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

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1. Electricity System

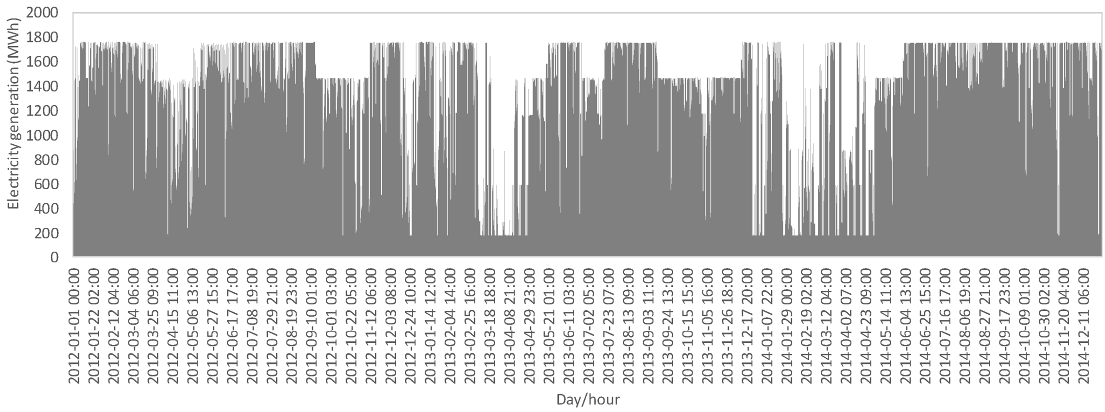

Figure S1. Hourly electricity generation from coal power plants in Portugal from 2012 to 2014 [1].

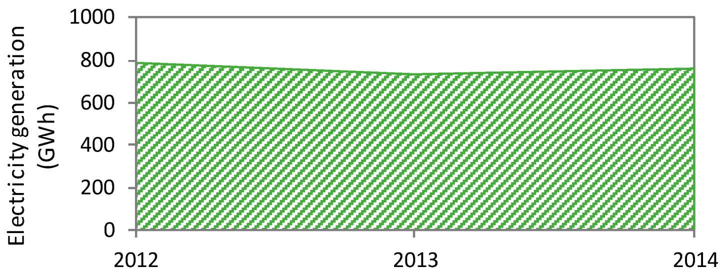

Figure S2. Annual electricity generation by biomass-fired plants in Portugal from 2012 to 2014 [2].

2. Data

Vehicle data was taken from [3]. Life-cycle GHG emissions were calculated using the dynamic fleet-based life-cycle model in [3].

Table S1. Distance travelled and electricity consumption of the BEV stock, based on [3].

BEV Stock (# Vehicles)		Distance Travelled (10^3 km)			Electricity Consumption (MWh)		
		Baseline [1]	Upper Bound [2]	Lower Bound [3]	Baseline [1]	Upper Bound [2]	Lower Bound [3]
2015	3381	14,611	18,356	11,014	8357	10,500	6300
2016	8231	27,347	34,357	20,614	20,086	25,235	15,141
2017	19516	50,212	63,085	37,851	47,026	59,082	35,449

[1] For scenarios 1–8; [2] For scenarios 1′, 3′, 5′, and 7′; [3] For scenarios 2′, 4′, 6′, and 8′.

Table S2. Characteristics of average new BEVs considered, based on [3].

Year	Vehicle Weight (kg)	Electricity Consumption (Wh·km^{-1})	First-Year VKT (km)
2012	1472	183	13,929
2013	1460	181	
2014	1448	179	
2015	1436	177	
2016	1424	174	
2017	1412	172	

Table S3. Characteristics of average new gasoline ICEVs considered, based on [3].

Year	Vehicle Weight (kg)	Fuel Consumption (L·100 km^{-1})	First-Year VKT (km)
2012	1090	6.1	11,227
2013	1082	5.9	
2014	1073	5.8	
2015	1064	5.6	
2016	1055	5.5	
2017	1046	5.3	

Table S4. Characteristics of average new diesel ICEVs considered, based on [3].

Year	Vehicle Weight (kg)	Fuel Consumption (L·100 km^{-1})	First-Year VKT (km)
2012	1418	5.3	21,825
2013	1406	5.2	
2014	1394	5.1	
2015	1983	4.9	
2016	1371	4.8	
2017	1360	4.6	

2.1. VKT Assumptions

Annual VKT for each ICEV technology (diesel and gasoline) were estimated based on vehicle inspection data for Portugal from [4]. In Portugal, diesel ICEVs are driven more than gasoline ICEVs. For BEVs, we assumed the same profile as gasoline ICEVs; however, since BEVs are about 70% more energy efficient than gasoline ICEVs, we assumed a higher distance traveled in order to account for the expected rebound effect, in line with [5]. More details about VKT assumptions can be found in [3] and the corresponding Supplementary files.

3. Validation of the Marginal Emission Factors to Assess BEV Impacts

The marginal emission factors developed are only valid to describe marginal changes in electricity demand in the near future; therefore, a verification of the validity of the model to the BEV application is required. In particular, it is necessary to verify: (i) if the change in demand induced by BEVs can be considered marginal in regards to total demand from the system; and (ii) if the additional hourly load to the system from BEV charging did not entail changes to the marginal operation of the system depicted in the model (i.e., if the probability of load exceeding the remaining capacity of marginal generators is low).

During the period under analysis (2015–2017), the maximum annual amount of electricity requested to the grid was calculated as 11 GWh (average electricity consumption of 175 kWh·km^{-1}), corresponding to an addition of less than 0.03% to baseline electricity demand, which was assumed to be a small-enough change to be considered marginal on a yearly basis. If all BEVs were charging at the same time in a 3.3 kW charger (normal charger), the maximum power requested to the grid would be below 36 MW. The remaining capacity of natural gas combined cycle generators was always above 1100 MW in all hours of 2012–2014, while coal power plants' remaining capacity was below 36 MW in about 25% of the hours (Figure S4). Because the probability of simultaneous charging of all BEVs is likely very low, the effect in GHG emissions due to the additional electricity requested to the grid by the BEV fleet in 2015–2017 may thus be described by the marginal emission factors calculated (see Section 3.1 in the original article).

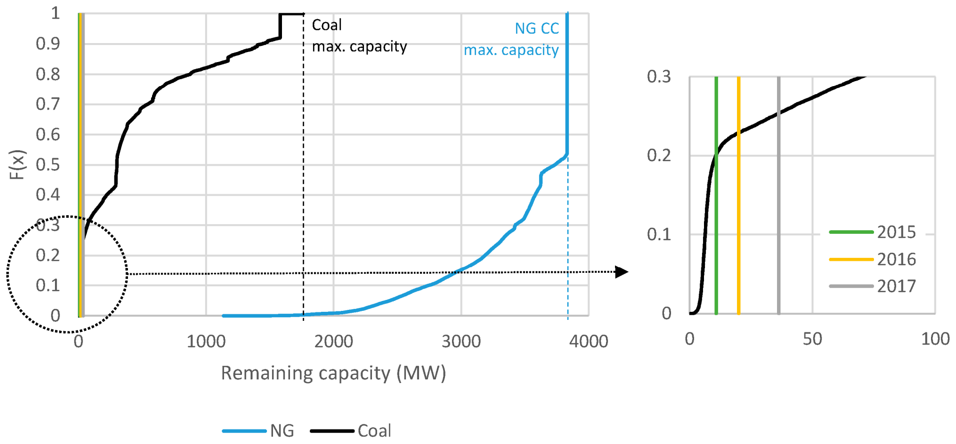

Figure S3. Cumulative probability distribution of remaining coal and natural gas combined cycle (NG CC) capacity in each hour of 2012–2014 and comparison with maximum BEV load for 2015, 2016, and 2017.

4. Monte Carlo Simulation

Monte Carlo simulation was used to quantify the uncertainty regarding charging times in each scenario. Parameter values (electricity emission factors) and probability distributions for Monte Carlo uncertainty propagation concerning the four charging patterns are shown in Table S5. Samples have been generated using a random sampling procedure and each simulation consisted of 10,000 iterations. The 5th, 25th, 50th, 75th, and 95th percentiles for the resulting probability distributions were calculated.

Table S5. Parameter values and probability distributions for Monte-Carlo uncertainty propagation.

Parameter	Distribution	Min	Max
Electricity marginal EF for scenarios 1 and 2 (kg CO_2 eq·MWh^{-1})	Uniform	730	748
Electricity marginal EF for scenarios 3 and 4 (kg CO_2 eq·MWh^{-1})	Uniform	798	819
Electricity marginal EF for scenarios 5 and 6 (kg CO_2 eq·MWh^{-1})	Uniform	692	785
Electricity marginal EF for scenarios 7 and 8 (kg CO_2 eq·MWh^{-1})	Uniform	629	940

5. Influence of Hydro Generation in the Marginal Emissions

Although constrained on an annual basis, large hydro power can influence the marginal generation: an increase in hydro generation in one hour may result in less hydro power available at some time in the future, and thus in an increase in the use of the marginal generation at that future time. To address this shifting effect, we first calculated the contribution of fuel sources to the change in demand and corresponding change in emissions considering that hydro is also used for load-following (see Table S6). This was performed following a similar approach to the one used in Section 2.1.2, but considering that hydro power is unconstrained. The emission factors calculated are lower than the ones in Table 3, because 32%–81% of the change in demand in each hour is satisfied by hydro power. These emission factors were then applied to calculate the change in emissions due to BEV charging in each scenario (uncertainty with regards to time of charging was also accounted for using Monte Carlo simulation; Parameter values and probability distributions for Monte-Carlo uncertainty propagation concerning the four charging patterns are shown in Table S7). In addition, we assumed that the amount of hydro generation used in an hour to satisfy BEV demand will not be available later on; therefore, the effect of BEV charging with (a percentage of) hydro power in an hour will be to increase the future use of the fossil marginal generation (NG and/or coal). In addition to the change in emissions due to BEV charging calculated using the marginal EFs from Table S6 (marginal $EF_{with\ hydro}$), we account for the increase in emissions due to the unavailability of hydro power in the future (Equation (S1)), calculated using the marginal emission factors from Table 3 (marginal $EF_{without\ hydro}$). Uncertainty in regards to the period affected by the shift was accounted for using Monte Carlo simulation. Parameter values and probability distributions for Monte-Carlo uncertainty propagation are shown in Table S7. We assumed that the reduction in hydro availability due to BEV charging will affect mostly peak hours, because hydro power is mostly used for load-following during the day. Results for the scenarios in Table 2 are shown in Figure S4.

Equation (S1)

Change in electricity emissions due to BEV charging (scenario *i*) =
BEV fleet electricity consumption × [marginal $EF_{with\ hydro}$ (scenario *i*) + % hydro generation in marginal $EF_{with\ hydro}$ (scenario *i*) × marginal $EF_{without\ hydro}$ (scenario *i*)] (S1)

Table S6. Marginal fuel sources and marginal emission factors (EFs) for each hour of the day for electricity generation in Portugal from 2012 to 2014, considering that hydro generation is used for load following.

Time of Day	Marginal Fuel Source		Hydro (%)	Marginal $EF_{with\ hydro}$
	Coal (%)	NG (%)		(kg CO_2 eq·MWh^{-1})
1 a.m.	35	18	47	432
2 a.m.	48	16	36	561
3 a.m.	55	8	37	598
4 a.m.	59	9	32	637
5 a.m.	45	16	39	526
6 a.m.	23	19	57	320
7 a.m.	17	29	55	290
8 a.m.	14	23	63	240
9 a.m.	19	19	62	276
10 a.m.	15	9	76	188
11 a.m.	14	15	71	208
12 a.m.	12	9	79	164
1 p.m.	13	10	77	172
2 p.m.	18	11	71	228
3 p.m.	20	18	62	278
4 p.m.	13	17	71	200
5 p.m.	11	12	77	164
6 p.m.	14	11	75	185
7 p.m.	12	10	78	162
8 p.m.	12	7	81	151
9 p.m.	8	18	75	154
10 p.m.	11	21	68	200
11 p.m.	15	31	54	283
12 p.m.	22	26	52	334

NG: natural gas.

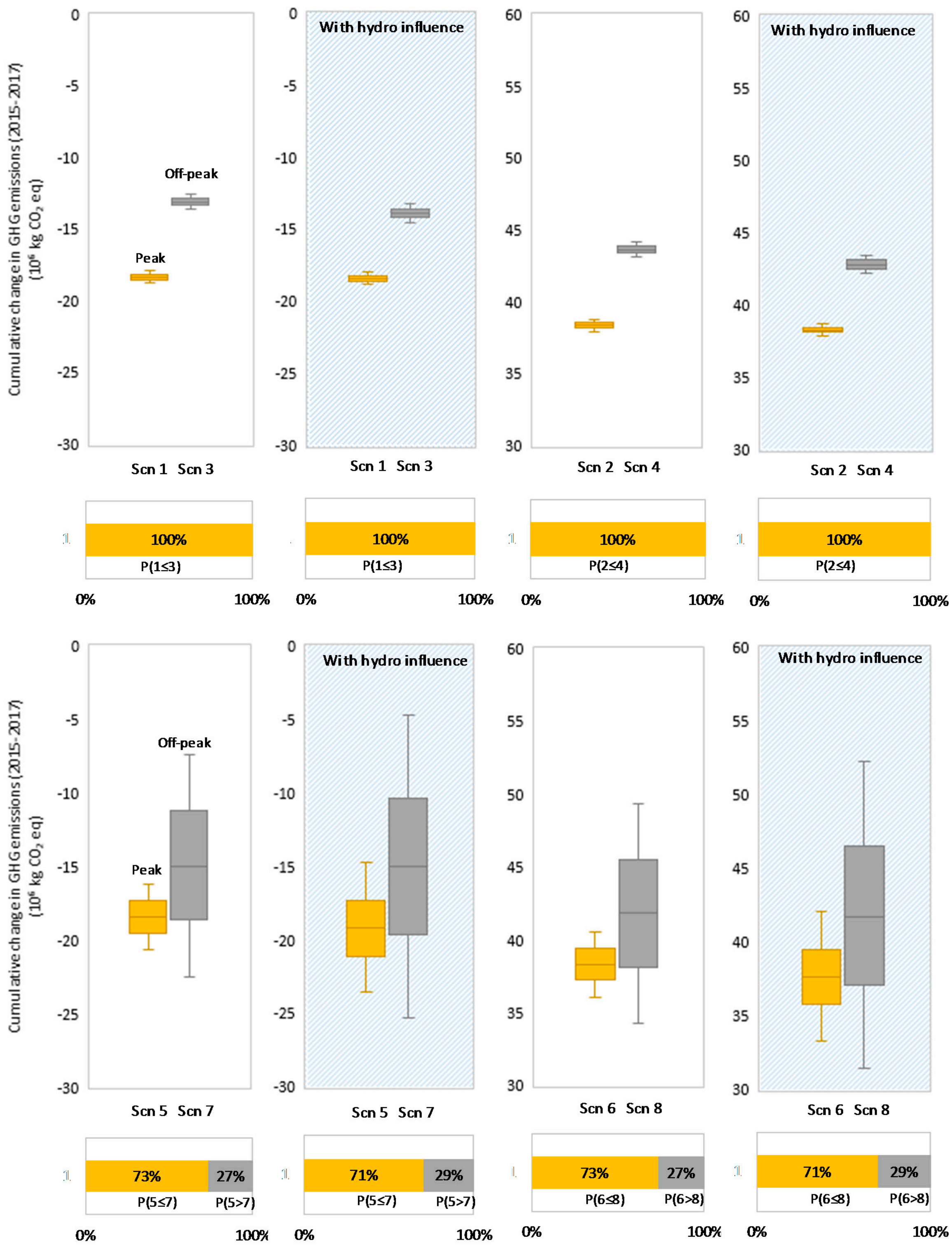

Figure S4. Cumulative change in GHG emissions due to the introduction of BEVs in the Portuguese light-duty fleet from 2015 to 2017 for the scenarios in Table 2. In blue, sensitivity analysis to the influence of hydro generation in marginal GHG emissions. Considering that coal-fired PP are constrained (non-dispatchable) would result in a cumulative change in emissions of −42 Gg CO_2 eq in scenarios 1, 3, 5, 7, and 14 Gg CO_2 eq in scenarios 2, 4, 6, 8.

Table S7. Parameter values and probability distributions for Monte Carlo uncertainty propagation (sensitivity analysis).

Parameter	Distribution	Min	Max
Electricity marginal $EF_{with\ hydro}$ for scenarios 1 and 2 (kg CO_2 eq·MWh^{-1})	Uniform	190	219
Electricity marginal $EF_{with\ hydro}$ for scenarios 3 and 4 (kg CO_2 eq·MWh^{-1})	Uniform	446	482
Electricity marginal $EF_{with\ hydro}$ for scenarios 5 and 6 (kg CO_2 eq·MWh^{-1})	Uniform	152	258
Electricity marginal $EF_{with\ hydro}$ for scenarios 7 and 8 (kg CO_2 eq·MWh^{-1})	Uniform	242	618
Electricity marginal $EF_{without\ hydro}$ for scenarios 1 to 4 (kg CO_2 eq·MWh^{-1})	Uniform	730	748
Electricity marginal $EF_{without\ hydro}$ for scenarios 5 to 8 (kg CO_2 eq·MWh^{-1})	Uniform	692	785

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