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Marginal Life-Cycle Greenhouse Gas Emissions of Electricity Generation in Portugal and Implications for Electric Vehicles

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Abstract: This article assesses marginal greenhouse gas (GHG) emissions of electricity generation in Portugal to understand the impact of activities that affect electricity demand in the near term. In particular, it investigates the introduction of electric vehicles (EVs) in the Portuguese light-duty fleet considering different displacement and charging scenarios (vehicle technologies displaced, EV charging time). Coal and natural gas were identified as the marginal energy sources, but their contribution to the margin depended on the hour of the day, time of year, and system load, causing marginal emissions from electricity to vary significantly. Results show that for an electricity system with a high share of non-dispatchable renewable power, such as the Portuguese system, marginal emissions are considerably higher than average emissions. Because of the temporal variability in the marginal electricity supply, the time of charging may have a major influence on the GHG emissions of EVs. Off-peak charging leads to higher GHG emissions than peak charging, due to a higher contribution of coal to the margin. Furthermore, compared to an all-conventional fleet, EV introduction causes an increase in overall GHG emissions in most cases. However, EV effects are very dependent on the time of charging and the assumptions about the displaced technology.

Keywords: life cycle assessment; marginal emissions; electric vehicle; greenhouse gas emissions; electricity; marginal technology

1. Introduction

Measures which aim to reduce energy consumption and greenhouse gas (GHG) emissions by promoting the increase in energy efficiency of end-use applications, the temporal shifting of electricity use, or the use of electricity over other fuels have an impact in the grid load profile. That is the case with the introduction of electric vehicles (EVs) in a fleet, which increases electricity demand by shifting the energy source used for transportation from mainly petroleum-based fuels to electricity.

Most life-cycle assessment (LCA) studies on EVs assumed that EVs are part of the total load of the system and used average emission factors for electricity supply to assess EV environmental impacts (e.g., [1–8]). These studies have found that vehicle use dominates over the vehicle production phase regarding energy consumption and GHG emissions, particularly for fossil-based electricity mixes [8]. Some studies also addressed the influence of the charging profile in the GHG emissions of EVs, with some reporting that EV charging during off-peak hours results in lower emissions than in peak hours [9–11]. On the other hand, a smaller group of studies looked at EVs as a new load added to the electricity system and assessed how the system would respond to this change by determining the marginal electricity supply and corresponding emissions (e.g., [12–15]). The different approaches used to determine electricity emissions often lead to very distinct results, which is problematic because of the importance of electricity emissions to the overall EV impacts [16].

In this article, we assessed both marginal and average GHG emission factors for the Portuguese electricity system using historical data for recent years (2012–2014) and applied them to the assessment of the introduction of EVs in Portugal in subsequent years (2015–2017). Marginal emission factors (MEFs) describe the GHG intensity of the marginal generators in the system, i.e., the last generators to follow demand at a given time and the first to respond to a change in demand [17]. MEFs for electricity generation in Portugal were assessed following an empirical approach based on regression of historical data that implicitly accounts for operation constraints and allows for a flexible temporal resolution. This approach was proposed by Hawkes [18] for estimating marginal emission factors for Great Britain to determine the CO_2 reduction performance of demand-side interventions. The author calculated linear regression coefficients of change in the system CO_2 emission rate versus the change in total system demand [18]. Based on this approach, Siler-Evans et al. [17] calculated MEFs for CO_2, NO_x, and SO_2 for the U.S. and further estimated the share of marginal generation from fossil-fired generators. Zivin et al. [12] took the calculations from Siler-Evans et al. [17] further by accounting for the effects of electricity trade within U.S. regions. Although these studies only assessed direct emissions, the empirical approach to derive MEFs is valid for determining the short-term marginal technologies in LCA without requiring sophisticated simulation models [12,17,18].

The empirical approaches to derive MEFs have been applied to assess the impacts of several demand-side interventions, such as efficiency improvements in lighting systems [17], utilization of microgeneration technologies for residential heating [18], and the deployment of distributed solar systems [12]. MEFs have also been used to assess the impacts of EVs, mainly in the U.S. [12–14]. It was found that depending on the time of day, the response of the electricity system to EV charging can be distinct, thus influencing EV GHG emissions [12,13]. In order to identify charging strategies that minimize environmental impacts from EVs, it is important to understand how marginal emissions from electricity generation vary over time. Because electricity generation also varies geographically (e.g., due to different technology portfolios, availability of renewables) [19], the assessment of marginal emissions needs to be performed considering the specific electricity system affected by the intervention.

This article aims to assess the change in GHG emissions resulting from: (i) increasing electricity demand by 1 MWh in Portugal; and (ii) introducing battery electric vehicles (BEVs) in the Portuguese light-duty fleet in 2015–2017. Portugal was chosen as a case study for its favorable conditions for EV deployment (charging network in place and policy incentives for buying EVs). Historical hourly generation data and corresponding emissions from 2012 to 2014 were used to estimate marginal GHG emissions. Trends in marginal emissions regarding electricity demand, time of day, and month were explored, and a comparison between average and marginal emissions provided. Marginal emission factors for electricity generation were then applied to assess the effects of the introduction of BEVs in Portugal from 2015 to 2017 for a range of displacement and charging scenarios. The marginal emission factors provided are suitable for assessing changes in the operation of the electricity system in the near term beyond the applications presented in this article.

2. Materials and Methods

LCA was used to assess, firstly, the marginal life-cycle GHG emissions of electricity generation in Portugal to understand the short-term impact of activities that affect electricity demand; and, secondly, the implication of using marginal emissions in the impacts of electric vehicles introduced in the Portuguese light-duty fleet for a range of displacement and charging scenarios. GHG emissions (in kg CO_2 eq) were assessed using the Intergovernmental Panel on Climate Change (IPCC) 2007 method (100-year Global Warming Potential) [20]. It should be emphasized that GHG emissions are only one of many dimensions of environmental impact and a complete LCA should include other impact categories.

2.1. Electricity System

2.1.1. System Boundary and Identification of Unconstrained Technologies

In the short-term, only changes to the operation of the existing capacity are at stake, since the addition of new capacity to satisfy short-term demand is unfeasible (building a new power plant implies long-term planning, high investments, and may face policy constraints). Currently, there is excess capacity in the Portuguese electricity system—in 2014, the total installed capacity was 18 GW (11 GW dispatchable, 7 GW non-dispatchable) and the peak load was 8 GW [21]. The system is mostly comprised by hydro (30%), wind (25%), natural gas combined cycle (NGCC) (20%), and coal (10%) generators (Figure 1A). The remaining capacity includes photovoltaic, non-renewable combined heat and power (CHP), biomass CHP, biomass, biogas, and waste incineration plants.

In Portugal, electricity generation from renewable and CHP plants (Special Regime) is promoted through a feed-in tariff and there is an obligation to purchase all electricity generated under the Special Regime in the period it benefits from the feed-in tariffs [22]. Furthermore, regarding the connection to the grid, priority is given to electricity generated from renewable energy sources, except for hydro plants with an installed capacity over 30 MW [22]. Coal, NGCC, and large hydro power plants are considered dispatchable technologies (i.e., can be ramped up or down to match demand) [21].

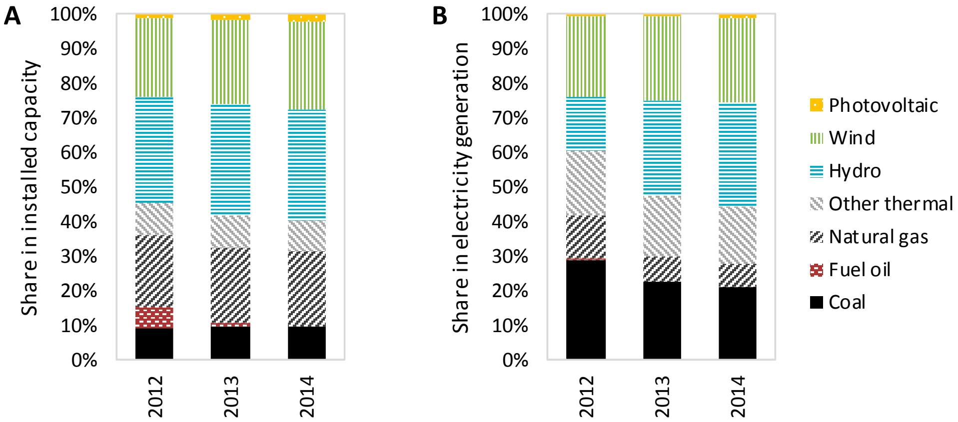

Figure 1. Installed capacity (**A**) and electricity generation (**B**) by energy sources in Portugal from 2012 to 2014 [21]. Other thermal includes non-renewable combined heat and power (CHP), biomass CHP, biomass, biogas, and waste incineration plants. Large fuel oil power plants stopped operation in 2011, although some installed capacity still remained in 2012–2013.

A change in electricity demand does not affect all generators, but only those that can respond to the change—the unconstrained generators. Table 1 presents the assumptions for identifying the unconstrained technologies operating in the Portuguese electricity system. Only coal and NGCC power plants (PP) respond to changes in electricity demand and can be considered unconstrained technologies; therefore, only these were assumed to take part in the marginal generation. Nevertheless, despite being constrained on an annual basis, a response to a change in demand might involve the use of hydro power. However, an increase in hydro reservoir generation in one hour may result in less hydro power available at some time in the future, and thus, result in an increase in the use of the marginal generation at that future time (e.g., coal or natural gas). Therefore, hydro reservoir may not be part of the marginal supply, but may influence the operation of marginal generators. This shifting effect will be analyzed in a sensitivity analysis. Moreover, due to a long start-up time, coal power plants may be considered a non-dispatchable technology, particularly if the NG price drops significantly, and would, therefore, be used as baseload only. In this case, only NGCC would be considered unconstrained. This scenario will also be explored in a sensitivity analysis.

Table 1. Assumptions for identifying the unconstrained technologies.

Technologies	Assumptions
NGCC	NGCC power plants are flexible with regard to adjusting power output and are used for load-following. They are assumed to be unconstrained technologies.
Coal-fired	Despite their long start-up time, coal-fired power plants in Portugal are considered a dispatchable technology and are used both for baseload and load-following, the latter particularly during winter and spring when there is a high availability of renewables (see Figure S1). The price of coal (currently lower than NG) also contributes to the use of these plants for load-following to the detriment of NGCC plants. Therefore, they are assumed to be unconstrained technologies.
Hydro reservoir	A response to a change in demand might involve the use of hydro power. On an hourly basis, hydro reservoir plants are often dispatched to meet daily peaks; however, on an annual basis, hydro may be considered an energy-constrained resource, because only a fixed amount of water is available annually and the system tends to maximize total production over a long period not affecting overall emissions [15,23,24].
CHP generators, biogas, and waste incinerators	Electricity from CHP, biogas, and waste incinerators is generated as a by-product (i.e., the main purpose of these activities is not to generate electricity); therefore, they do not to respond to an increase in demand and are assumed to be constrained technologies.
Biomass	Because of the slow response time of the system and the cyclic nature of operation, these plants are not used for load-following. Annual electricity generation from biomass direct-fired power plants has been approximately constant in the last few years (see Figure S2), despite the variations in demand, indicating it is a constrained technology.
Wind, solar, and run-of-river hydro	Wind, solar, and run-of-river hydro power plants rarely alter their output as a result of additional demand, given their lack of load-following ability and weather dependency. Wind, solar, and run-of-river hydro are thus constrained technologies in the short-term (i.e., their output will be fully utilized irrespective of the additional demand) [25]. Only in cases of renewable curtailment could these plants be on the margin. In Portugal, curtailment of renewable power is only occasional due to the country's pumped hydro storage capacity; therefore, this scenario was not considered.

The system boundary for the assessment of the impacts of a marginal change in electricity demand are displayed in Figure 2, and include extraction, processing, and transport of fuels (coal and natural gas), operation of power plants (coal and natural gas combined cycle), and waste management. Life-cycle inventories compiled in [26] for the Portuguese electricity system are used here. Electricity trading with Spain was not accounted for as the net transfer amounts to a few percent of total Portuguese consumption in most years, corresponding to an even smaller proportion of supply in Spain.

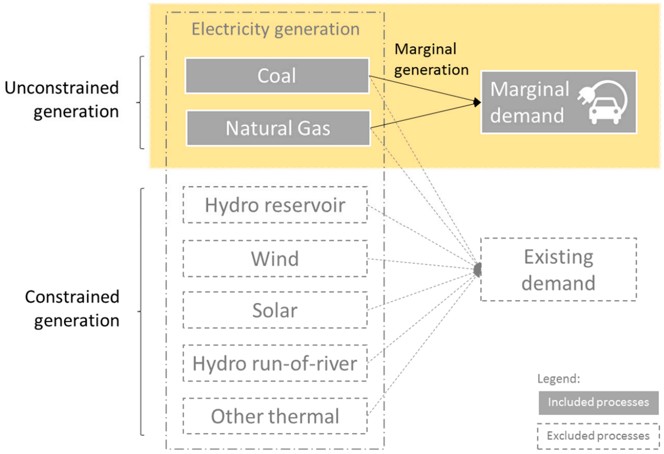

Figure 2. System boundary for the assessment of marginal life-cycle GHG emissions of electricity generation in Portugal.

2.1.2. Determining Marginal Electricity Supply and GHG Emissions

A data-driven approach accounting for time dynamics on marginal generators and emissions based on the actual historical performance of the system was used to assess marginal electricity supply. The method is based on an analysis of historic generation data of the Portuguese electricity system and builds on Hawkes [18] and Siler-Evans et al. [17], but differs from these by: (i) explicitly excluding constrained technologies from the assessment, focusing on how unconstrained generation responds to changes in demand; and (ii) considering a life-cycle perspective, by including fuel supply chain impacts (but excluding electrical infrastructure, because a marginal change in electricity demand is not deemed to affect the existing infrastructure).

The Portuguese electricity system is comprised of a much larger share of renewable resources than any of the systems assessed in [17,18] (50% against 14% in the UK [27] and 13% in the U.S. [28], in 2013). Electricity from most renewables (such as wind, solar, and mini-hydro) has priority over electricity from other sources fed into the grid, serving as a kind of variable base load. For this reason, a high share of the change in demand may be randomly satisfied by this variable, non-dispatchable load. The unconstrained technology operation adapts to the variable renewable generation by either filling the need for additional generation, if the change in renewable generation is not enough to meet the additional demand, or reducing generation, if the change in renewable generation exceeds the additional demand. Both scenarios are of interest as to describe what the marginal electricity supply in a certain period of time is, because in both cases the response of the unconstrained technology to a change in the system is depicted. Our analysis thus focuses on how unconstrained generation changes hourly and how that affects marginal GHG emissions.

Hourly generation data for the Portuguese electricity system from 2012 to 2014, provided by *Redes Energéticas Nacionais* (REN) [21], were used to calculate the hourly change in unconstrained (coal and NGCC) generation (ΔG) and the corresponding hourly change in GHG emissions (ΔE). GHG emissions were assessed using technology life-cycle emission factors for Portugal [26], excluding infrastructure impacts (coal PP: 1006 kg CO_2 eq$\cdot$MWh^{-1}; NGCC: 420 kg CO_2 eq$\cdot$MWh^{-1}). The marginal emission factor corresponds to the slope of a linear regression of ΔE on ΔG, as plotted in Figure 3. Increasing demand by 1 MWh is expected to increase electricity system emissions by, on average, 723 kg CO_2 eq, assuming that only fossil-based generation can change in response to a change in demand.

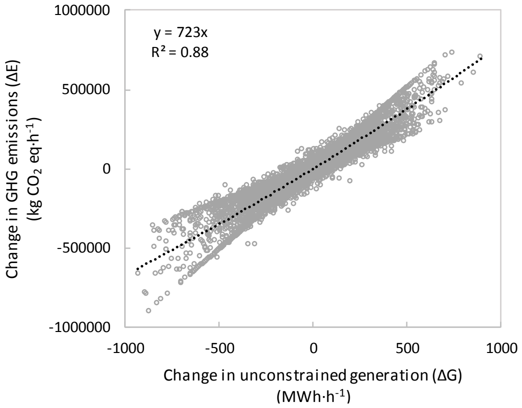

Figure 3. Linear regression of ΔE on ΔG for Portugal (data for 2012 to 2014). The slope of the regression line gives the marginal GHG emission rate (723 kg CO_2 eq$\cdot$MWh^{-1}).

The marginal emission factor estimated in Figure 3 gives an average figure for 2012–2014, but does not provide any insight on how marginal emission factors vary with electricity demand, time of day, or between months. Trends in marginal emission factors were assessed by applying the method explained above to different subsets of the data, similar to [17,18]. Regarding electricity demand, marginal emission factors were calculated by disaggregating the data (ΔE and ΔG) by every fifth percentile of the corresponding electricity demand, and performing separate regressions for each set of data. The first set includes the 5% of data occurring at the lowest-demand hours, and the last set includes the 5% of data occurring during the highest-demand hours. Hourly and monthly marginal emissions factors were estimated by performing 24 and 12 separate regressions of ΔE on ΔG for all observations occurring at a given hour and month, respectively.

The degree to which different generators respond to changes in demand (i.e., the share of marginal generation from coal and NG generators) was also assessed using a variation of the above method, similarly to [17]. The change in fossil generation between one hour and the previous (ΔG) was calculated as well as the corresponding change in coal-based (ΔF_{coal}) and natural gas-based (ΔF_{NG}) generation and then separate regressions of ΔG on ΔF were performed to estimate the share of marginal generation for each fuel.

2.2. Introduction of Battery Electric Vehicles in the Portuguese Light-Duty Fleet

2.2.1. System Boundary

The system boundary for the assessment of the effects of the introduction of BEVs in Portugal from 2015 to 2017 is shown in Figure 4. The main vehicle life-cycle stages are included, namely production (including extraction and processing of raw materials, parts and components manufacturing, and vehicle assembly), use (vehicle operation and maintenance, and fuel and marginal electricity production and distribution), and end-of-life (vehicle and battery dismantling, recycling, and disposal of components). Life-cycle inventories are based on [29]. Road infrastructure, refueling stations for internal combustion engine vehicles (ICEVs), and charging points for EVs were not included, as their contributions to the impacts are minor [30]. A dynamic fleet-based life-cycle model [29] was used to assess the displacement of ICEVs by EVs from 2015 to 2017. The model allows for the assessment of: (i) electricity demand by the EV fleet in each year (see Table S1); and (ii) changes in emissions from personal road vehicles. The main characteristics of the vehicles considered are presented in Tables S2–S4. Details about the model structure, data sources, and assumptions can be found in [29].

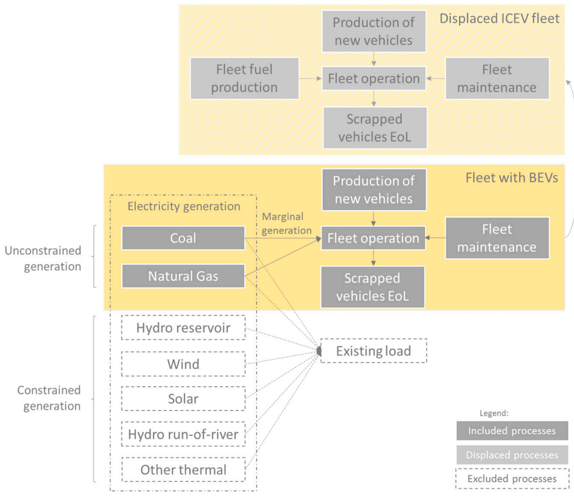

Figure 4. System boundary for the assessment of the effects of the introduction of BEVs in Portugal.

2.2.2. Scenarios

Eight scenarios, summarized in Table 2, have been developed to assess how the introduction of BEVs in the Portuguese light-duty fleet from 2015 to 2017 would influence overall GHG emissions. Four generic BEV charging patterns combining different charging times (peak and off-peak) and durations (2-h and 8-h charge) were considered. Under peak charging, vehicles are assumed to charge between 8 a.m. and 10 p.m.; for the off-peak charging mode, we assume that vehicles charge between 10 p.m. and 8 a.m., according to peak and off-peak timings considered by the electricity provider [31]. Monte Carlo simulation is used to quantify the uncertainty regarding charging times in each scenario. Details about the Monte Carlo simulation are shown in the Supplementary Materials (Section 4; Table S5).

Table 2. Summary of the scenarios considered.

Scenarios	Duration of Charging	Charging Time	Displaced Technologies
1	8-h charge	Peak	70% new diesel/30% new gas ICEVs
2	8-h charge	Peak	New gasoline ICEV
3	8-h charge	Off-peak	70% new diesel/30% new gas ICEVs
4	8-h charge	Off-peak	New gasoline ICEV
5	2-h charge	Peak	70% new diesel/30% new gas ICEVs
6	2-h charge	Peak	New gasoline ICEV
7	2-h charge	Off-peak	70% new diesel/30% new gas ICEVs
8	2-h charge	Off-peak	New gasoline ICEV

gas: gasoline; ICEV: internal combustion engine vehicle.

Scenarios also consider possible conventional technologies displaced by BEVs in the fleet. Two options for the displaced technology were considered: (i) of the new BEVs, 70% are assumed to displace new diesel and 30% to displace new gasoline ICEVs (according to recent trends in the market share of these technologies in Portugal), while the fuel consumption of the new ICEVs is assumed to decrease over time according to the European Union targets (70% new diesel/30% new gas ICEVs); and (ii) BEVs displace new gasoline ICEVs. The main characteristics of the displaced technologies are depicted in the Supplementary Materials (Tables S3 and S4).

3. Results and Discussion

3.1. Marginal Electricity Supply and Marginal GHG Emissions

3.1.1. Marginal Emissions as a Function of System Load

The trend in marginal emissions as a function of total demand is depicted in Figure 5. In low demand hours, coal was the dominant marginal technology, with about 84% of the share, whilst natural gas dominated at high demand hours with 66% of the share. The share of coal in marginal generation tended to decrease as load increased. Conversely, marginal GHG emissions also decreased as load increased, varying between 626 and 925 kg CO_2 eq·MWh^{-1}.

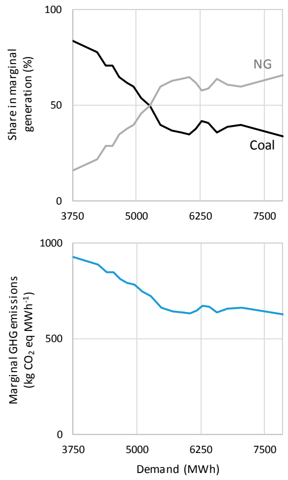

Figure 5. Share in marginal generation (**top**) and marginal GHG emissions (**bottom**) from 2012 to 2014 as a function of total demand.

3.1.2. Temporal Trends

Regarding temporal trends (Figure 6), marginal GHG emissions were higher during late-night (1–5 a.m., corresponding to the off-peak period), and lower in the early-morning (6–7 a.m., corresponding to the beginning of the morning peak) and evening (9–11 p.m., corresponding to the declining of the evening peak), with an overall maximum difference of 35%. During daytime, fluctuations in marginal emissions were lower; differences were below 18%. Increasing demand for electricity by 1 MWh at night might result in an additional emission of 943 kg CO_2 eq; during the day, an additional MWh demanded from the grid would result in an emission of at least 644 kg CO_2 eq. Marginal emission rates were higher during spring and fall, and lower in the summer. Between 2012 and 2013, marginal GHG emissions increased 15%, but stabilized in 2014. 2012 was considered a dry year, with less hydro availability; consequently, natural gas was more often on the margin than in 2013 and 2014, both wet years.

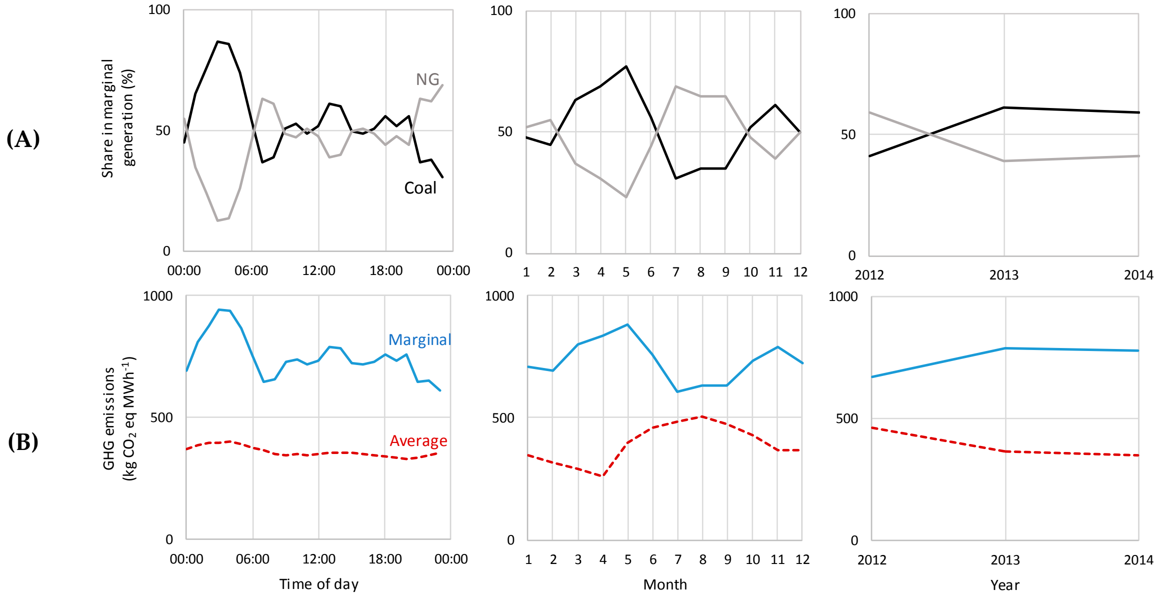

Figure 6. Temporal variations in the contribution of technologies to the marginal generation (**A**); and marginal and average GHG emissions (**B**), based on the data for 2012 through 2014.

3.1.3. Comparison between Marginal and Average Emissions

Marginal emissions were consistently higher than average emissions (42%–58% higher considering the time of day), as the latter included high shares of low-carbon renewable sources (Table 3). Emissions followed a similar trend along the day (higher during the night and lower during the day), but marginal emissions showed much higher variation (Figure 6). Conversely, marginal and average emissions were negatively correlated on a monthly and annual basis. Further analyzing the data, it is apparent that as the availability of hydro power increases (dry versus wet years; summer versus winter), the utilization of natural gas power plants decreases, due to their high operation costs. As a result, coal is more often on the margin, increasing marginal emissions, but at the same time there is more hydro providing power, decreasing average emissions.

Whilst average emissions describe the life-cycle impacts of generating 1 MWh of electricity, marginal emissions depict the life-cycle impacts of increasing electricity generation by 1 MWh. For the Portuguese electricity system, with a high share of non-dispatchable renewable power and excess capacity for the near term, marginal emissions are considerably higher than average emissions. Increasing electricity generation by 1 MWh means increasing fossil-based generation (either coal or natural gas), resulting in higher emissions than the renewable-based average. Therefore, using average emissions to assess the impacts of implementing a new technology which uses or displaces electricity can underestimate the burdens and the savings achieved, respectively.

Table 3. Marginal fuel sources, marginal emission factors (EFs), and comparison with average EFs for each hour of the day for electricity generation in Portugal from 2012 to 2014.

Time of Day	Marginal Fuel Source		Marginal EF (kg CO_2 eq·MWh^{-1})	Average EF (kg CO_2 eq·MWh^{-1})	Difference (%)
	Coal (%)	NG (%)			
1 a.m.	65	35	812	385	53
2 a.m.	76	24	877	394	55
3 a.m.	87	13	943	397	58
4 a.m.	86	14	937	400	57
5 a.m.	74	26	866	391	55
6 a.m.	55	45	752	377	50
7 a.m.	37	63	644	366	43
8 a.m.	39	61	656	352	46
9 a.m.	51	49	728	347	52
10 a.m.	53	47	740	348	53
11 a.m.	49	51	716	347	52
12 a.m.	52	48	734	349	52
1 p.m.	61	39	788	356	55
2 p.m.	60	40	782	356	54
3 p.m.	50	50	722	356	51
4 p.m.	49	51	716	351	51
5 p.m.	51	49	728	345	53
6 p.m.	56	44	758	339	55
7 p.m.	52	48	734	334	55
8 p.m.	56	44	758	329	57
9 p.m.	37	63	644	333	48
10 p.m.	38	62	650	345	47
11 p.m.	31	69	608	354	42
12 p.m.	45	55	692	371	46

NG: natural gas.

3.1.4. Limitations

The marginal emission factors used in this analysis were calculated based on regression models that use historical data. As noted by [13], whilst these models describe the electricity system historically, they do not capture potential changes in the system over time, and thus can only be used to assess changes in electricity demand in the near term [16]. Nevertheless, only small changes to the electricity system portfolio are expected to occur in the next few years, and as new data becomes available, it is possible to regularly update the analysis to reflect the changes in the electricity sector.

We use average emission factors to estimate the change in upstream emissions from the fuel supply chain of providing an additional MWh of electricity, although marginal effects may differ from the average. Additionally, electricity trading with neighboring systems (Spain) was not accounted for because the percent of electricity imported is low. In order to determine the effects of electricity trading, power system optimization models should be used [16].

3.2. Application to Battery Electric Vehicles

3.2.1. Change in Electricity GHG Emissions due to BEV Charging

The effect on GHG emissions of adding BEV charging to the Portuguese electricity system was assessed for 2015–2017. This period was chosen because it represents a timeframe for which the marginal emissions factors assessed in Section 3.1 are valid (more details in Section 3 of the Supplementary Materials; Figure S3). The additional emissions resulting from BEV charging in each scenario (Table 2) were calculated by determining the average additional electricity demand in each hour (assuming an average electricity transmission and distribution, and charging efficiencies of 92% and 95%, respectively) and applying the marginal emission factor calculated for that hour (Table 3). Uncertainty regarding charging times was accounted for using Monte Carlo simulation. A sensitivity analysis was also performed considering the potential influence of hydro generation in the marginal GHG emissions as well as the scenario in which coal power plants would not be considered dispatchable. Details about the assessment of the influence of hydro generation in the marginal emissions are presented in the Supplementary Materials (Section 5; Tables S6 and S7). Cumulative emissions from 2015 to 2017 were calculated for all cases and are presented in Figure 7.

The addition of BEVs to the Portuguese electricity system in 2015–2017 would entail a higher increase in GHG emissions if vehicles were charged during off-peak hours for an 8-h charge (Figure 7A) and in about 74% of the cases for a 2-h charge (Figure 7B). The temporal difference in BEV charging emissions could reach 11% for an 8-h charge and 26% for a 2-h charge. Considering the potential influence of hydro generation in marginal GHG emissions increases uncertainty, but does not significantly change the results (variations below 6%). On the other hand, considering that coal-fired PP are non-dispatchable, and therefore, constrained, would result in a lower cumulative change in emissions (32 Gg CO_2 eq) in all scenarios.

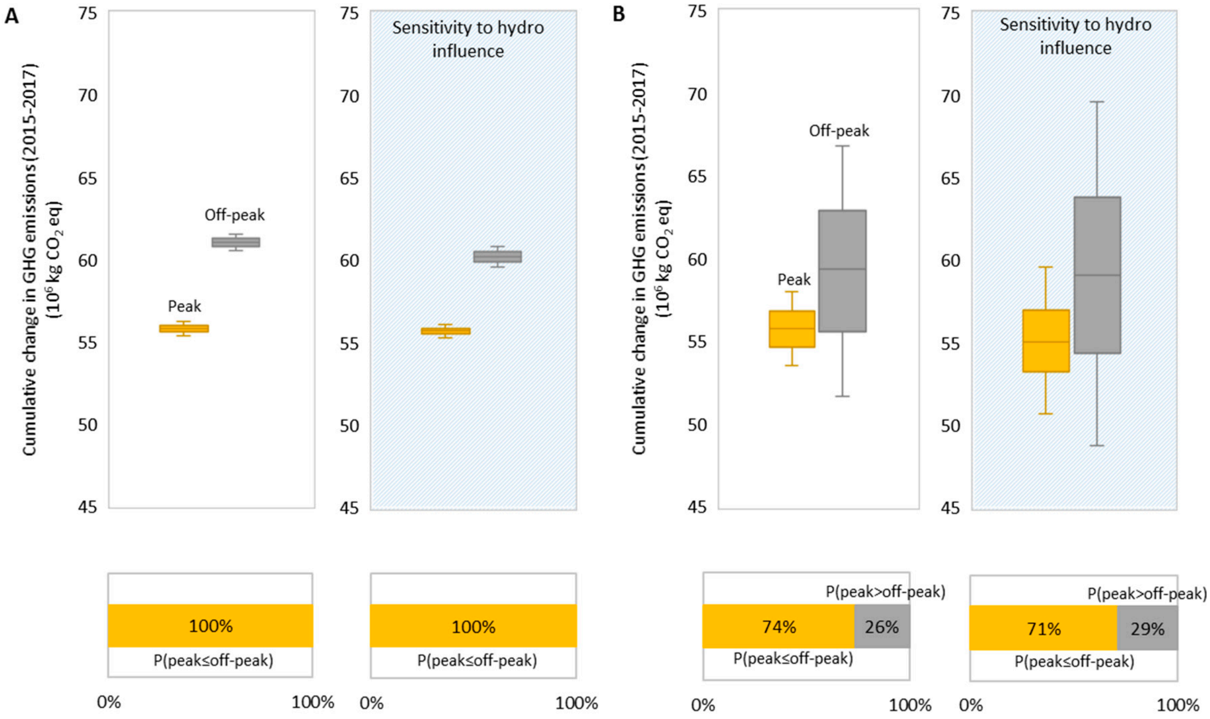

Figure 7. Cumulative change in electricity GHG emissions as a result of the introduction of BEVs in Portugal from 2015 to 2017 and the probability that peak charging emissions are lower than off-peak charging considering different scenarios for vehicle charging: (**A**) 8-h charging; (**B**) 2-h charging. In blue (dashed), sensitivity analysis to the influence of hydro generation in marginal GHG emissions. Considering that coal-fired PP are constrained (non-dispatchable) would result in a cumulative change in emissions of 32 Gg CO_2 eq in all scenarios.

3.2.2. Fleet-Wide Change in GHG Emissions Resulting from the Introduction of BEVs

Apart from the change in the operation of the electricity system and corresponding change in GHG emissions as a result of the additional electricity demand by BEV charging, the introduction of BEVs in Portugal also entail the displacement of conventional technologies in the fleet and corresponding change in GHG emissions. Whilst the effect of the new BEV fleet over the electricity system translates into an increase in emissions (as shown in Figure 7), the displacement of the ICEV fleet may result in GHG savings depending on how BEVs compare with the displaced technologies.

The cumulative change in GHG emissions due to the introduction of BEVs for the scenarios in Table 2 are presented in Figure 8. BEV charging during off-peak hours leads to higher emissions than in peak hours for an 8-h charge and in about 73% of the cases for a 2-h-charge. For some scenarios, off-peak charging can more than double cumulative emissions compared to peak charging. These conclusions are also not affected by considering the influence of hydro generation in marginal emissions (see Figure S4 in the Supplementary Materials). Displacing an average new ICEV leads to GHG savings (scenarios 1, 3, 5, and 7). Conversely, displacing gasoline ICEVs results in an increase in GHG emissions (scenarios 2, 4, 6, and 8). When assuming that coal-fired PP are constrained, the same conclusions are obtained but the cumulative change in emissions is lower (see Figure S4 in the Supplementary Materials).

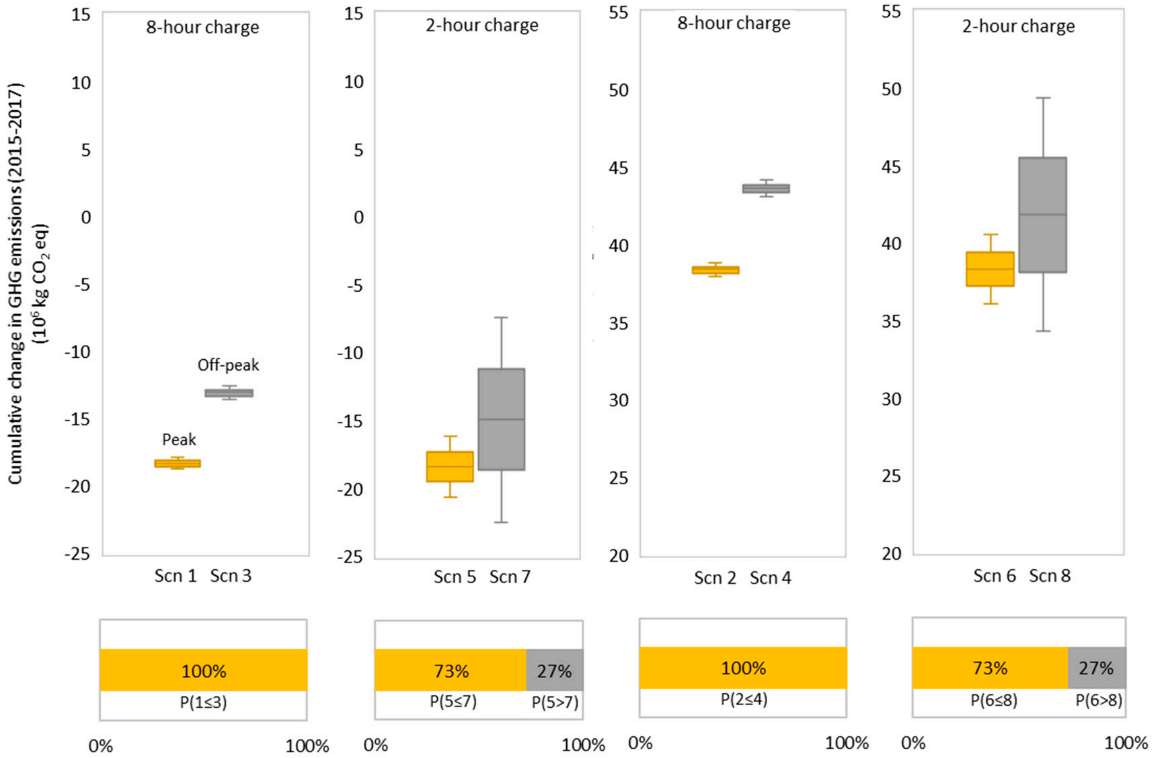

Figure 8. Cumulative change in GHG emissions due to the introduction of BEVs in the Portuguese light-duty fleet in 2015–2017 for the scenarios in Table 2.

The results presented in Figure 8 may be influenced by the different vehicle kilometers traveled (VKT) of the vehicles displaced (diesel ICEVs are assumed to have higher VKT than BEVs, but BEVs were assumed to be driven more than gasoline ICEVs—see Tables S1–S3 in the Supplementary Materials). Therefore, a sensitivity analysis was performed to assess the effect of the assumptions regarding BEV VKT on the results. For the sensitivity analysis (Figure 9), BEV VKT was changed to match that of the displaced technology in each scenario, i.e., for scenarios 1′, 3′, 5′, and 7′, BEV VKT took the upper bound value in Table S4; for scenarios 2′, 4′, 6′, and 8′, the lower bound value. Only if BEVs displace an average new ICEV and charge during peak hours (scenarios 1′ and 5′) does the BEV introduction result in GHG savings in all cases (Figure 9). This is because the marginal GHG emissions of the grid are low enough to make the GHG emissions per km driven by a BEV lower than an average new ICEV. However, if charged during off-peak hours, BEV introduction increases GHG emissions in all cases for scenario 3′ and in about 50% of the cases for scenario 7′. When BEVs displace gasoline ICEVs, an increase in emissions is verified in all scenarios, though lower compared to Figure 8. This results from the increase in vehicle manufacturing GHG emissions resulting from BEV introduction, which represent a higher share in the overall change in GHG emissions as VKT decreases, making the displacement of gasoline ICEVs in scenarios 2′, 4′, 6′, and 8′ worse than the displacement of an average new ICEV in scenarios 1′, 3′, 5′, and 7′, respectively.

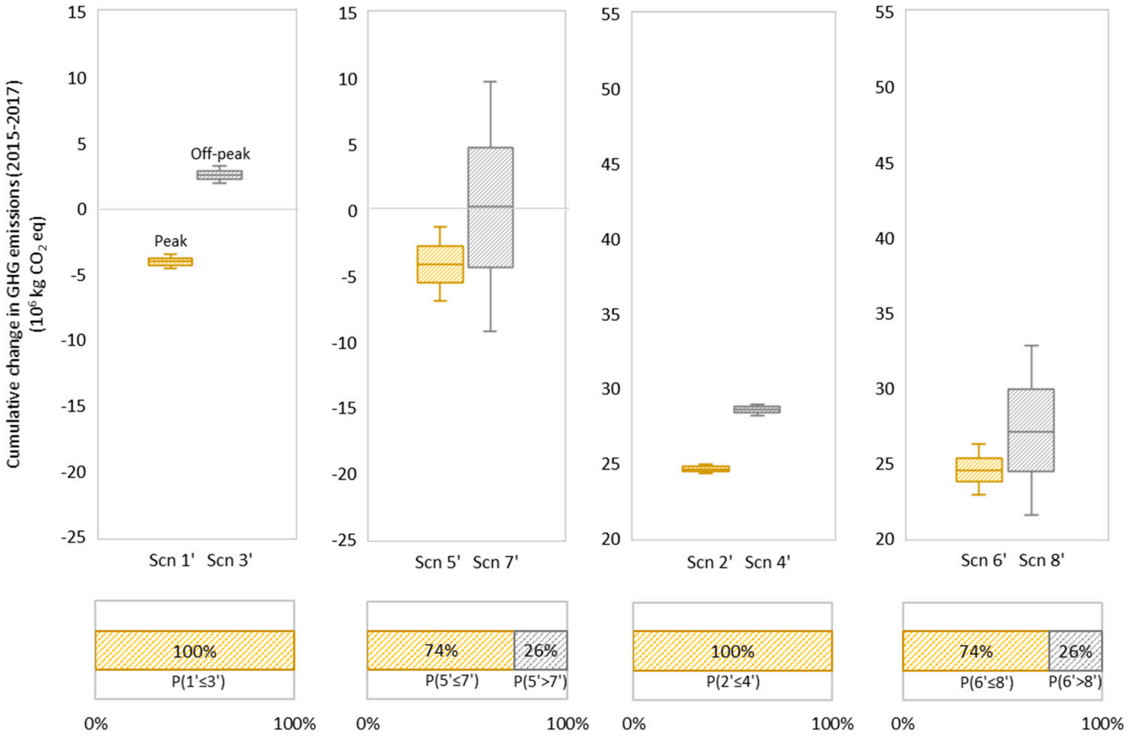

Figure 9. Sensitivity analysis of the cumulative change in GHG emissions due to the introduction of BEVs in the Portuguese light-duty fleet from 2015–2017 to BEV VKT.

4. Conclusions

Marginal greenhouse gas (GHG) emissions of electricity generation in Portugal were assessed, aiming to understand the impact of activities that affect electricity demand in the near term, namely the introduction of BEVs in the Portuguese light-duty fleet for a range of displacement and charging scenarios.

Coal and natural gas were identified as the marginal energy sources, but their contribution to the margin depended on the hour of the day, time of year, and system load, causing marginal emission factors to vary significantly. Increasing electricity consumption during off-peak hours was found to induce a higher increase in GHG emissions than in peak hours, due to a higher contribution of coal to the margin. In periods of low demand or high hydro availability, coal is often the marginal technology to the detriment of NGCC, as a result of the currently lower fuel operation costs.

For an electricity system with a high share of non-dispatchable renewable power and excess capacity in the near term, such as the Portuguese system, marginal emissions are considerably higher than average emissions. Increasing electricity generation generally means increasing fossil-based generation (either coal or natural gas), resulting in higher emissions than the renewable-based average. For the Portuguese system, marginal GHG emissions can be up to 58% higher than average emissions, considering the time of day. When the goal is to assess the GHG emissions of implementing a technology which entails a change in electricity consumption (may it be increasing or decreasing consumption), marginal emission factors should be used. Because marginal effects have a distinct and larger magnitude than the average behavior of the electricity system, using average emission factors to assess the impacts of implementing a new technology which uses or displaces electricity can underestimate the burdens or the savings achieved.

The application of the model to assess the GHG effects of BEVs in Portugal showed that BEVs induce, in the near term, a much higher burden than an average approach can depict. Even considering the displacement of ICEVs, BEVs increase overall GHG emissions in the majority of scenarios. However, BEV effects on GHG emissions are very dependent on the time of charging and on the assumptions about the displaced technology, including the activity level of both BEVs and displaced ICEVs.

As a result of the temporal variability in the marginal electricity supply, the time of charging can have a major influence on the GHG benefits of BEVs in the near term. What has been considered, in general, the most favorable charging time from the economic standpoint and operation of the electricity system perspective (off-peak hours), may not be so from an environmental standpoint. In Portugal, simply encouraging charging during the night may result in a higher increase in GHG emissions from the electricity system as a result of the coal-based marginal electricity supply. Therefore, understanding how marginal emissions from electricity generation vary over time is crucial in the design of charging strategies that minimize environmental impacts from EVs.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/5/4/41/s1, Table S1: Distance travelled and electricity consumption of the BEV stock; Table S2: Characteristics of average new BEVs considered; Table S3: Characteristics of average new gasoline ICEVs considered; Table S4: Characteristics of average new diesel ICEVs considered; Table S5: Parameter values and probability distributions for Monte-Carlo uncertainty propagation; Table S6: Marginal fuel sources and marginal emission factors (EFs) for each hour of the day for electricity generation in Portugal in 2012–2014, considering that hydro generation is used for load following; Table S7: Parameter values and probability distributions for Monte Carlo uncertainty propagation (sensitivity analysis); Figure S1: Hourly electricity generation from coal power plants in Portugal in 2012–2014; Figure S2: Annual electricity generation by biomass-fired plants in Portugal in 2012–2014; Figure S3: Cumulative probability distribution of remaining coal and NG CC capacity in each hour of 2012–2014 and comparison with maximum BEV load for 2015, 2016 and 2017; Figure S4: Cumulative change in GHG emissions due to the introduction of BEVs in the Portuguese light-duty fleet in 2015–2017 for the scenarios in Table 2.

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Author Contributions: R.G. designed the research, collected the data, performed the analysis, and wrote the manuscript; F.F. supervised the research, discussed the results and revised the manuscript.

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