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Assessing electric vehicle CO_2 emissions in the Portuguese power system using a marginal generation approach

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ABSTRACT

In this work the electric vehicle (EV) specific CO_2 emissions resulting from the EV integration on the Portuguese power system are analysed, considering a large set of scenarios combining the system renewable capacity versus EV share, under a night charge scenario. For this purpose, a unit commitment and economic dispatch (UCED) is applied to the power units scheduling. The optimization procedure is implemented in General Algebraic Modeling System (GAMS) and performs the dispatch of the thermal and hydro units, in order to minimize the operation costs. The model is applied to an entire year of operation in an hourly basis using a marginal methodology. According to the results obtained, for the scenarios considered, the EV specific CO_2 emissions range from 57 g CO_2/km, for high wind capacity and low EV penetration, to 129 g CO_2/km, for low wind capacity and low EV penetration. However, if a controlled charge strategy, aiming the minimizing of generation costs, is considered, the range of results is wider, varying from 26 g CO_2/km, for high wind capacity and low EV penetration, to 133 g CO_2/km for low wind capacity and low EV penetration. From the results, it can be concluded that, with the current wind capacity of the Portuguese system, and with a night charge strategy, the impact of the EV in terms of CO_2 emissions is not beneficial when compared to the 95 g CO_2/km target, for penetrations lower than 1 million vehicles, but if a controlled charge is considered, it would be not beneficial for a EV penetration of 180 thousand vehicles. Results also show that EVs can be integrated in an environmental beneficial way, if increasing EV penetrations are combined with an increase in the installed wind capacity.

Keywords:

CO_2 emissions;
Electric vehicles;
Marginal emissions;
Renewable energy integration;
Unit Commitment;

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1. Introduction

Presently, climate is changing and it exists an increasing consensus on the need to reduce the greenhouse gases emissions (GHG), in order to slow global warming.

Worldwide, the energy sector and the transportation sector are the two major contributors to the global emissions with, respectively, 41.4% and 24.5% of the world CO_2 emissions in 2017 [1], being also responsible for most of the fossil fuel consumption.

The transportation sector is dominated by internal combustion vehicles (ICEV) and relies almost entirely on oil as primary energy source. About 94% of the world energy used for transportation in 2017 came from oil and projections estimate 82%, by 2050 [2]. Besides, transportation is the sector which shows the highest level of dependence on a single primary energy source, being the road transportation the major contributor for the sector emissions.

As a consequence, political, economic and environmental concerns arise, and worldwide, a fast growth is being verified in the power generation from renewable sources. Moreover, these concerns also motivated efforts

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List of Abbreviations

EV	Electric vehicle
EVEI	Electric vehicles emission index
GAMS	General algebraic modeling system
GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
LDV	Light duty vehicle
MILP	Mixed integer linear programming
PRE	Special regime producers/Produção em regime especial
PSH	Pumped storage hydro
RES	Renewable energy sources
SOC	State of charge
TSO	Transmission systems operator
UCED	Unit commitment and economic dispatch
V2G	Vehicle-to-grid

in terms of increasing energy efficiency as well as the search for new transportation solutions.

Electric vehicles (EVs) present zero tailpipe emissions, higher efficiency than ICEV, lower noise and are considered to have a great potential to contribute to the GHG emissions reduction. Moreover, the EV integration in the vehicle fleet presents an opportunity to decrease the energy demand from the transportation sector [3] and, consequently, the share of oil as primary energy source, thus reducing energy dependence. In addition to these advantages, considering that electric vehicles are off the road most of the time, some authors consider the possibility of their use in a perspective of grid support. The possibility of connecting an electric vehicle to the grid in a bi-directional way (V2G) with the purpose of, not only charging the battery, but also to provide power back to the grid was for the first time addressed by Kempton and Letendre in 1997 [4]. Besides the potential to improve the integration of the intermittent renewable energy sources (RES), EVs could provide peak power, spinning reserves, and frequency regulation [5-7]. In [8], the authors concluded that the use of a LDV fleet equipped with V2G is a viable option for regulation but specially to support the intermittent renewable integration into the grid. In a similar concept, vehicle-to-home (V2H), the unused storage capacity of the EV can be made available for the residential energy system with high beneficial outcomes [9]. However, some authors consider that discharging power back to the grid is not an interesting option, essentially due to the battery degradation costs [10,11]. Among the overall vehicle fleet, light-duty vehicles (LDV) accounted in 2010 for 52% of the world energy use in transportation [12] as well as, with approximately two thirds of the world CO_2 emissions originated from the transportation sector [13,14]. Considering the high contribution to the sector emissions, much of the focus concerning new transportation solutions is targeted to the LDV fleet.

Worldwide many countries have defined ambitious targets concerning the electrification of the vehicle fleet [15], and the use of EVs is expected to increase substantially in the next years [16,17].

For 2050, the European Commission (EC) targeted a minimum reduction of 60% in the GHG emissions from the transportation sector when compared to 1990 values [18]. In line with this long term target the European Parliament approved in February 2014 the ambitious target of 95g CO_2/km for the whole passenger vehicle fleet in 2020 [19]. Recently, in 2019, the European Parliament and Council defined new emission targets, for the years 2025 and 2030. According to these targets, for 2030, reductions of 37.5% and 31%, based on 2021 values, are defined for, respectively, newly registered passenger cars and light commercial vehicles [20].

However, uncertainties exist about the ability of the EVs to effectively reduce the GHG emissions. In fact, besides the advantage in terms of emissions resettlement, the expected impact on the overall CO_2 emissions is highly dependent on the power mix used to supply the EVs, and so, effects can vary substantially from country to country [21]. This fact has been put in evidence by many works [22-25].

In [22], the impact of the EV on the CO_2 emissions, energy security and air pollution in India is analysed for a period between 2010 and 2050. The analysis was performed for several policy scenarios and results showed that only in the scenarios, in which policies put in place promote a deep decarbonisation of the generation mix, the reduction in CO_2 emissions is considerable. Manjunath and Gross [23] proposed the Electric vehicles emission index (EVEI), which is a metric to compare the CO_2 emissions of a specific EV with a gasoline vehicle. The EVEI was computed for all the US, for the year 2010, and results showed that in states with higher shares of fossil fuels in the generation mix, the EV emissions were similar or even higher than the emissions of the gasoline vehicle. The importance of the generation mix is also highlighted by [24], which compared EV and ICEV GHG emissions, in 12 European countries, using life-cycle assessment and concluded that the UK, Germany and the Netherlands must increase the penetration of renewables to ensure reductions in GHG emissions with increasing penetration of EV. Moreover, [25] in a study comparing Germany and Italy found out that even if the share of renewables is similar in both countries the impact of EV does not lead to similar results in terms of reduction in CO_2 emissions. In fact, for Germany, for lower installed capacity of renewables, there is almost no change in CO_2 emissions, whereas, for Italy, CO_2 emissions are always reduced. This stems from the fact that the installed capacity in Germany is not adequate to supply the increase in demand due to the EV, thus, there is a need to resort to imports from neighbouring countries.

Also, the EV CO_2 emissions depend on when the EVs are charged. This fact was observed by [26] in a study for electric buses in Germany, where the results showed that the CO_2 emissions impact was lower when charging occurred at night than when it occurred at noon. When the comparison is made between an uncontrolled charge and a controlled charge the differences in CO_2 emissions can be significant as [27] found out in a study for Germany for 2030. The results showed that with an optimal controlled strategy of EV charging, aiming to shift EV demand to low load or high RES generation hours, the CO_2 emissions can be reduced by 14% or 30% (depending on the methodology used to account for CO_2 emissions) when compared to an uncontrolled charge. In a work analysing the CO_2 emissions of a French-German commuter EV fleet, [28] concluded that the EV should be charged in Germany in windy and sunny hours, and that the time of charging is much more important in Germany than in France, since the later has more stable CO_2 emissions during the day. Also, using a smart charging strategy to avoid grid overloading and for a scenario of complete electrification of private transport and a six fold increase of renewables installed capacity, [25] reported an increase in CO_2 emissions reduction of 31.5% and 26.3% in Italy and Germany, respectively, when compared to a charge made exclusively according to driver's needs.

Furthermore, in an analysis for the Swedish energy and transportation system, for 2050, [29] verified that when the EVs are charged during night time, the annual system costs are 0.8% higher and the needed increase in transmission capacity is 10% higher than when EV are charged in a more flexible manner.

1.1. Scope

Owing to the expected increasing importance of the EV in the LDV fleet worldwide and, in particular, in Portugal, this paper aims to answer to the questions: what is the impact of an increasing EV penetration in the CO_2 emissions of the Portuguese power system? How does this impact vary for different levels of installed wind capacity in the Portuguese power system?

1.2. Analytical approach

To attain the aims of this paper, a scenario framework approach is used. A set of scenarios, combining increasing levels of installed wind capacity, for different EV penetration levels is analysed, for the Portuguese power system. For this purpose, a unit commitment and economic dispatch (UCED) model, formulated as a mixed integer linear programming (MILP), is applied for the power units scheduling. The optimization procedure proposed is implemented in General Algebraic Modeling System (GAMS) and performs the dispatch of the thermal, reservoir hydro and pumped hydro units, in order to minimize the operation costs. The implemented model is applied to an entire year of operation on an hourly basis and assumes a marginal approach to account for CO_2 emissions. This methodology compares the generation which would be necessary if EVs were not present, with the generation required to supply the entire new load (including EVs). From the differences obtained in the optimization results, the marginal data which effectively respects to the EVs, in each of the scenarios considered, is assessed. However, for the sake of comparison, the average CO_2 emissions of the power mix are also presented. Besides, the CO_2 emissions for all scenarios considered are also computed for two different charging strategies. The first strategy considered is night charge, in which, the EVs are charged according to drivers' need, and the second strategy is a controlled charge, performed to minimize total generation costs, which, in turn, minimizes renewable curtailment.

The main contribution of this work is to analyse the impact of increasing EV penetrations in the Portuguese power system, applying an UCED model developed to the Portuguese power system, in order to account the emissions using a marginal approach.

2. Model description

To achieve the purpose of the work, a UCED model of the thermal and storage hydro units was formulated. The purpose of the model is to minimize variable costs of the generating units while satisfying a set of thermal and hydro unit's constraints, as well as, overall power system constraints. In the formulated model, the thermal units were treated individually, whereas, the hydro units were treated as two aggregated units, one representing the set of reservoir units and, the other, the set of pumped-storage hydro (PSH) units. In what concerns run-of-river hydro units, since they have reduced water storage, the generation from these units is considered as input data.

2.1. Objective function

The objective function, which includes the generation and start-up costs of the thermal units, as well as, a penalty for the curtailment of wind generation, is defined as:

$$min\sum_{t=1}^{T}\left\{\sum_{j=1}^{J}\left[C_G^j\cdot P^j\left(t\right)\cdot\delta t+C_{SU}^j\cdot y^j\left(t\right)\right]-C_{RC}\cdot P_{RC}\left(t\right)\cdot\delta t\right\} \quad (1)$$

Where T is the number of time periods t, J is the number of thermal units j, C_G^j is the generation cost of thermal unit j, in €/MWh, $P^j(t)$ is the power generated by the thermal unit j at period t, in MW, δt is the time interval between t and $t+1$, C_{SU}^j is the start-up cost of thermal unit j, in €, $y^j(t)$ is a binary variable, associated with the start-up of thermal unit j at period t, C_{RC} is the renewable generation curtailment penalty, in €/MW and $P_{RC}(t)$ is the renewable generation curtailment at period t, in MW (since $P_{RC}(t)$ represents a non-supplied power, it assumes values lower or equal to zero).

The minimization of Eq. (1) is subject to a set of constraints, which refer to thermal units, reservoir hydro units, PSH units, load balance and spinning reserve.

2.2. Thermal units constraints

The set of thermal units constraints is related with the technical limits of operation of the thermal units, which in this study refers to maximum and minimum power output, as well as, ramp-up and ramp-down power rates. These constraints are presented in Eq. (2) to (4).

$$P_{min}^j\cdot u^j\left(t\right)\le P^j\left(t\right)\le P_{max}^j\cdot u^j\left(t\right) \quad (2)$$

Where P_{min}^j and P_{max}^j are the minimum and maximum power outputs of the thermal unit j, in MW, and $u^j(t)$ is a binary variable, which indicates if unit j is running in period t.

$$P^j\left(t\right)-P^j\left(t-1\right)\le P_{up}^j \quad (3)$$

$$P^j\left(t-1\right)-P^j\left(t\right)\le P_{down}^j \quad (4)$$

Where P_{up}^j and P_{down}^j are the ramp-up and ramp-down power rates of the thermal unit j, in MW/h. Besides Eq. (2) to (4), to guarantee the consistency of the operation of the thermal units during the simulation period, the following constraint must be added:

$$u^j\left(t\right)-u^j\left(t-1\right)=y^j\left(t\right)-s^j\left(t\right) \quad (5)$$

Where $s^j(t)$ is a binary variable which indicates if unit j shuts down in period t.

2.3. Reservoir hydro unit constraints

The constraints of the reservoir hydro unit are related with the technical limits of this unit and with the energy stored in the reservoir. The constraints are presented in Eq. (6) to (8).

$$P_{H\,min}\cdot u^H\left(t\right)\le P_H\left(t\right)\le P_{H\,max}\cdot u^H\left(t\right) \quad (6)$$

Where $P_{H\,min}$ and $P_{H\,max}$ are the minimum and maximum output powers of the reservoir hydro unit, in MW, $u^H(t)$ is a binary variable which indicates if the unit is running in period t, and $P_H(t)$ is the power output of the reservoir hydro unit, in MW.

$$P_H\left(t\right)-P_H\left(t-1\right)\le P_{H\,up} \quad (7)$$

$$P_H\left(t-1\right)-P_H\left(t\right)\le P_{H\,down} \quad (8)$$

Where $P_{H\,up}$ and $P_{H\,down}$ are the ramp-up and ramp-down power rates of the reservoir hydro unit, in MW/h. The energy stored by the reservoir hydro unit, which depends on the energy stored in the previous period, on the energy inflow and on the power output in the period, can be written as follows:

$$E_H\left(t\right)=E_H\left(t-1\right)-P_H\left(t\right)\cdot\delta t+E_{H\,Inf}\left(t\right) \quad (9)$$

Where E_H (t) is the energy stored, in the hydro unit in period *(t)*, in MWh, and $E_{H\,Inf}$ (t) is the energy inflow of the reservoir hydro unit in period t, in MWh. Also, the limits of the energy stored in the reservoir hydro unit are considered in Eq. (10):

$$E_{H\,min}\le E_H\left(t\right)\le E_{H\,max} \quad (10)$$

Where, $E_{H\,min}$ and $E_{H\,max}$ are respectively, the minimum and maximum storage capacities of the reservoir hydro unit, in MWh. The model also considers a final energy condition, which relates the final and the initial values of the energy stored in the reservoir hydro unit. The condition is written as follows:

$$E_{H\,fin} - E_{H\,Init} = \sum_{t=1}^{T} E_{H\,Inf}(t) - \sum_{t=1}^{T} P_H(t) \cdot \delta t \qquad (11)$$

Where $E_{H\,fin}$ and $E_{H\,Init}$ are, respectively, the final energy and the initial energy stored in the reservoir hydro unit, in MWh.

2.4. PSH unit constraints

The constraints that must be considered for a PSH unit are quite similar to those considered for the reservoir hydro unit but, these constraints must be extended to include the pumping capability of the hydro unit. Thus, Eq. (12) and (13) define the generation and pumping output power limits of the PSH unit:

$$P_{PH\,min} \cdot u^{PH}(t) \le P_{PH}(t) \le P_{PH\,max} \cdot u^{PH}(t) \qquad (12)$$

$$-P_{PH\,max} \cdot u^{PH_p}(t) \le P_{PH_p}(t) \le -P_{PH\,min} \cdot u^{PH_p}(t) \qquad (13)$$

Where $P_{PH}(t)$ is the power output of the PSH unit when it is generating, in MW, $P_{PHp}(t)$ is the power output of the PSH unit when it is pumping, in MW, $P_{PH\,min}$ and $P_{PH\,max}$ are, respectively, the minimum and maximum power output limits, in MW and, $u^{PH}(t)$ and $u^{PH_P}(t)$, are binary variables, which are equal to 1 when the PSH unit is generating or pumping, respectively, in period t. The ramp-up and ramp-down power rates constraints are set respectively by Eq. (14) and (15).

$$P_{PH}(t) - P_{PH}(t-1) \le P_{PH\,up} \qquad (14)$$

$$P_{PH}(t-1) - P_{PH}(t) \le P_{PH\,down} \qquad (15)$$

Where $P_{PH\,up}$ and $P_{PH\,down}$ are, respectively, the ramp-up and ramp-down power rates of the PSH unit, in MW/h. Since the PSH unit is an aggregate representation of the PSH units of the Portuguese system, it must be assured that, at each period t, the overall generation and pumping output power must not exceed the maximum power output of the PSH unit. This is expressed by the following constraint:

$$P_{PH}(t) - P_{PH_p}(t) \le P_{PH\,max} \qquad (16)$$

The limits for the energy stored in the PSH unit are imposed by the following constraint:

$$E_{PH\,min} \le E_{PH}(t) \le E_{PH\,max} \qquad (17)$$

Where $E_{PH\,min}$ and $E_{PH\,max}$ are, respectively, the minimum and maximum storage capacity of the PSH unit, in MWh, and E_{PH} (t) is the stored energy in the unit at period t, in MWh. The energy stored by the PSH unit is given by:

$$E_{PH}(t) = E_{PH}(t-1) - \left[P_{PH_p}(t) \cdot \eta_{PH} + P_{PH}(t) \right] \cdot \delta t + E_{PH\,Inf}(t) \qquad (18)$$

Where, η_{PH} is the pumping cycle efficiency and $E_{PH\,Inf}(t)$ is the energy inflow, in period t, in MWh. The constraint which relates the final and initial stored energy is written as follows:

$$E_{PH\,fin} - E_{PH\,Init} = \sum_{t=1}^{T} E_{PH\,Inf}(t) - \sum_{t=1}^{T} \left[P_{PH_p}(t) \cdot \eta_{PH} + P_{PH}(t) \right] \cdot \delta t \qquad (19)$$

Where $E_{PH\,fin}$ and $E_{PH\,Init}$ are, respectively, the final energy and the initial energy stored in the PSH unit, in MWh.

2.5. Load balance constraints

The model must also assure the balance between supply and demand in all time periods. This is accomplished by:

$$\sum_{j=1}^{J} P^j(t) + P_H(t) + P_{PH}(t) = P_L(t) + P_{EV}(t) - P_R(t) - P_{RC}(t) + P_{PH_p}(t) \qquad (20)$$

Where $P_L(t)$ is the load, referred to generation, in period t, in MW, $P_{EV}(t)$ is the charging power of the EV battery, in period t, in MW, $P_R(t)$ and is the sum of run-of-river hydro and special regime generation, in period t, in MW.

2.6. Spinning reserve constraints

Spinning reserve allows system operators to compensate for unexpected imbalances between load and generation, which may be caused by a sudden outage of a generating unit, unexpected increase in load demand or fails in the commitment of defined generation schedules.

In this model, the spinning reserves requirements are accounted in the following constraint:

$$\sum_{j=1}^{J} P^j_{max} \cdot u^j(t) + P_{H_{max}} \cdot u^H(t) + P_{PH_{max}} \cdot u^{PH}(t) \ge P_L(t) + P_{EV}(t) + P_{RES}(t) \qquad (21)$$

Where $P_{RES}(t)$ is the required power reserve, in period t, in MW.

2.7. Thermal generation costs

The objective function of the model, presented in Eq. (1), comprises the minimization of costs. Besides the penalty to the wind curtailment, the costs considered are related with thermal generation. The thermal generation costs considered are the variable generation costs due to fuel consumption and CO_2 emissions, and the start-up costs.

2.7.1. Thermal generation variable costs

The variable costs associated with each thermal unit j, can be written as follows:

$$C_G^j = C_{fuel}^j + C_{CO_2}^j \tag{22}$$

Where C_G^j is the variable cost of thermal unit j, in €/MWh, C_{fuel}^j is the variable cost of thermal unit j, in €/MWh, due to fuel consumption and $C_{CO_2}^j$ is the variable cost of thermal unit j, in €/MWh, due to CO_2 emissions. The variable costs due to fuel consumption depend on the fuel price and characteristics, and on the unit's efficiency, according to the following equation:

$$C_{fuel}^j = \frac{pc_{fuel}}{\eta^j \cdot LHV} \tag{23}$$

Where pc_{fuel} is the fuel price in €/kg or €/Nm^3, for coal and natural gas, respectively, η^j is the global efficiency of the thermal unit j, and LHV is the lower heating value of the fuel used, in MWh$_t$/kg or MWh$_t$/Nm^3, for coal and natural gas, respectively. The variable cost due to CO_2 emissions, not only depends on the fuel quality and thermal units efficiency, but also on the specific CO_2 emissions of the fuel and the price of the CO_2 emissions allowances, according to the following equation:

$$C_{CO_2}^j = \frac{E_{CO_2\,fuel}}{\eta^j \cdot LHV} \cdot pc_{CO_2} \tag{24}$$

Where $E_{CO_2 fuel}$ is the specific CO_2 emissions of the fuel, in kg CO_2/kg, for coal, or kg CO_2/Nm^3, for natural gas, and pc_{CO_2} is the price of the CO_2 emissions allowances in €/kg CO_2.

2.7.2. Thermal generation start-up costs

Start-up costs are costs that the thermal unit incurs when it is turned on and are given by Eq. (25) [30,31].

$$C_{SU}^j = C_{Ab}^j + C_{SU\ fuel}^j + C_{SU\ CO_2}^j \tag{25}$$

Where C_{SU}^j is the start-up cost of thermal unit j, in €, C_{Ab}^j is the abrasion cost of thermal unit j, in €, $C_{SU\ fuel}^j$ is the start-up fuel consumption cost of thermal unit j, in €, and $C_{SU\ CO_2}^j$ is the start-up CO_2 emissions cost of thermal unit j, in €. The abrasion cost is considered proportional to the installed capacity of the thermal unit and is given by:

$$C_{Ab}^j = sc_{Ab}^j \cdot P_{max}^j \tag{26}$$

Where sc_{Ab}^j is the specific abrasion cost of thermal unit j, in €/MW, and P_{max}^j is the maximum power output of thermal unit j, in MW, which is considered equal to the installed capacity. The start-up fuel consumption cost is given by:

$$C_{SU\ fuel}^j = \frac{pc_{fuel}}{LHV} \cdot sc_{fuel}^j \cdot P_{min}^j \tag{27}$$

Where sc_{fuel}^j is the specific start-up fuel consumption of thermal unit j, in MWh$_t$/MW, and P_{min}^j is the minimum power output of thermal unit j, in MW. The start-up CO_2 emissions cost is given by:

$$C_{SU\ CO_2}^j = \frac{E_{CO_2\,fuel}}{LHV} \cdot sc_{fuel}^j \cdot P_{min}^j \cdot pc_{CO_2} \tag{28}$$

3. Data and assumptions

The assumptions made are mostly supported in extrapolations of the historical data as well as on predictions from the Portuguese government and the Portuguese transmission systems operator (TSO). The analysis performed is based on the generation system and is not focused on the grid. Eventual constraints that may occur, at the different grid voltage levels, are neither considered, nor analysed. All scenarios are run under the assumption of null exchanges with the neighbouring Spanish power system, as this was considered a better option than use historical exchange profiles.

3.1. Installed capacity

The forecasted installed capacity for the simulation year was obtained from the Portuguese TSO [32] and respective values, by technology, are presented in Table 1.

From Table 1, one can see that special regime, in which wind power is included, will account for more than 40% of the total installed capacity. The thermal capacity will only account for 25% of the total and the hydro installed capacity, due to planned new power plants, will reach almost one third of the total installed capacity.

3.2. Thermal generation

Table 2 describes the technical characteristics of the thermal units considered in the simulations.

Regarding thermal units costs presented in Table 3, thermal units' efficiency is considered constant and independent of the power output. Also, the start-up costs are considered constant.

Table 1: Expected installed capacity in the Portuguese power system [32]

Technology	Capacity (MW)	Share (%)
Thermal	**7245**	**25.0**
Coal	1756	6.0
CCGT/Cogeneration	5489	19.0
Hydro	**9535**	**32.9**
Pumped	4921	17.0
Reservoir	2031	7.0
Run-of-river	2583	8.9
Special regime	**12182**	**42.1**
Wind	6875	23.7
Small hydro	750	2.6
Photovoltaic	1500	5.2
Cogeneration	2250	7.8
Biomass	557	1.9
Wave	250	0.9
Total	**28962**	**100.0**

3.3. Fuel and CO_2 prices

The prices and characteristics of the fuels, as well as, the CO_2 allowances price are presented in Table 4. For the coal, it was considered the API2 index price and for natural gas it was assumed the Title Transfer Facility (TTF) Virtual Trading Point index. For the price of the CO_2 emissions allowances, the price considered was 10 €/ton, which corresponds to a value higher than the average EUA Bluenext index price between 2011 and 2017, which was 7.1 €/ton.

3.4. Hydro generation

As mentioned above, the hydro units, except run-of-river units, were considered as two aggregated units. One represents the set of reservoir hydro units and, the other, the set of PSH units.

The characteristics of the hydro units, such as installed capacity, and storage levels and capacity, were set accordingly with data available in [38,39]. The historical data of daily net inflows, in terms of energy, were obtained from [38]. In order to be used in the simulation year, the historical daily net inflows values were converted to an hourly basis and then scaled to an average year in terms of hydro availability. Additional inflows correspondent to new hydro power plants were calculated with base on the technical data presented in [40] and on primary energy estimated in [41,42]. For the PSH units, the pumping cycle efficiency considered was obtained from data regarding pumped power and respective generation power available in [43] and set to 80%.

Table 2: Technical characteristics considered for the Portuguese thermal units [33,34]

Power Plant	Installed capacity	P_{max}	P_{min}	Efficiency	Ramp up	Ramp down	Start-up fue	Abrasion
	(MW)	(MW)		(%)	(MW/h)		(MWh_t/MW)	(€/MW)
Coal								
Sines	4 × 295	295	103	37	140	270	6.2	5
Pego	2 x 288	288	101	37	145	296	6.2	5
Natural gas								
Ribatejo	3 × 392	392	127	57	267	366	3.5	8
Lares	2 × 413	413	130	57	270	370	3.5	8
Pego	2 × 419	419	130	57	270	370	3.5	8
T. Outeiro	3 × 330	330	95	55	256	330	3.5	8
Lavos	2 × 415	415	130	57	270	370	3.5	8
Sines	2 × 415	415	130	57	270	370	3.5	8

Table 3: Generation and start-up costs of the Portuguese thermal generation units [31,35,36]

Power Plant	Fuel consumption		CO_2 emissions		Generation costs			Start-up costs			
	(kg/MWh_t) or (Nm^3/MWht)	(kg/MW) or (NM^3/MW)	(kg/MWh_e)	(kg/MW)	(€/MWh_e)			(€/Start-up)			
	Generation	Start-up	Generation	Start-up	Fuel	CO_2	Total	Fuel	CO_2	Abrasion	Total
Coal											
Sines	138.6	859.1	895.1	2053.3	32.8	8.95	41.76	7751	2115	1475	11356
Pego	138.6	859.1	895.1	2053.3	36.08	8.95	45.04	8361	2074	1440	11894
Natural gas											
Ribatejo	93.6	327.6	354.3	706.8	39.47	3.54	43.02	10001	898	3136	14035
Lares	93.6	327.6	354.3	706.8	39.47	3.54	43.02	10238	919	3304	14292
Pego	93.6	327.6	354.3	706.8	39.47	3.54	43.02	10238	919	3352	14292
T. Outeiro	93.6	327.6	367.2	706.8	40.91	3.67	44.58	7481	671	2640	10793
Lavos	93.6	327.6	354.3	706.8	39.47	3.54	43.02	10238	919	3304	14292
Sines	93.6	327.6	354.3	706.8	39.47	3.54	43.02	10238	919	3304	14292

Table 4: Fuel prices, characteristics and CO_2 prices considered for the Portuguese thermal units [37]

Power Plant	Price		LHV		Specific CO_2 emissions		
	(€/ton)	(€/MWh_t)	(KWh_t/kg)	(kWh_t/Nm^3)	(kg CO_2/GJ)	(kg CO_2/kg)	(kg CO_2/Nm_3)
Coal	87.6	12.14	7.22	-	92.0	2.39	–
Natural	–	22.50	–	10.68	56.1	–	2.16
CO_2	10.0	–					

Table 5: Characteristics of the PSH and reservoir hydro units [38]

Unit	Energy (GWh)				
	Capacity	Initial	Final	Maximum	Minimum
Pumped-storage hydro	1885	1112	1112	1508	848
Reservoir hydro	1478	776	776	1182	665

Table 5 presents the characteristics of the aggregated hydro units.

Due to their reduced water storage, run-of-river hydro generation was considered as input data, taking into account the historical data provided by the Portuguese TSO. These values were then adjusted to the simulation year, considering an average year in terms of hydro availability and scaled up according to the expected installed capacity.

3.5 Special regime generation

Likewise run-of-river hydro units, historical data for special regime generation, provided by the Portuguese TSO was considered, and then adjusted to an average year in terms of hydro and wind availability and scaled up, for each technology, according to the expected installed capacity.

3.6. Demand

For the demand, historical data was also considered and then scaled up according to estimated growth. According to the assumed growth, a 56.3 TWh power demand is expected, with a peak demand of 10.2 GW.

3.7. EV charging models

In this work, two different EV charging strategies are considered. In both strategies, the EVs are considered to charge in slow charging mode (3.7 kW), at home, work or public charging points.

Also, the complete set of the EVs batteries is aggregated and modelled as one big battery which can be charged from the grid, according to the conditions of the strategy under study, and discharged when the vehicles are on the road. It is assumed that the average EV is equipped with a 24-kWh lithium battery (battery capacity of the previous Nissan leaf model), and drive, in mean, 38 km a day [44]. For the EV efficiency, a value of 0.167 kWh/km, which corresponds to 6 km/kWh, is considered, with a 85% efficiency of charge [45].

3.7.1. Night charge

According to [46] most of the EVs charge will likely occur when the vehicles are parked at home. This off-peak charging strategy is assumed as the most likely to occur in the next years, given the existing price incentives for off-peak energy use. An off-peak electricity rate starting at 10 p.m. and consistent with a dual tariff policy is assumed to be in place. In this strategy, it is assumed that vehicles owners charge their vehicles, at night, mostly at home and, eventually in public slow charging stations. Also, it is considered that, most consumers delay the starting of the EV charge until 10 p.m. to benefit from the off-peak low electricity prices, as well as, due to eventual power constraints at the residential level. In fact, given that most of Portuguese households have a contract capacity lower than 7 kW [47], it is very unlikely to conciliate a hypothetical EV charge with the typical electrical load from home appliances connected in the evening. The EVs are modelled as electrical loads and to simulate the beginning of the charge, a normal distribution (μ = 10 p.m., σ = 1 h) is considered.

The battery charging profile considered in this strategy, has two constant current charging levels, and a period of approximately eight hours is required to fully recharge an empty battery. According to the batteries capacity, mean daily driving distance and efficiency considered, a full charge will provide 144 km driving range, value which corresponds, in mean, to about 3.8 driving days. Thus, it is assumed that, in mean, each driver fully charges a depleted battery each 3.8 days. It is also assumed that the EV daily charging profile as a similar shape throughout the whole year.

The resulting normalized EV load profile is presented in Figure 1.

3.7.2. UCED controlled charge

In this charging strategy the charge of the EVs battery is dispatched by the UCED model in order to minimize the generation costs and, thus, to maximize the renewable integration. As the adoption of this approach takes into account the power system conditions, a more efficient management of the available power resources is expected. However, it is important to have in mind that the restrictions imposed to the battery's state of charge (SOC) and also the limited availability of the EVs, in order to accept charge, may have a significant effect on the merit of the strategy.

The aggregated EVs battery has a variable energy level of stored energy, discharges when vehicles are on the road, and can be charged whenever the vehicles are parked and connected to the grid. This charging process may take place at home, in a public charging point or at work. As the daily charging of the batteries is performed by the UCED model, in order to minimize the overall generation costs, this means that whenever possible, the hours with excess generation will be first chosen. However, even when there is no excess generation, the

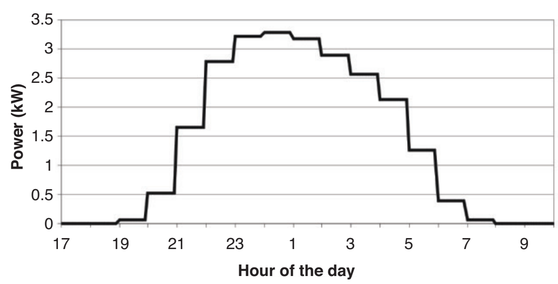

Figure 1: Unitary EV load profile - night charge

UCED model has to guarantee a minimum SOC level according to the assumptions.

According to the restrictions imposed, a minimum SOC of 30% must be maintained every hour in the EVs battery in order to guarantee that drivers have enough battery to return home, as the "range anxiety" when driving an EV is a big issue [48]. Also, considering that most drivers begin their trips in the morning after 7 a.m., a minimum battery's SOC of 70% must be guaranteed everyday by that hour. Also, the maximum charging power allowed is defined by Eq. (30).

EV discharge

The availability of detailed driving patterns is a major issue in order to create an adequate discharge model for the EVs battery. The EV discharge model adopted for this strategy is based on existing traffic surveys for the Portuguese vehicle fleet [49,50].

According to the data collected, as expected, the beginning of the daily trips is concentrated in two daily peaks, which are verified in the morning and in the evening. For the EVs battery discharge, it is assumed that EVs driving follows similar patterns to those of the conventional vehicles.

For the purpose of defining a normalized EV discharging profile for this strategy, it is considered that: 30% of the daily EV power consumption is concentrated in the morning peak and follows a normal distribution profile (μ = 8 a.m. , σ = 1 h); 10% of the daily consumption is concentrated in the midday hours following a normal distribution profile (μ = 1 p.m. , σ = 1 h); another 30% of the daily power consumption is concentrated in the evening peak, also following a normal distribution profile (μ = 7 p.m. , σ = 1.3 h); the remaining 30% power consumption is distributed by two periods along the day - 90% of this value is uniformly distributed in the period from 7 a.m. to 11 p.m. and the residual 10% is uniformly distributed in the night period, from 12 p.m. to 7 a.m.

According to the previous assumptions for the EVs consumption, the unitary daily discharging profile for the EVs battery is presented in Figure 2.

The global hourly EVs discharge profile, which corresponds to the EVs consumption, is given by Eq. (29):

$$P_{EV\,load}\left(t\right) = N_v.P_{EV\,load\,unit}\left(t\right) \quad (29)$$

Where, $P_{EV\,load}(t)$ is the power consumption of the whole fleet in time t, in MW, $P_{EV\,load\,unit}(t)$ is the unitary hourly discharge profile, and Nv is the number of vehicles in the fleet, for the scenario under analysis.

EV charging availability

Most of the time, even during the hourly peak transportation demand, only a small fraction of the vehicles (20% maximum) are driving [51]. We have assumed that in the traffic peak hours 25% of the vehicles are driving, while the remaining 75% are parked and, potentially available to receive charge (connected to the grid).

The maximum admissible charging power for the EVs fleet is given by Eq. (30).

$$P_{EVmax}\left(t\right) = N_v.P_{EV}.N_v.EV_{P\,Share}\left(t\right).EV_{C\,Share}\left(t\right) \quad (30)$$

In which, $P_{EV\,max}(t)$ is the maximum admissible charging power of the EVs aggregated battery, at time t, Nv is the number of vehicles, P_{EV} is the line capacity for each vehicle, $EV_{P\,Share}(t)$ is the share of vehicles which are parked, at time t, and $EV_{C\,Share}(t)$ is the share of parked vehicles which are connected to the power grid (grid connection share), at time t. For the grid connection share a value of 0.5 is considered for the period from 7 a.m. to 10 p.m., while a value of 0.7 is considered for the night period from 10 p.m. to 7 a.m. The resulting profile for vehicle maximum charging power is presented in Figure 3.

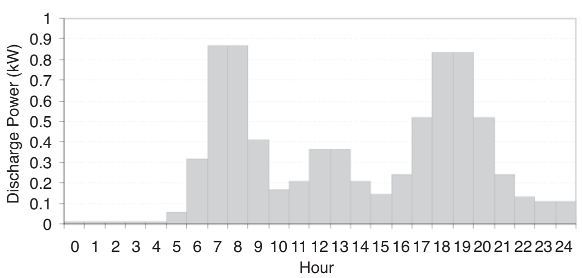

Figure 2: Unitary hourly EV discharge profile - UCED controlled charge

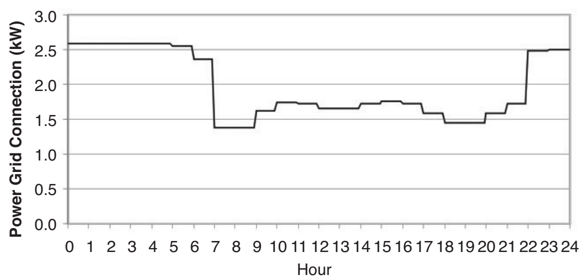

Figure 3: Maximum admissible unitary charging power - UCED controlled charge

4. Results

Chronological simulations were performed considering a set of 49 scenarios with increasing levels of wind capacity: 5000, 5600, 6875, 7500, 8700, 1000 and 11000 MW, and increasing levels of EV penetration: 0, 0.18, 0.6, 1.5, 3.0, 4.5, and 6.0 million EVs, which corresponds to 0, 3, 10, 25, 50, 75 and 100%, respectively, of the light-duty Portuguese vehicle fleet. The CO_2 emissions associated with the EVs were computed using a marginal generation approach, that is, the emissions of the additional generation needed to supply the EVs. This is obtained by the difference between the emissions resulting from the generation needed to supply all the demand (including the additional EV demand) and the emissions of the generation needed to supply the demand previous to the EV integration, named as the base case. Moreover, the average CO_2 emissions of the power mix are also presented. Evaluating the EV specific CO_2 emissions defines the set of scenarios under which the EV performs better than the ICEV, taking the 95 g CO_2/km target for the later.

4.1. Night charge

In the night charge strategy, the EVs are charged according to drivers' need. For each scenario of wind capacity under analysis there is a base case that is used to compare with the corresponding scenarios with increasing EV penetration, as presented in Table 6.

The presented results show a wide variation of EV specific CO_2 emissions, ranging from less than 60 g CO_2/km, for scenarios with low EV penetration and high wind capacity, to more than 100 g CO_2/km, especially for scenarios with low penetration of EV and low wind capacity. Scenarios in which the EV presents better performance than the ICEV in terms of CO_2 emissions are identified in Table 6 (bold), corresponding to combinations of EV penetration/wind capacity with CO_2 emissions below 95 g CO_2/km.

Two key points must be emphasized in order to fully understand the results presented. Firstly, as the marginal approach used in this work accounts the emissions of the additional generation needed to supply the EV, the analysis of the results must be focused on the available generation that is not used in the base case (without EV), as this will be the mix that supplies the EV. Secondly, under the economic dispatch context, demand is supplied on a least cost basis. Thus, under the conditions presented, where coal generation is less costly than gas, the merit order of the available technologies is wind, coal and gas. Additionally, when the EV charging replaces the pumping from reversible hydro units, there will be an extra gain which results from the avoided pumping losses, which is also accounted for the EV. Therefore, the EV can be supplied by a mix of avoided losses, wind, coal and gas.

Taking into account the CO_2 emissions of the thermal power plants presented in Table 3, the EV specific CO_2 emissions range from 0 g CO_2/km, if EVs are supplied only with wind power to a maximum of 175 g CO_2/km, if the EVs are supplied only with generation from coal power plants.

Wind will only be available for the EV charging when there is curtailment in the base case. Avoided losses will account for the EV only when the charging is synchronous with the pumping. Coal and gas will supply the EV, in this order, up to their available capacity. Needless to say, if no wind is available, the EV will be supplied firstly by coal units, which have a more negative impact in terms of CO_2 emissions than natural gas units. This is the case of the scenarios with wind capacity up to 7500 MW, in which no wind curtailment exists in the base case, as presented in Table 7.

Table 6: Marginal EV specific CO_2 emissions (g CO_2/km), with reference to scenarios which present EV specific emissions lower than 95 g CO_2/km (bold) – night charge

EVs	Wind capacity (MW)						
	5000	5600	6875	7500	8700	10000	11000
3%	129.3	103.1	**65.6**	115.8	**82.3**	**83.9**	**57.2**
10%	104.8	97.4	95.2	98.2	**94.2**	107.1	**56.8**
25%	**83.8**	**87.2**	96.1	101.6	95.6	**78.4**	**68.7**
50%	**78.3**	**79.6**	**87.0**	**93.5**	95.3	**84.0**	**77.3**
75%	**73.0**	**75.4**	**80.9**	**85.1**	**88.8**	**85.0**	**81.3**
100%	**72.6**	**73.2**	**77.3**	**80.5**	**83.5**	**82.3**	**80.6**

Table 7: Renewable curtailment, (in % of available wind generation) – night charge

EVs	Wind capacity (MW)						
	5000	5600	6875	7500	8700	10000	11000
0%	0	0	0	0	0.27	2.37	5.17
3%	0	0	0	0	0.12	1.78	4.61
10%	0	0	0	0	0	1.56	3.24
25%	0	0	0	0	0	0.26	1.21
50%	0	0	0	0	0	0.02	0.17
75%	0	0	0	0	0	0.02	0.15
100%	0	0	0	0	0	0.02	0.14

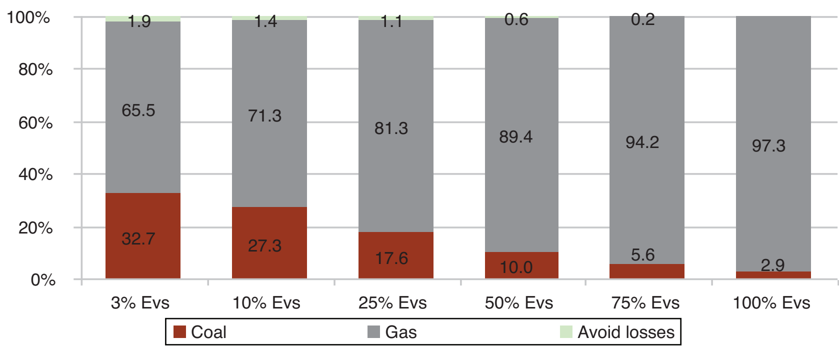

Figure 4: Marginal EV supply mix for increasing EV penetration with 5600 MW of wind capacity – night charge

To illustrate one of these scenarios of lower wind capacity (5600 MW), the EV marginal mix is presented in Figure 4.

It can be observed that, for 0.18 million EVs (3%), the additional demand induced by the EV is supplied by 1.9% of avoided losses, 32.7% of coal and 65.5% of natural gas. For increasing levels of EVs, the share of natural gas increases over the coal in the EV supply mix. This results from the limited installed capacity of the less costly coal units, being the remaining EV demand supplied by natural gas. Therefore, since natural gas specific CO_2 emissions are lower, the EV specific emissions decrease for increasing levels of EV penetration, as the share of coal also decreases. An illustrative example of a specific month of simulation is presented in Figure 5 for two scenarios (1.5 and 4.5 million EVs).

From the analysis of the results presented in Figures 4 and 5, it is clear the increased share of gas over coal and a consequent reduction of the EV specific CO_2 emissions, when increasing the EV penetration.

Figure 6, illustrates scenarios with a higher wind capacity (10000 MW), in which wind curtailment exists in the base case.

From Figure 6, it is clear that the EV succeeds in the integration of wind power that would be, otherwise, curtailed. In this situation of high wind capacity, the additional EV demand is supplied with a higher share of wind. In the particular case of 0.18 million EVs (3%), the wind power that supplies the EV comes from wind (26%) that otherwise would be curtailed or used for pumping. Moreover, since less pumping is needed, there is an efficiency gain due to the avoided losses from the pumping cycle, which accounts for 1.1% of the EV supply.

For higher levels of EV penetration, the share of the wind integration reduces, as the amount of wind power is distributed for more EVs. Furthermore, such a high level of wind capacity, in the base case, not only induces curtailment, but also reduces the use of other technologies, such as coal that is the less costly thermal technology, which becomes available to supply the EV. Consequently, the share of coal is considerably high, namely when compared with the 5600 MW wind capacity scenarios. The decline of the coal in the EV supply occurs now for higher EV penetration levels.

It can also be seen in Figure 6, that the share of coal is 31.3% for 0.18 million EVs and increases to 46% for

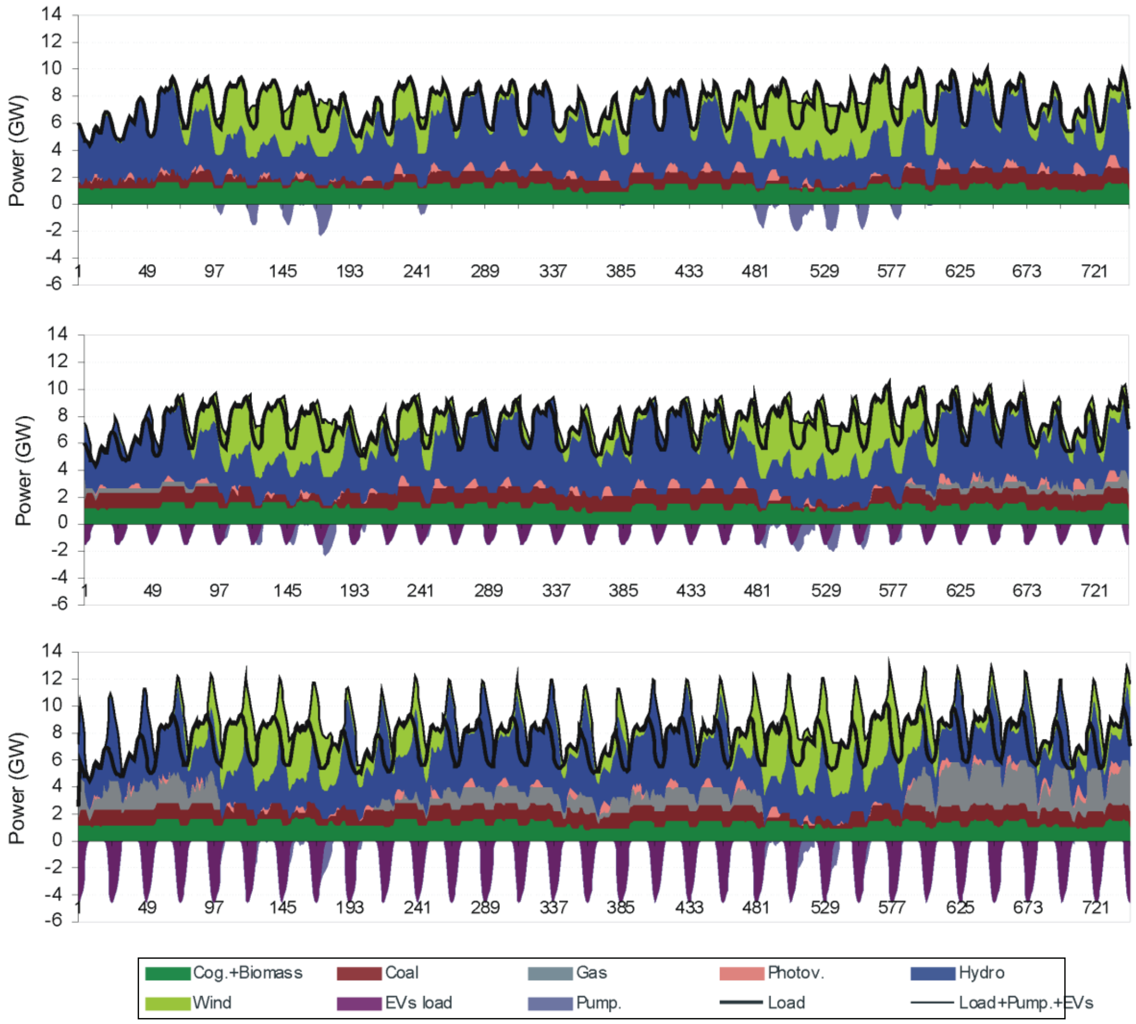

Figure 5: Generation by technology for 5600 MW of wind capacity and, respectively 0 EVs (top), 1.5 million EVs (middle) and 4.5 million EVs (bottom), for the month of January – night charge

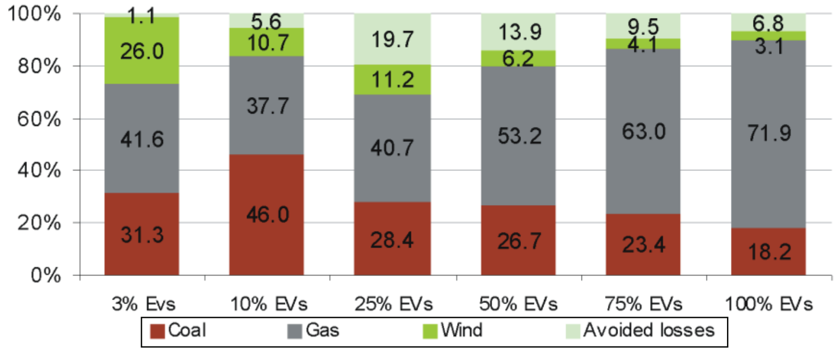

Figure 6: Marginal EV supply mix for increasing EV penetration - 10000 MW wind capacity scenarios – night charge

0.6 million EVs. However, for even higher EV penetration levels, since coal reaches the installed capacity, the same amount of coal generation will be used to supply a higher number of EVs, which results in a coal share decrease. The CO_2 specific emissions of the EV, in each scenario, result from the generation mix that supplies the

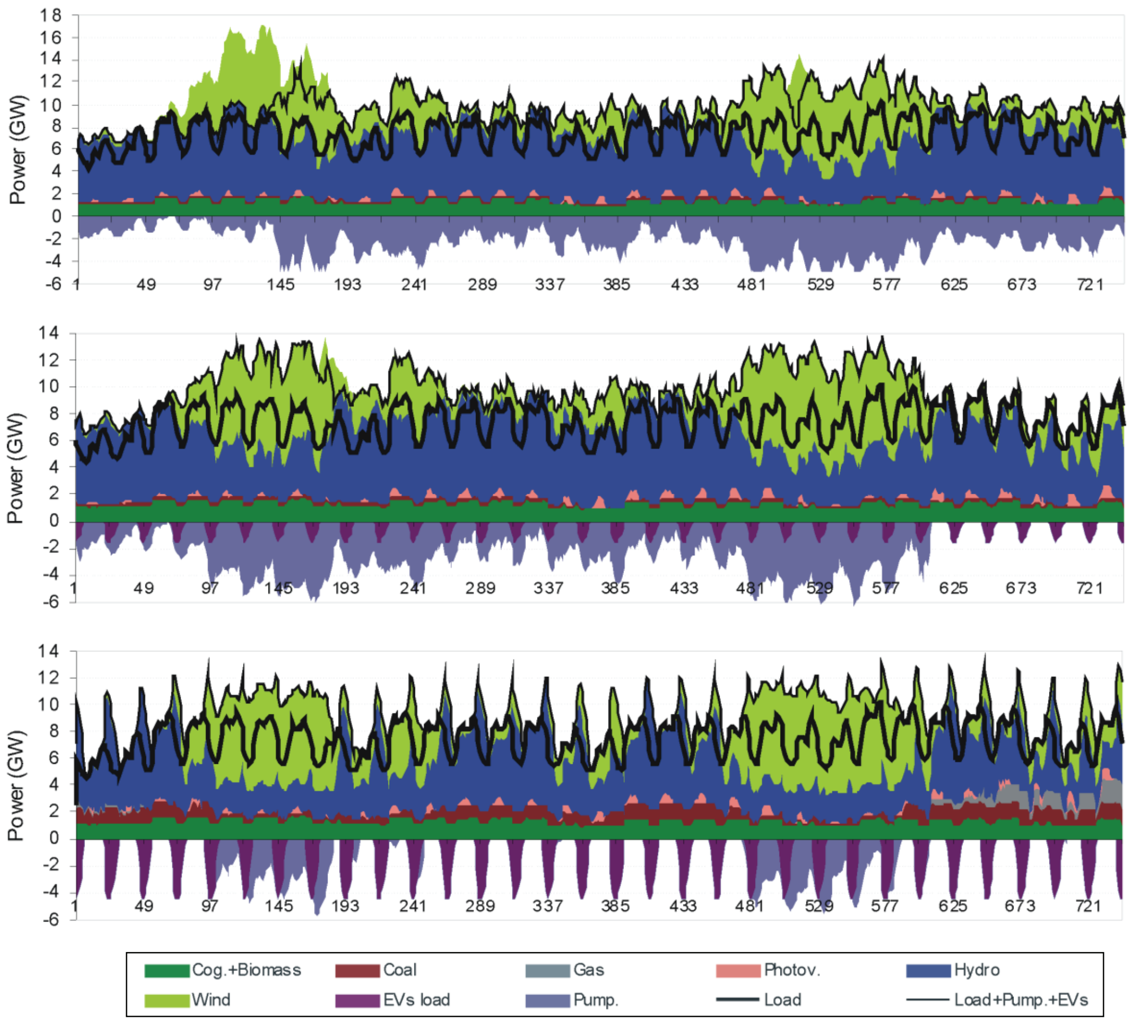

Figure 7: Generation by technology for 10000 MW of wind capacity and, respectively 0 EVs (top), 1.5 million EVs (middle) and 4.5 million EVs (bottom) for the month of January – night charge

EV, with the combined effect of the high emissions of coal, the intermediate emissions of gas and the zero emissions of wind and avoided pumping losses.

To illustrate some of the above-mentioned aspects, Figure 7 presents the generation by technology for a single month of simulation, for the 10000 MW wind capacity without EVs and with 1.5 million (25%) and 4.5 million (75%) EVs.

For the 25% EV penetration, wind is used to supply the EV, to lower the thermal generation to minimum (no gas and very little coal) and to increase pumping, which leads to additional hydro generation. For the 75% EV penetration, more wind will be directly used to supply this additional EV demand, reducing the amount of pumping and the consequent hydro generation. As this wind power is not enough to supply the EV in some periods, more thermal generation is used, mostly based on coal. For the periods in which the coal capacity is reached, gas units are also dispatched, as shown in Figure 7 (bottom) for the last days of the month.

The results presented in this section highlight the CO_2 emissions associated with the EV, based on the additional power generation needed for the EV charging. The EV emissions in each scenario result from the charging mix of coal (high emissions), gas (intermediate emissions), wind and avoided pumping losses (zero emissions). The analysis of a broad range of scenarios considered for the wind capacity, from the actual to more than double of the installed capacity, is not straightforward, as the additional wind power that results from more wind capacity is not necessarily used to charge the EV. In fact, in the base case more wind power in the generation mix will replace thermal generation and only the eventually curtailed wind generation will be used to supply the EV. The remaining EV demand will be supplied by thermal generation, firstly by the least costly technology, which is coal, and then by gas.

The impact of an increasing EV penetration is explained better by splitting the installed wind capacity into the non-curtailment and the curtailment scenarios. In the scenarios where no wind curtailment exists in the base case, the EV is supplied exclusively by coal and gas. As coal is firstly dispatched, but has a limited capacity, more EV integration leads to a decrease in the share of coal and the corresponding increase in the share of gas, with a positive effect in terms of CO_2 emissions.

Moreover, for the scenarios corresponding to the current wind capacity installed in the Portuguese system (about 5000 MW), if a linear evolution of the EV specific emissions between the EV penetration scenarios is considered, it can be observed that only for a penetration of about 1 million EVs, the emissions of the EV fleet are lower than the 95 g CO_2/km target. In the scenarios where wind curtailment exists in the base case, the EV emissions depend on a complex trade-off among the negative effect of coal, the intermediate effect of gas, and the positive effect of wind and avoided pumping losses.

Therefore, increasing the installed wind capacity in the Portuguese system up to a certain level does not assure a positive impact on the EV specific emissions. Also, critical to these results is the fact that coal generation, the most emitting technology, is cheaper than gas, thus first dispatched for charging the EV. Nonetheless, comparing the EV specific emissions with the 95 g CO_2/km target set by the European Union (EU) for the ICEV, the EV performed better in most scenarios analysed, especially those with low EV penetration and high wind capacity.

In what concerns the marginal EV costs, values are presented in Table 8. It can be verified, as expected, that the EV costs are lower for scenarios in which excess of wind generation is verified.

For the purpose of comparison, Table 9 presents the EV emissions considering a mix-based analysis. It can be verified that values are substantially different from the marginal values and follow a pattern. By one side, emissions decrease when increasing wind capacity, as more zero emissions generation is integrated. On the other side, emissions increase when increasing the EV

Table 8: Marginal EV specific costs (c€/km) – night charge

EVs	Wind capacity (MW)						
	5000	**5600**	**6875**	**7500**	**8700**	**10000**	**11000**
3%	0.89	0.82	0.76	0.85	0.53	0.61	0.35
10%	0.84	0.82	0.80	0.77	0.66	0.70	0.42
25%	0.84	0.83	0.81	0.80	0.72	0.58	0.51
50%	0.84	0.84	0.83	0.82	0.77	0.67	0.59
75%	0.85	0.84	0.83	0.83	0.79	0.73	0.66
100%	0.85	0.85	0.84	0.84	0.81	0.76	0.71

Table 9: EV mix based specific CO_2 emissions (g CO_2/km) – night charge

EVs	Wind capacity (MW)						
	5000	**5600**	**6875**	**7500**	**8700**	**10000**	**11000**
0%	38.0	35.6	30.6	27.8	23.5	20.0	17.6
3%	38.8	36.2	30.9	28.6	24.0	20.6	17.9
10%	39.8	37.3	32.4	29.8	25.5	22.5	18.7
25%	41.1	39.1	35.0	32.8	28.4	24.0	21.0
50%	43.1	41.2	37.7	36.1	32.6	28.1	25.1
75%	44.2	42.7	39.6	38.1	35.1	31.7	28.9
100%	45.8	44.0	41.1	39.7	37.0	34.0	31.7

Table 10: Marginal EV specific CO_2 emissions (g CO_2/km) for the UCED controlled charge and, comparison between controlled charge and night charge values (%)

EVs	Wind capacity (MW)						
	5000	**5600**	**6875**	**7500**	**8700**	**10000**	**11000**
3%	96.31	133.34	69.05	96.48	98.60	25.96	51.80
	–25.5%	**29.3%**	**5.3%**	**–16.7%**	**19.8%**	**–69.0%**	**–9.4%**
10%	94.22	107.66	98.90	105.64	92.97	65.56	51.14
	–10.1%	10.6%	3.9%	7.5%	–1.3%	–38.7%	–10.0%
25%	94.24	105.28	98.61	101.27	93.73	71.05	63.25
	12.4%	20.8%	2.6%	–0.3%	–2.0%	–9.3%	–7.9%
50%	81.12	86.13	94.46	99.08	97.69	83.65	77.56
	3.6%	8.2%	8.6%	6.0%	2.5%	–0.5%	0.4%
75%	77.67	80.98	88.52	93.47	97.83	89.01	79.44
	6.4%	7.4%	9.4%	9.9%	10.1%	4.7%	–2.3%
100%	89.30	78.81	84.86	88.22	91.56	89.98	87.23
	23.0%	7.7%	9.8%	9.6%	9.7%	9.4%	8.2%

Table 11: Marginal EV specific costs (c€/km) for the UCED controlled charge and, comparison between controlled charge and night charge values (%)

EVs	Wind capacity (MW)						
	5000	**5600**	**6875**	**7500**	**8700**	**10000**	**11000**
3%	0.79	0.81	0.73	0.73	0.59	0.38	0.34
	–11.2%	**–1.2%**	**–3.9%**	**–14.1%**	**11.3%**	**–37.7%**	**–2.9%**
10%	0.80	0.80	0.77	0.74	0.62	0.52	0.38
	–4.8%	–2.4%	–3.8%	–3.9%	–6.1%	25.7%	–9.5%
25%	0.83	0.82	0.78	0.77	0.68	0.54	0.47
	–1.2%	–1.2%	–3.7%	–3.8%	–5.6%	–6.9%	–7.8%
50%	0.83	0.83	0.81	0.80	0.74	0.64	0.55
	–1.2%	–1.2%	–2.4%	–2.4%	–3.9%	–4.5%	–6.8%
75%	0.86	0.83	0.82	0.82	0.78	0.70	0.63
	1.2%	–1.2%	–1.2%	–1.2%	–1.3%	–4.1%	–4.5%
100%	0.89	0.84	0.83	0.83	0.79	0.73	0.67
	4.7%	–1.2%	–1.2%	–1.2%	–2.5%	–3.9%	–5.6%

penetration, as the integrated wind generation and potential avoided losses are distributed for a larger number of vehicles.

4.2. Controlled charge

In this strategy, charging is controlled by the UCED and, whenever possible, charging will occur when there is available wind that, in the absence of EVs, is used for pumping or eventually curtailed. However, a complex trade-off among battery's SOC, EVs discharge, charging availability and wind availability is verified and, as the system must guarantee a minimum SOC, by the morning, coal or gas generation will be used if no wind is available. Tables 10 to 12 present the results obtained for

Table 12: EV mix based specific CO_2 emissions (g CO_2/km) for the UCED controlled charge, and comparison between controlled charge and night charge values (%)

EVs	Wind capacity (MW)						
	5000	5600	6875	7500	8700	10000	11000
3%	38.5	36.5	30.9	28.4	24.1	20.1	17.8
	–0.7%	**0.7%**	**0.1%**	**–0.6%**	**–0.6%**	**–2.4%**	**–0.3%**
10%	39.6	37.6	32.5	30.0	25.4	21.3	18.5
	–0.7%	0.8%	0.4%	0.7%	–0.2%	–5.2%	–1.0%
25%	41.8	40.3	35.2	32.8	28.2	23.5	20.7
	1.7%	3.1%	0.5%	–0.1%	–0.5%	–2.0%	–1.7%
50%	43.4	42.0	38.7	36.8	32.9	28.1	25.2
	0.8%	2.0%	2.5%	1.9%	0.9%	–0.1%	0.2%
75%	45.1	43.7	40.9	39.6	36.8	32.4	28.6
	1.9%	2.3%	3.4%	3.9%	4.6%	2.2%	–1.1%
100%	49.5	45.3	42.8	41.4	38.8	35.8	33.2
	8.2%	2.9%	4.1%	4.3%	4.9%	5.1%	4.7%

the UCED controlled charge, as well as, the comparison of these values with those previously obtained for the night charge strategy.

From the values presented in Table 10, it can be seen that controlled charging performs better than night charge, mostly in scenario in which curtailment exists when the EVs are not present. This is because in these scenarios, controlled charging provides a more effective integration of wind generation that otherwise would be curtailed. In what concern the EV marginal costs presented in Table 11, it is verified that, in almost all scenarios, controlled strategy lead to a decrease in generation costs

In what concerns the EV emissions, calculated with base on mix, the values are presented in table 12.

When compared to the night charge strategy, as for the marginal EV specific CO_2 emissions, when accounting the EV mix based specific CO_2 emissions, the controlled charge tends to perform better in scenarios where wind curtailment is higher and EV penetration is lower, since with this type of charging strategy more generation with zero emissions is used to charge the EV.

5. Conclusions

Nowadays, global warming is seen with growing concern. Aware of this problem, governments, all over the world, are taking measures to tackle global warming. Some of these measures are directed to promote the replacement of ICEVs by EVs, due to the null tailpipe emissions of the later. However, the EV specific CO_2 emissions, resulting from the electricity generation, are highly dependent on the specific CO_2 emissions of the generation mix used to supply the EV demand. In this regard, caution must be taken when making aprioristic assumptions about the better performance of EVs over ICEVs. In this work, the impact, in terms of CO_2 emissions, of increasing EV penetration in the Portuguese vehicle fleet, is analysed for a whole year on an hourly basis.

The analysis considers several scenarios for EV penetration, as well as, scenarios for the installed wind capacity. Also, the advantages of replacing ICEVs by EVs in the different scenarios are analysed and compared against the 95 g CO_2/km target set by the EU.

Among the different ways to account the EV specific CO_2 emissions, this work used the marginal power mix approach, which computes the EV specific emissions from the difference between the specific CO_2 emissions of the power system when supplying the demand, including the EV demand, and the specific emissions of the power system when supplying the demand without EVs. Thus, paramount to the impact of the EV penetration in terms of CO_2 emissions is the available generation that is not used without EVs. If the EVs are supplied only with wind power the EV specific CO_2 emissions will be zero and this will be the case where EVs are environmentally more beneficial. The worst situation would be the one where EVs were only supplied from coal power plants, presenting specific CO_2 emissions of about 175 g CO_2/km. In between the referred situations would be the case where EVs were supplied only from gas power plants, with specific CO_2 emissions of 70 g CO_2/km.

According to the results obtained, for the scenarios considered, the marginal EV specific CO_2 emissions range from 57 g CO_2/km, for high wind capacity and low EV penetration, to 129 g CO_2/km, for low wind capacity and low EV penetration for the night charge strategy, whereas for controlled charge, it varies from 26 g CO_2/km, for high wind capacity and low EV penetration to 133 g CO_2/km, for low wind capacity and low EV penetration. The better performance of controlled charge is due to a better integration of wind especially in scenarios where wind curtailment exists. Another conclusion derived from the results is the fact that with the current wind capacity of the Portuguese system (about 5000 MW), the impact of the EV in terms of CO_2 emissions is not beneficial when compared to the 95 g CO_2/km target, for penetrations lower than 1 million vehicles. However, if a controlled charge strategy is put in place, the impact would not be beneficial only for EV penetrations of 180 thousand vehicles. Notwithstanding, results also show that, even with coal having merit over gas, it is possible to integrate EVs in the system, in an environmental beneficial way, if increasing EV penetrations are combined with an increase in the installed wind capacity.

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References

[1] IEA, CO_2 emissions from fuel Combustion-Highlights, 2019 edition, Tech. rep., International Energy Agency (Nov. 2019).

[2] EIA, International Energy Outlook 2019, Tech. rep., U.S. Energy Information Administration (Set. 2019).

[3] L. Setiartiti, R. Hasibi, Low carbon-based energy strategy for transportation sector development, International Journal of Sustainable Energy Planning and Management 19 (2019) 29-44. https://doi.org/10.5278/ijsepm.2019.19.4.

[4] W. Kempton, S. E. Letendre, Electric vehicles as a new power source for electric utilities, Transportation Research Part D: Transport and Environment 2 (3) (1997) 157–175. https://doi.org/10.1016/S1361-9209(97)00001-1.

[5] W. Kempton, J. Tomic, Vehicle-to-grid power fundamentals: Calculating capacity and net revenue, Journal of Power Sources 144 (1) (2005) 268–279. https://doi.org/10.1016/j.jpowsour.2004.12.025.

[6] Y. Zhao, M. Noori, O. Tatari, Vehicle to grid regulation services of electric delivery trucks: Economic and environmental benefit analysis, Applied Energy 170 (2016) 161–175. https://doi.org/10.1016/j.apenergy.2016.02.097.

[7] N. Juul, G. Pantuso, J. Iversen, T. Boomsma, Strategies for charging electric vehicles in the electricity market, International Journal of Sustainable Energy Planning and Management 7. https://doi.org/10.5278/ijsepm.2015.7.6.

[8] W. Kempton, J. Tomic, Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy, Journal of Power Sources 144 (1) (2005) 280–294. https://doi.org/10.1016/j.jpowsour.2004.12.022.

[9] D. Keiner, M. Sterner, Cost and self-consumption optimized residential PV prosumer systems in Germany covering residential electricity, heat and mobility demand, International Journal of Sustainable Energy Planning and Management 21 (2019) 35-58. https://doi.org/10.5278/ijsepm.2019.21.4.

[10] T. K. Kristoffersen, K. Capion, P. Meibom, Optimal charging of electric drive vehicles in a market environment, Applied Energy 88 (5) (2011) 1940–1948. https://doi.org/10.1016/j.apenergy.2010.12.015.

[11] N. Juul, P. Meibom, Optimal configuration of, an integrated power and transport system, Energy 36 (5) (2011) 3523–3530. https://doi.org/10.1016/j.energy.2011.03.058.

[12] WEF, Repowering Transport, Tech. rep., World economic Forum (Apr. 2011).

[13] OECD/ITF, Reducing Transport Greenhouse Gas Emissions -Trends & Data 2010, Tech. rep., International Transport Forum (2010).

[14] IEA, CO_2 Emissions from Fuel Combustion - Highlights, 2009 edition, Tech. rep., International Energy Agency (2009).

[15] S. Bellekom, R. Benders, S. Pelgrom, H. Moll, Electric cars and wind energy: Two problems, one solution? a study to combine wind energy and electric cars in 2020 in the Netherlands, Energy 45 (1) (2012) 859–866, the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy, ECOS 2011. https://doi.org/10.1016/j.energy.2012.07.003.

[16] IEA, Global EV Outlook 2017, Tech. rep., International Energy Agency (Jun. 2017).

[17] W. P. Schill, C. Gerbaulet, Power system impacts of electric vehicles in Germany: Charging with coal or renewables?, Applied Energy 156 (2015) 185–196. https://doi.org/10.1016/j.apenergy.2015.07.012.

[18]European Parliament, Roadmap to a single European transport area - towards a competitive and resource efficient transport system, [Online], Available https : //eur - lex.Europa.eu/legal - content/EN/TXT/PDF/?uri = CELEX : 52011DC0144&from = EN (Mar. 2011).

[19] European Parliament, Parliament backs law to cut car CO_2 emissions, [Online], Available http : //www.europarl.Europa.eu (accessed 25-08-2014).

[20] European Commission, CO_2 emission performance standards for cars and vans (2020 onwards), [Online], Available https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en (accessed 28-11-2019).

[21] K. Hedegaard, H. Ravn, N. Juul, P. Meibom, Effects of electric vehicles on power systems in northern Europe, Energy 48 (1) (2012) 356–368. https://doi.org/10.1016/j.energy.2012.06.012.

[22] S. Dhar, M. Pathak, P. Shukla, Electric vehicles and india's low carbon passenger transport: A long-term co-benefits assessment, Journal of Cleaner Production https://doi.org/10.1016/j.jclepro.2016.05.111.

[23] A. Manjunath, G. Gross, Towards a meaningful metric for the quantification of GHG emissions of electric vehicles (EVs), Energy Policy 102 (2017) 423-429. https://doi.org/10.1016/j.enpol.2016.12.003.

[24] L. Canals Casals, E. Martinez-Laserna, B. García, N. Nieto, Sustainability analysis of the electric vehicle use in Europe for CO_2 emissions reduction, Journal of Cleaner Production 127. https://doi.org/10.1016/j.jclepro.2016.03.120.

[25] S. Bellocchi, K. Klockner, M. Manno, M. Noussan, M. Vellini, On the role of electric vehicles towards low-carbon energy systems: Italy and Germany in comparison, Applied Energy 255 (2019) 113848. https://doi.org/10.1016/j.apenergy.2019.113848.

[26] M. Rupp, N. Handschuh, C. Rieke, I. Kuperjans, Contribution of country-specific electricity mix and charging time to environmental impact of battery electric vehicles: A case study of electric buses in Germany, Applied Energy 237 (2019) 618–634. https://doi.org/10.1016/j.apenergy.2019.01.059.

[27] P. Jochem, S. Babrowski, W. Fichtner, Assessing CO_2 emissions of electric vehicles in Germany in 2030, Transportation Research Part A: Policy and Practice 78 (2015) 68–83. https://doi.org/10.1016/j.tra.2015.05.007.

[28] A. Ensslen, H. Steffens, W. Fichtner, O. Wollersheim, K. Stella, P. Jochem, Empirical carbon dioxide emissions of electric vehicles in a French-German commuter fleet test, Journal of Cleaner Production 142. https://doi.org/10.1016/j.jclepro.2016.06.087.

[29] K. Skytte, R. Bramstoft, Decarbonizing Sweden's energy and transportation system by 2050 (2017) 3 https://doi.org/10.5278/ijsepm.2017.14.2.

[30] D. J. Swider, Compressed Air Energy Storage in an Electricity System with Significant Wind Power Generation, Energy Conversion, IEEE Transactions on 22 (1) (2007) 95 -102. https://doi.org/10.1109/TEC.2006.889547.

[31] S. Faias, J. de Sousa, R. Castro, Environmental dispatch of the Portuguese power system for CO_2 emissions reduction, in: Energy Market (EEM), 2011 8th International Conference on the European Energy Market, 2011, pp. 389 -394. https://doi.org/10.1109/EEM.2011.5953043.

[32] REN, Plano de Desenvolvimento e Investimento da Rede de Transporte 2012-2017(2022), Tech. rep., Rede Elétrica Nacional (Apr. 2011).

[33] REN, Centro de Informação - Centrais Termoeléctricas, [Online], Available http : //www.centrodeinformacao.ren.pt/PT/InformacaoTecnica/Paginas/CentraisTermoelectricas.aspx (2012).

[34] S. A. Lothar Balling, Fast cycling and rapid start-up: new generation of plants achieves impressive results (Jan. 2010).

[35] T. Traber, C. Kemfert, Gone with the wind? - Electricity market prices and incentives to invest in thermal power plants under increasing wind energy supply, Energy Economics 33 (2) (2011) 249-256. https://doi.org/10.1016/j.eneco.2010.07.002.

[36] ERSE, Comercio europeu de licenças de emissão de gases com efeito de estufa - análise para portugal do periodo 2005-2010, Tech. rep., Entidade Reguladora dos Serviços Energéticos (Jan. 2012).

[37] Agência Portuguesa do Ambiente, CELE - Tabela de valores de Poder Calorifico Inferior e Factor de Oxidação de CO_2, [Online], Available http : //www.apambiente.pt/_ zdata/DPAAC/CELE/tab_val_PCI_FE_FO.pdf, (2008).

[38] REN, Centro de Informação - Estatistica Diária, [Online], Available http://www.centrodeinformacao.ren.pt/PT/InformacaoExploracao/P aginas/EstatisticaDiariaHidraulica.aspx (2012).

[39] Instituto da Agua I.P., Barragens de portugal, http://cnpgb.inag.pt/gr_barragens/gbportugal (accessed 19-06-2012). URL cnpgb.inag.pt/gr_barragens/gbportugal

[40] COBA/PROCESL, PNBEPH - Programa nacional de barragens com elevado potencial hidroeléctrico, Tech. rep., DGEG/IA/REN (Nov. 2007).

[41] Instituto da Agua I.P., PNBEPH, http://pnbeph.inag.pt/np4/p/projectos (accessed 16-07-2013). http://pnbeph.inag.pt /np4 /p /projectos.

[42] EDP, Novas Barragens, [Online], Available http ://www.a-nossa-energia.edp.pt/centros_produtores (accessed 16-07-2013).

[43] REN, Caracterização da Rede Nacional de Transporte para Efeitos de Acesso à Rede em 31 de Dezembro de 2011, Tech. rep., REN (Mar. 2012).

[44] European Union, EU transport in figures - Statistical pocketbook 2018, 2018.

[45] P. MERGE, Mobile energy resources in grids of electricity, Tech. Rep. WP 3 Task 3.2 (Part II) Deliverable D 3.2, European Commission (Feb. 2012).

[46] M. Collins, G. Mader, The timing of EV recharging and its effect on utilities, IEEE Transactions on Vehicular Technology 32 (1) (1983) 90–97. https://doi.org/10.1109/T-VT.1983.23948.

[47] ERSE, Caracterizaçãoo da procura de energia eléctrica em 2016, Tech. rep., Entidade Reguladora dos Serviços Energéticos (Dec. 2015).

[48] E. D. Tate, M. O. Harpster, P. J. Savagian, The electrification of the automobile: from conventional hybrid, to plug-in hybrids, to extended-range electric vehicles, Tech. Rep. 2008-01-0458, Oak Ridge National Laboratory (ORNL) (2008).

[49] Mobilidade casa - trabalho da população empregada residente na AMP - 2000, Tech. rep., Instituto Nacional de Estatistica (INE) (2003).

[50] Inquérito à mobilidade nas áreas metropolitanas do porto e de lisboa - 2017, Tech. rep., Instituto Nacional de Estatistica (INE), INE (2018).

[51] H. Lund, W. Kempton, Integration of renewable energy into the transport and electricity sectors through V2G, Energy Policy 36 (9) (2008) 3578-3587. https://doi.org/10.1016/j.enpol.2008.06.007.

[52] P. Ferreira, I. Soares, R.M. Johannsen, P.A. Østergaard, Policies for new energy challenges, International Journal of Sustainable Energy Planning and Management 26 (2019). https://doi.org/10.5278/ijsepm.3552.