**−4094**
Celorico de Basto	16,665	16,463	14,344	11,958	9501	6973	4372	1695	**−1058**	**−3890**	**−6801**
Fafe	46,908	46,394	41,028	34,974	28,731	22,293	15,657	8816	1767	**−5495**	**−12,975**
Guimarães	159,252	157,623	140,599	121,385	101,558	81,102	60,003	38,244	15,811	**−7314**	**−31,146**
Póvoa de Lanhoso	18,025	17,796	15,396	12,689	9898	7021	4055	998	**−2151**	**−5395**	**−8735**
Vieira do Minho	13,669	13,548	12,260	10,828	9372	7893	6391	4864	3314	1738	139
Vila Nova de Famalicão	105,635	104,195	89,273	72,308	54,665	36,325	17,265	**−2535**	**−23,098**	**−44,446**	**−66,603**
Vizela	14,513	14,250	11,529	8427	5192	1821	**−1692**	**−5351**	**−9160**	**−13,125**	**−17,250**
Amarante	31,004	30,445	24,566	17,971	11,207	4273	**−2835**	**−10,121**	**−17,587**	**−25,239**	**−33,077**
Baião	12,229	12,035	9983	7692	5356	2973	544	**−1933**	**−4459**	**−7033**	**−9657**
Felgueiras	36,560	35,952	29,618	22,451	15,037	7368	−561	**−8757**	**−17,228**	**−25,980**	**−35,021**
Lousada	35,577	35,064	29,753	23,707	17,411	10,858	4038	**−3055**	**−10,430**	**−18,097**	**−26,064**
Marco de Canaveses	41,031	40,476	34,691	28,146	21,372	14,365	7118	**−376**	**−8122**	**−16,128**	**−24,400**
Paços de Ferreira	52,414	51,787	45,313	37,924	30,211	22,161	13,764	5007	**−4119**	**−13,629**	**−23,534**
Paredes	53,358	52,455	43,044	32,398	21,386	9999	**−1773**	**−13,940**	**−26,512**	**−39,500**	**−52,914**
Penafiel	45,096	44,346	36,522	27,677	18,532	9082	**−684**	**−10,772**	**−21,191**	**−31,948**	**−43,054**
Mondim de Basto	6567	6496	5740	4898	4043	3173	2289	1390	477	**−452**	**−1395**
Cinfães	10,592	10,404	8417	6205	3955	1667	**−660**	**−3026**	**−5431**	**−7877**	**−10,363**
Resende	5016	4912	3807	2577	1325	52	**−1243**	**−2561**	**−3901**	**−5263**	**−6649**
Total	732,145	722,347	620,156	504,645	385,246	261,856	134,371	2682	**−133,321**	**−273,750**	**−418,723**

Table A7. Scenario 3: Impact (available power–required power) of the BEV fleet on the grid during off-peak hours (values in kVA).

Municipality	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Castelo de Paiva	16,491	16,329	14,621	12,706	10,742	8729	6665	4550	2384	163	**−2111**
Cabeceiras de Basto	17,847	17,683	15,961	14,032	12,056	10,035	7965	5847	3680	1463	**−805**
Celorico de Basto	20,445	20,243	18,124	15,738	13,281	10,753	8152	5475	2722	**−110**	**−3021**
Fafe	58,915	58,401	53,035	46,981	40,738	34,300	27,664	20,823	13,774	6512	**−968**
Guimarães	193,870	192,241	175,217	156,003	136,176	115,720	94,621	72,862	50,429	27,304	3472
Póvoa de Lanhoso	22,914	22,685	20,285	17,578	14,787	11,910	8944	5887	2738	**−506**	**−3846**
Vieira do Minho	16,410	16,289	15,001	13,569	12,113	10,634	9132	7605	6055	4479	2880
Vila Nova de Famalicão	132,199	130,759	115,837	98,872	81,229	62,889	43,829	24,029	3466	**−17,882**	**−40,039**
Vizela	19,923	19,660	16,939	13,837	10,602	7231	3718	59	**−3750**	**−7715**	**−11,840**
Amarante	43,252	42,693	36,814	30,219	23,455	16,521	9413	2127	**−5339**	**−12,991**	**−20,829**
Baião	16,045	15,851	13,799	11,508	9172	6789	4360	1883	**−643**	**−3217**	**−5841**
Felgueiras	51,378	50,770	44,436	37,269	29,855	22,186	14,257	6061	**−2410**	**−11,162**	**−20,203**
Lousada	46,231	45,718	40,407	34,361	28,065	21,512	14,692	7599	224	**−7443**	**−15,410**
Marco de Canaveses	53,227	52,672	46,887	40,342	33,568	26,561	19,314	11,820	4074	**−3932**	**−12,204**
Paços de Ferreira	66,467	65,840	59,366	51,977	44,264	36,214	27,817	19,060	9934	424	**−9481**
Paredes	69,480	68,577	59,166	48,520	37,508	26,121	14,349	2182	**−10,390**	**−23,378**	**−36,792**
Penafiel	60,670	59,920	52,096	43,251	34,106	24,656	14890	4802	**−5617**	**−16,374**	**−27,480**
Mondim de Basto	8265	8194	7438	6596	5741	4871	3987	3088	2175	1246	303
Cinfães	14,407	14,219	12,232	10,020	7770	5482	3155	789	**−1616**	**−4062**	**−6548**
Resende	7091	6987	5882	4652	3400	2127	832	**−486**	**−1826**	**−3188**	**−4574**
Total	935,529	925,731	823,540	708,029	588,630	465,240	337,755	206,066	70,063	**−70,366**	**−215,339**

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